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► **To cite this version:**

Nicolas Pinoteau, Pauline Anest Bavoux (Dir.). FSF 2019, 3rd International Symposium on Fire Safety of Facades. ANEST-BAVOUX P.; PINOTEAU N. CSTB, 2019. hal-03388290

HAL Id: hal-03388290

<https://cstb.hal.science/hal-03388290v1>

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FIRE SAFETY OF FACADES 2019

Edited by Pauline Anest-Bavoux & Nicolas Pinoteau



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EDITORIAL

The 3rd International Fire Safety of Facade (FSF 2019) is held in Paris, France from September 25 to 27 st, 2019. Organised by CSTB (Centre Scientifique et Technique du Bâtiment), the French Building Research Institute, FSF is a three-day event that fosters dialogue among scientists, academics and professionals from around the world related to the research and development in the field of facade fire safety.

FSF 2019 promote the cooperation between manufacturers and researchers. In the attempt to contribute to risk mitigation to reduce consequences on human life and property, the objectives of the international symposium are the following:

- to present the latest state of the art in the knowledge of fire safety for facade,
- to gather experts of this domain to discuss research questions and practical application,
- to emphasize the importance of further development of research.

Symposium scope & topics:

FSF 2019 encourages participation of engineers, researchers, industrialists and regulation experts working in the field of facade fire safety.

Participants interested in presenting scientific work are invited submit abstracts related to the following topics:

- 1-Facade materials and systems behaviour in fire
- 2-Facade testing and fire propagation
- 3-Facade testing and assessments methods
- 4-Numerical modelling and case studies
- 5-Risk Management and Regulation

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PARTNERSHIP

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SECURO



SESSION 1: FACADE MATERIALS AND SYSTEMS BEHAVIOUR IN FIRE

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Christian Northe, Judith Küppers, Jochen Zehfuß
Technische Universität Braunschweig, Institute of Building Materials,
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FIRE BEHAVIOUR OF FAÇADE PRODUCTS

T Richard Hull
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ABSTRACT

The fire enveloping Grenfell Tower spread rapidly round the combustible façade system, killing 72 people. The fire behaviour of different types of façade product was investigated using micro-scale and bench-scale methods, in order to understand the rapid fire spread and lethality of the fire. The polyethylene-aluminium composite panels showed fifty times greater peak heat release rates (pHRR) and seventy times greater total heat release (THR), while widely-used high-pressure laminate panels showed twenty five times greater pHRR and over one hundred times greater THR, compared to the least combustible panel products. The insulation materials also showed large differences: polyisocyanurate (PIR) foam showed fifteen times more pHRR and over thirty times more THR, while phenolic foam (PF) showed ten times more pHRR and fifty times more THR. Smoke from PIR was fifteen, and PF five times more toxic than from mineral wool insulation. A kilogram of burning PIR insulation is sufficient to fill a 50 m³ room with an incapacitating and ultimately lethal effluent.

1 INTRODUCTION

The presence of combustible material on building envelopes is most critical to fire safety in the case of tall and multi-occupancy structures. Fire safety is usually ensured through compartmentation: the use of fire resistant walls, doors, ceilings and floors prevents fire spreading from one compartment to another inside the building. If there is inadequately protected combustible cladding on the external walls this undermines the compartmentation strategy by providing a conduit to spread the fire to the other compartments via the facade. When such external fire spread occurs, it endangers the people who follow the UK fire service advice for occupants of tall buildings to “stay put” (wait to be rescued).

The Grenfell Tower was completed in 1974, with concrete exterior walls. It is a 67 m structure with 24 storeys, of which the upper 22 were residential accommodation. In 2016, an £8.7 million refurbishment was completed, including £2.6 million for an insulated rainscreen façade system of combustible foam insulation and aluminium-polyethylene composite material, separated by a ventilated cavity around the exterior of the building. The intensity of the fire caused both the aluminium and polyethylene (PE) in the ACM to melt, drip and burn. The cavity barriers were rendered useless without an ACM surface on which to form a seal.

The Grenfell Tower fire was not an isolated incident. There have been several fires in tall buildings where the fire spread rapidly up the outside, but only involved PE filled ACM, without combustible insulation. In the 2013 Grozny City Towers fire in Chechnya, the combustion of PE filled ACM and stone wool insulation led to a rapid flame spread, but the fire did not cause any deaths or spread into the building, which re-opened in 2015. The Address Downtown Hotel fire in Dubai, just before New Year 2016, also involved PE filled ACM but no insulation: again the fire did not spread inside the building, and there were no deaths, although one guest had a heart attack during the evacuation. Thus, it seems likely that it was the combination of the PE filled ACM, cavity and insulation that led to the

Grenfell tragedy. This resulted in a more severe external fire, which then penetrated almost every apartment in the tower. In general, the biggest killer, and biggest cause of injury in fires is not heat, burns or structural collapse, but the toxicity of the fire effluent. This has been the case for several decades and has been reported regularly in summaries of the UK and US fire statistics [1, 2].

This paper presents highlights from a more detailed study, which includes thermal analysis and simple models which predict large scale test behaviour [3]. The aim of this paper is to assess the suitability of typical rainscreen façade products using micro-scale and bench-scale flammability assessments and toxic product evolution.

2 EXPERIMENTAL

2.1 Materials

Commercial products, designed for use in façade systems, were the subject of this study. These included: panel products, ACMs filled with polyethylene (PE), fire retarded polyethylene (FR), and an essentially non-combustible core (NC), together with phenol-formaldehyde high pressure laminates with (HPL_FR) and without (HPL_PF) fire retardants and mineral wool boards (MWB); insulation products, polyisocyanurate (PIR), phenolic foams (PF) and mineral wool (MW) are also included in the study.

2.2 Reaction-to-fire behaviour

The fire behaviour of the products was assessed using microscale combustion calorimetry (ASTM D 7309) and cone calorimetry (ISO 5660). The combustion toxicity of the insulation products was assessed using the steady state tube furnace (ISO/TS 19700).

3 RESULTS AND DISCUSSION

3.1 Flammability

3.1.1 Microscale Combustion Calorimetry

The rate of heat release of the panel fillings is shown in Figure 1, with a peak of heat release under pyrolysis conditions for all ACM filler materials just below 500 °C. The large and sharp peak of the PE filling is very significant, both to this work, and the Grenfell Tower fire. The total heat release is the area under each curve, and the peak is the pyrolysis temperature. This shows the contribution different filler loadings make to the heat release rate, and that the peak decomposition temperature of the polymeric fuel is always close to 500 °C, except for the HPL products (HPL_PF, 350 °C and HPL_FR, 290 °C).

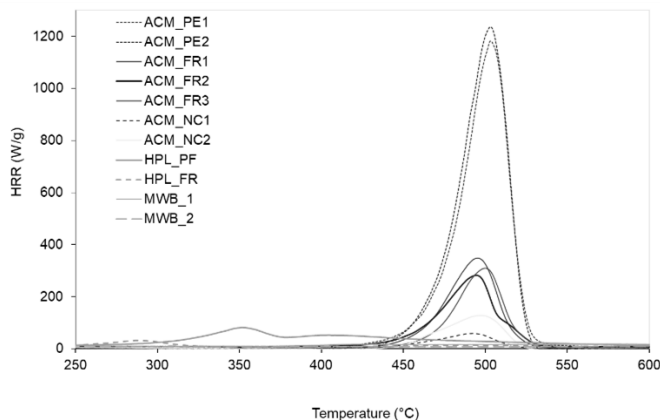


Figure 1 Heat release of panel filling material by microscale combustion calorimetry

Figure 2 shows very different rate of heat release data for the insulation, with much more gradual heat release occurring over the full temperature range (70 to 700 °C), and distinct peaks at 300 to 400 °C for PIR foams and at 500 °C for phenolic foams. The steady, low heat release from the binders of the stone and glass wool show clear differences between these products and the foams.

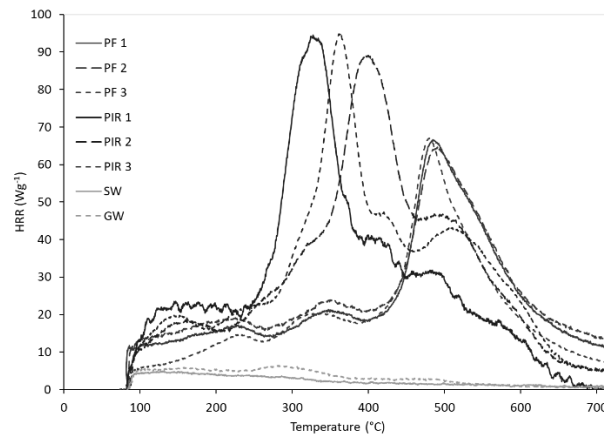


Figure 2 Heat release of insulation materials by microscale combustion calorimetry (note the use of different scales to Figure 1).

3.1.2 Cone Calorimetry

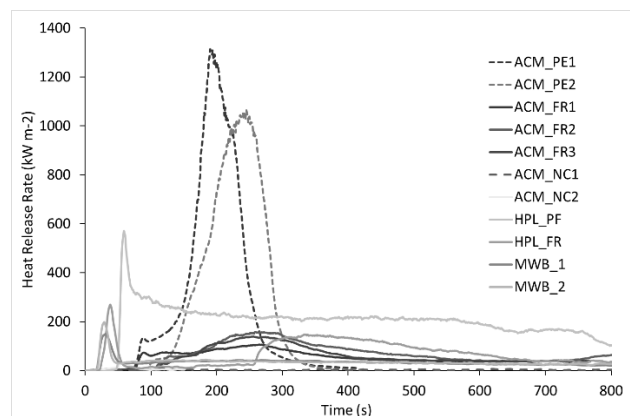


Figure 3 HRR of 70 x 70 mm² panels in the cone calorimeter at 50 kW m⁻².

The heat release rate (HRR) in cone calorimetry (Figure 3) also shows notable differences in combustibility of the different panels. All of the panel materials ignited in the cone calorimeter, although this only involved the paint finish for ACM_NC1 and NC2 and MWB_1 and MWB_2. High, sharp peaks of heat release rate were observed for ACM_PE1 and ACM_PE2, reaching a maximum of 1300 and 1050 kW m⁻² at 190 and 250 s respectively. Moreover, ACM_PE1 and ACM_FR1, both from the same manufacturer, showed a notably earlier time to ignition than their competitor panels. Almost no residue remained between the aluminium plates after the test for PE1 and PE2. The ACM_FRs underwent sustained flaming, but with a significantly lower HRR. It is clear that the combination of the protective aluminium sheets, and the metal hydroxide fire retardant at 65% loading, effectively reduces the flammability under these conditions. The Al(OH)₃ of ACM_FR2 [3] is notably less effective than the Mg(OH)₂ of ACM_FR1 [3] and ACM_FR3 at similar loadings. The initial peak from MWB_1 and MWB_2 and smaller peak from ACM_NC2 are also believed to result from the burning paint.

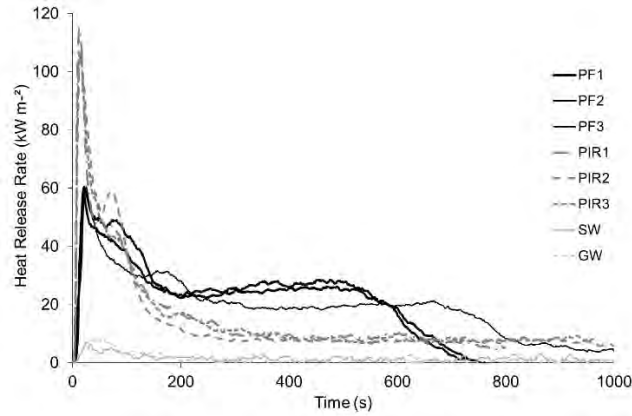


Figure 4 HRR of insulation materials in the cone calorimeter at 50 kW m².

Figure 4 shows all the insulation foams undergo very rapid ignition and early peak of heat release rate (pHRR). However, the highest peaks are an order of magnitude less than those of the ACM_PE. There are clear differences between the burning behaviour of PIR and phenolic foams. The PIRs show a higher initial pHRR and lower steady burning rate, after formation of a protective char layer; the phenolic foams show a lower initial pHRR, but a higher steady burning rate.

3.2 Smoke Toxicity

The fire condition and hence the toxicity of burning ACM fillings on the side of a tower is too difficult to predict from bench scale experiments. The burning of the PIR and phenolic foam behind the ACM on Grenfell Tower would almost certainly have been under-ventilated (uv) possibly with initial conditions lying between small (650 °C) and large (825 °C) developed flaming conditions. Figure 5 shows the relative contribution to incapacitation from HCN and CO from burning 1 kg of insulation material after 5 min exposure under the stated fire condition, with the effluent dispersed over an arbitrary volume of 50 m³ (a large room or small apartment). Burning this amount of phenolic foam in uv conditions is predicted to cause incapacitation to somewhat less than 50% of the exposed population, as the FED is less than one. However, burning this amount of any of the three PIR foams used in this study would exceed the threshold for incapacitation by a factor of between 2 and 4 if the burning was ventilation-controlled. The higher toxicity of PIR results from the presence of nitrogen in the polymer, which forms HCN on burning, particularly in under-ventilated conditions. Once incapacitation has occurred, the victim can no longer effect of their own escape, and unless rescued, will continue to uptake CO and HCN until breathing ceases. The very low levels of binder in SW and GW generate correspondingly low levels of asphyxiants.

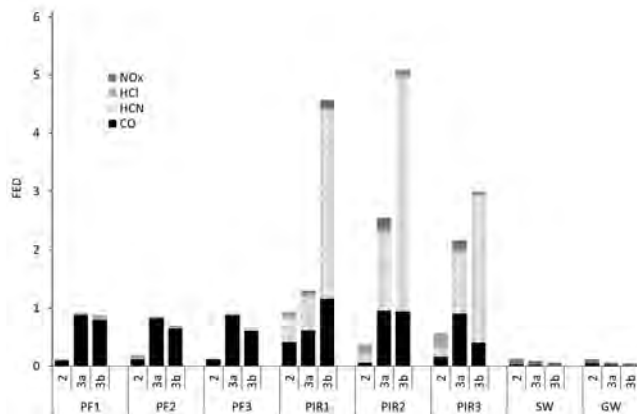


Figure 5 FED for incapacitation following 5 minutes exposure from burning 1 kg with the effluent dispersed in a volume of 50 m³.

The material-LC₅₀ values shown in *Table 1* provide the most direct route to estimating a safe loading of insulation material. The material-LC₅₀ is the mass of material required to produce a lethal concentration of effluent per unit volume. It is therefore inversely proportional to toxicity. For example, 5 g of PIR 1, burning in large under ventilated conditions at 825 °C uv would fill 1 m³ with an effluent lethal to 50% of the exposed population.

Table 1 Material-LC₅₀ values for each insulation material and fire condition

Sample	Temperature /°C	Material-LC ₅₀ /g m ⁻³
PF1	650	45.57
	650	14.01
	825	17.01
PF2	650	43.94
	650	14.55
	825	20.99
PF3	650	43.02
	650	12.47
	825	15.98
PIR1	650	13.29
	650	9.98
	825	5.00
PIR2	650	21.04
	650	6.28
	825	5.30
PIR3	650	18.52
	650	6.95
	825	7.75
SW*	650 – NF	74.19
	650 – NF	117.39
	825 – NF	163.96
GW*	650 – NF	66.69
	650 – NF	100.03
	825 - NF	171.36

* The mineral wool samples did not ignite (hence NF non-flaming), but for completeness they were also tested under the same conditions as the flaming samples.

4 CONCLUSIONS

In the aftermath of the Grenfell Tower tragedy there are a number of unanswered questions. This study came about because of the lack of published information relating to the fire behaviour and smoke toxicity of façade products, and the reliance on the large-scale tests.

- The data show good consistency between scales and highlight large differences in fire behaviour between different products, both for panels and insulation products.

- Similar products of the same generic type (e.g. ACM_FR, or PIR) show little difference in the burning behaviour for that product type, or in the case of the insulation materials, in the smoke toxicity.
- The bench-scale burning behaviour shows the most dramatic differences between the ACM_PE and the ACM_FR and ACM_NC materials. This illustrates clearly how ACM_PE contributes to very rapid fire spread when used to clad the exterior of a building. It also identifies a potential problem with HPL_PF. The bench-scale burning behaviour of the PIR and PF shows the contrasting effect of the more resilient char on the PIR (higher initial peak followed by lower HRR) compared to the PF (lower peak HRR but a higher steady HRR). The lack of heat release from the stone and glass wool materials is expected, but is crucially important in understanding how to prevent further tragedies, demonstrating the availability of alternative non-combustible insulation.
- In the under-ventilated conditions of flaming within the cavity, the SSTF data show a factor of 3 increase in smoke toxicity for PIR, compared to PF. The non-combustible GW and SW products show smoke toxicity lower than the PF by a factor of around 30. Again, these results have very clear implications for those selecting products to ensure the fire safety of occupants.
- The evidence presented in this paper challenges the statements such as “the test results with regard to heat release rates, smoke and toxic gas emissions show that the organic polyisocyanurate insulation and the mineral fibre insulation behave similarly during the fire” made by the combustible foam industry⁴, that their insulation products do not constitute a safety hazard.
- If combustible materials had been prohibited from the outside of tall buildings, as they are in most of Europe, this tragedy could not have occurred. Instead, in the UK, there is a convoluted process through large-scale tests and “desktop studies” where “combustible” can be considered as “non-combustible” allowing combustible materials to be put on the outside of buildings, with disastrous consequences.

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-
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 - [2] Hall, J. R., Fatal Effects of Fire, National Fire Protection Association, Quincy, MA, (2011). <https://www.nfpa.org/News-and-Research/Fire-statistics-and-reports/Fire-statistics/Demographics-and-victim-patterns/Fatal-effects-of-fire>
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FIRE SAFETY OF PREFABRICATED TIMBER FRAMED FAÇADE SYSTEMS ON MID- AND HIGH- RISE BUILDINGS

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ABSTRACT

Prefabricated timber framed façade systems represent an interesting and upcoming way to realise energy and resource efficient building envelopes. These systems can be applied for building renovations but also for new buildings (hybrid constructions).

The façade system needs to fulfil country-specific fire resistance and fire behaviour requirements. Especially for mid- and high rise buildings the wooden substructure has to be protected in such a way that they do not contribute to the fire during a certain time period.

This paper represents research results concerning the fire resistance of such prefabricated timber framed façade systems and the protection ability of gypsum fibre boards exposed to the external fire exposure curve. The test results are compared to test results of fire resistance tests using the standard temperature-time curve. Additionally, numerical simulations are presented to allow the prediction of the test results. Finally, the test results were also used to classify the fire resistance of the non-load bearing prefabricated façade system as EI 90-ef_(o→i).

1 INTRODUCTION

Building envelopes with prefabricated timber framed façade systems ensure energy and resource efficiency for thermal building refurbishment and new external walls. Considerable research results regarding planning, mounting, building physics, fire safety of prefabricated timber framed façade systems are published by the Chair of Timber Structures and Building Construction of the Technical University of Munich [1-3] and by the Department of Timber Engineering of the University of Innsbruck [4-8].

The combustible wooden substructure in the prefabricated façade system is a deviation of conventional requirements in Austria and other countries for mid- and high rise buildings. One way to argue with local building authorities is to show that all combustible parts are protected in such a way that they do not contribute to the fire during a specific time period.

Conventionally fire resistance tests as well as tests to determine the fire protection ability of coverings are conducted by using the standard temperature-time curve. But for building envelopes, which are exposed to an external fire, the external fire exposure curve acc. to ÖNORM EN 1363-2 [9] can be appropriate. Acc. to ÖNORM EN 1991-1-2 [10] the external fire curve is a “*nominal temperature-time curve intended for the outside of separating external walls which can be exposed to fire from different parts of the façade, i.e. directly from the inside of the respective fire compartment or from a compartment situated below or adjacent to the respective external wall*”.

So far, there are hardly any information and literature about tests conducted with the external fire curve – neither in the commercial nor in the scientific field.

2 FIRE TEST

A fire resistance test for non-loadbearing walls according to ÖNORM EN 1364-1 [11] is performed with two different arrangements of coverings. The temperature developments are recorded and evaluated in the oven, between the wooden substructure and the gypsum fibreboard, between the insulation and the gypsum fibreboard and additionally on the non-fire exposed side of the element. One key issue was to determine the fire protection abilities of the two arrangements of the gypsum fibre board coverings. Furthermore, fire resistance tests and test reports provided by the producer allow the comparison of the fire protection ability of the coverings exposed to different nominal temperature-time curves (Fig. 1a). Numerical simulations were conducted to show the predictability of such fire tests.

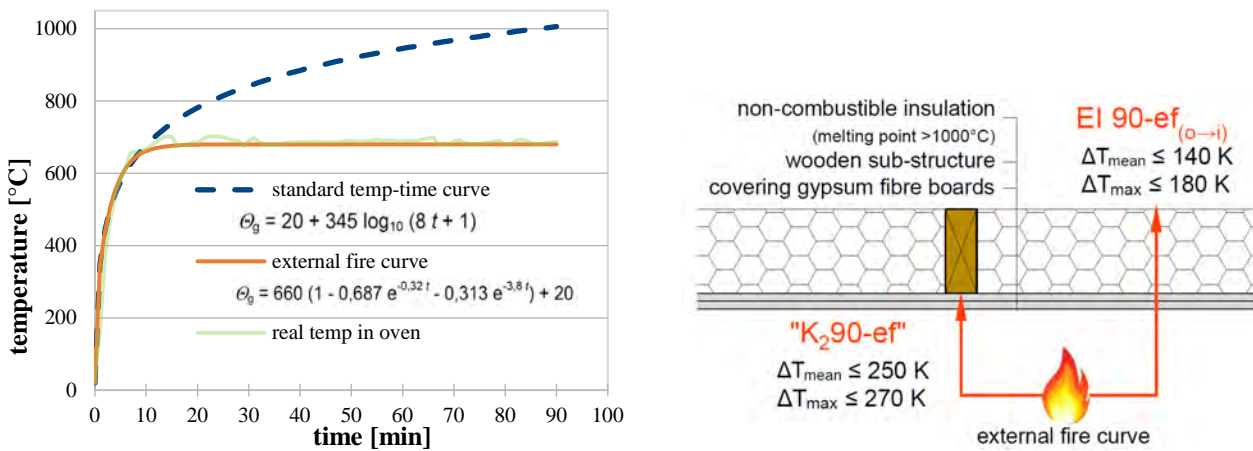


Fig. 1. a) standard vs. external temp-time curve;
 b) performance criteria for the fire resistance and the fire protection ability

The performance criteria for the fire resistance test and for the fire protection ability of coverings are defined in ÖNORM EN 13501-2 [12] and are visualised in Fig. 1b. The temperature increase on the non-fire exposed side has to be below 140 K respectively 180 K during the test period. Since this test is based on a fire resistance test of non-loadbearing walls according to ÖNORM EN 1364-1 [11] and ÖNORM EN 13501-2 [12] the façade system can be classified as EI 90-ef_(o→i) if the requirements are fulfilled.

To evaluate the fire protection ability of the covering the limit temperature increase of the wooden substructure is either the mean temperature increase of 250 K or the maximum temperature increase of 270 K. This temperature criterion corresponds quite well with definitions defined in timber specific standards, acc. to ÖNORM EN 1995-1-2 [13] and ÖNORM prEN 13381-7 [14] “the border-line between char layer and the residual cross section assumed to be equal with the position of the 300°C isotherm.”

Due to the fact that acc. to ÖNORM EN 13501-2 [12] the fire protection ability K₂ is not defined for a classification period of 90 minutes the protection ability of the covering is called “K₂90-ef” in Fig. 1b. Additionally, acc. to ÖNORM EN 14135 [15] for classification a horizontal furnace shall be used with the standard temperature-time curve as fire exposure.

2.1 Test specimen

Two different compositions of coverings were tested and are shown in *Fig. 2 a* and *b*:

V1: two-layer of 15 mm Fermacell Firepanel A1 (continuously)

V2: one*-layer of 15 mm Fermacell Firepanel A1, with an *additional second layer along the wooden substructure (with 40 mm overlaying)

The covering panels are arranged with a horizontal and vertical offset and butt joints ≤ 1 mm. Isover Ultimate mineral wool with a melting point $\geq 1000^\circ\text{C}$ is used as insulation material. The wooden substructure consists of spruce structural timber in strength class C24.

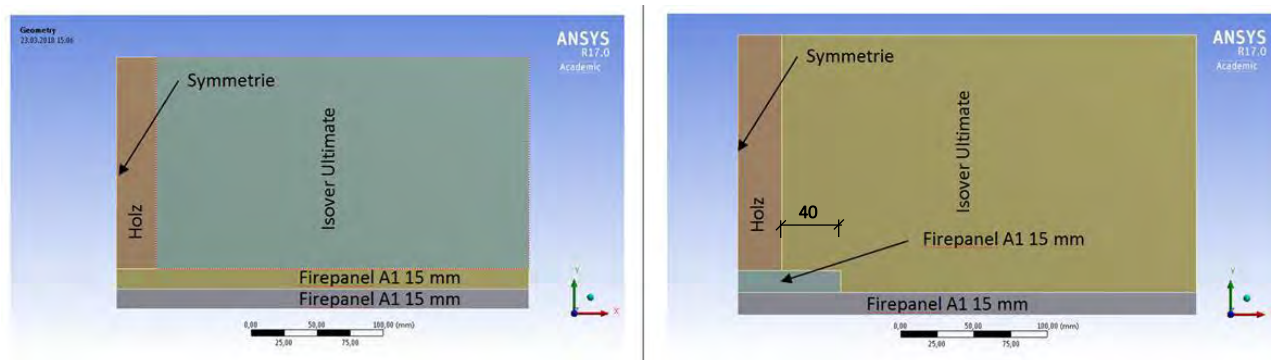


Fig. 2. a) V1: two-layers of 15 mm; b) V2: one*-layer of 15 mm Fermacell Firepanel A1

The fire resistance test was carried out at the IBS (Institute for Fire Protection and Safety Research) in Linz (Austria). In *Fig. 3* the specimen, the arrangement of the thermocouples between wooden substructure and coverings and the specimen after 90 minutes of testing are visualised.



Fig. 3. a) arrangement of thermocouples; b) specimen ready for transport; c) specimen after 90 min testing

During the test, the following criteria were observed and documented:

- temperatures
- smoke escape from joints
- cracking of gypsum fibreboard (as long as possible)
- discoloration of the insulation

2.2 Evaluation

On the non-fire exposed side the specimen V1 remained unharmed during the whole test period. The insulation of specimen V2 turned dark in colour, beginning after approx. 47 minutes.

After the test period of 90 minutes, the fire chamber was opened and the planking was removed.

The following incidents were documented (*Fig. 4*):

- V1: the gypsum fibre boards had few cracks in the middle of the panels; low carbonisation and pyrolysis are visible on timber studs in the area around the cracks.
- V2: the gypsum fibre boards had many deep cracks, strong carbonisation and pyrolysis are visible on the timber frame.



Fig. 4. a) Specimen V2: large thermal cracks b) Specimen V1: few thermal cracks in the first layer; c) Specimen V1: wooden substructure lightly charred

Specimen V1: The temperature increase between the gypsum fibre boards and the timber frame are shown in Fig. 5a and stayed below the temperature limits during the whole test period. The temperatures between covering and insulation are shown in Fig. 5b.

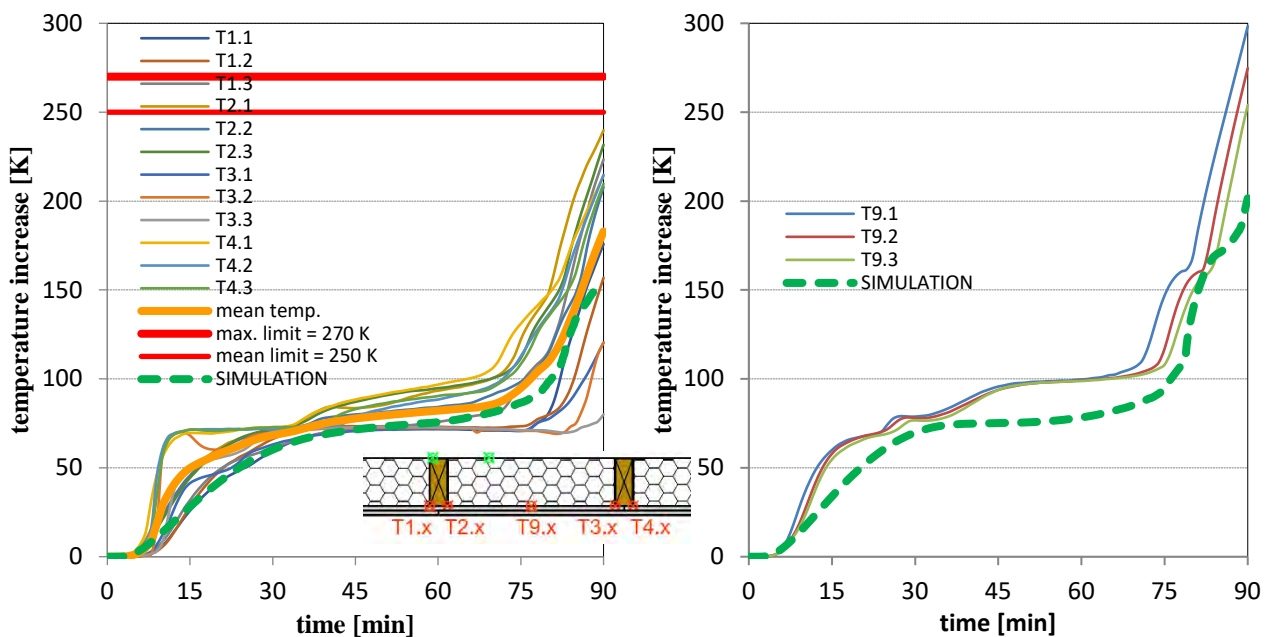


Fig. 5. a) Specimen V1: temperature increase between covering and timber b) Specimen V1: temperature increase between covering and insulation

Specimen V2: The limit temperature increase of 270 K between the covering layers and the timber frame was reached after 80 minutes and the mean temperature increase of 250 K occurred at minute 84 (Fig. 6a). The temperature increase between the gypsum fibre board and the insulation is shown in Fig. 6b.

The temperatures on the non-fire exposed side were measured and evaluated acc. to ÖNORM EN 13501-2 [12] and ÖNORM EN 1364-1 [11]. The limit temperatures of 140 K respectively 180 K were not exceeded for both specimens V1 and V2. The wall structure V1 (two layers) is now classified as EI 90-ef_(o→i) [16, 17].

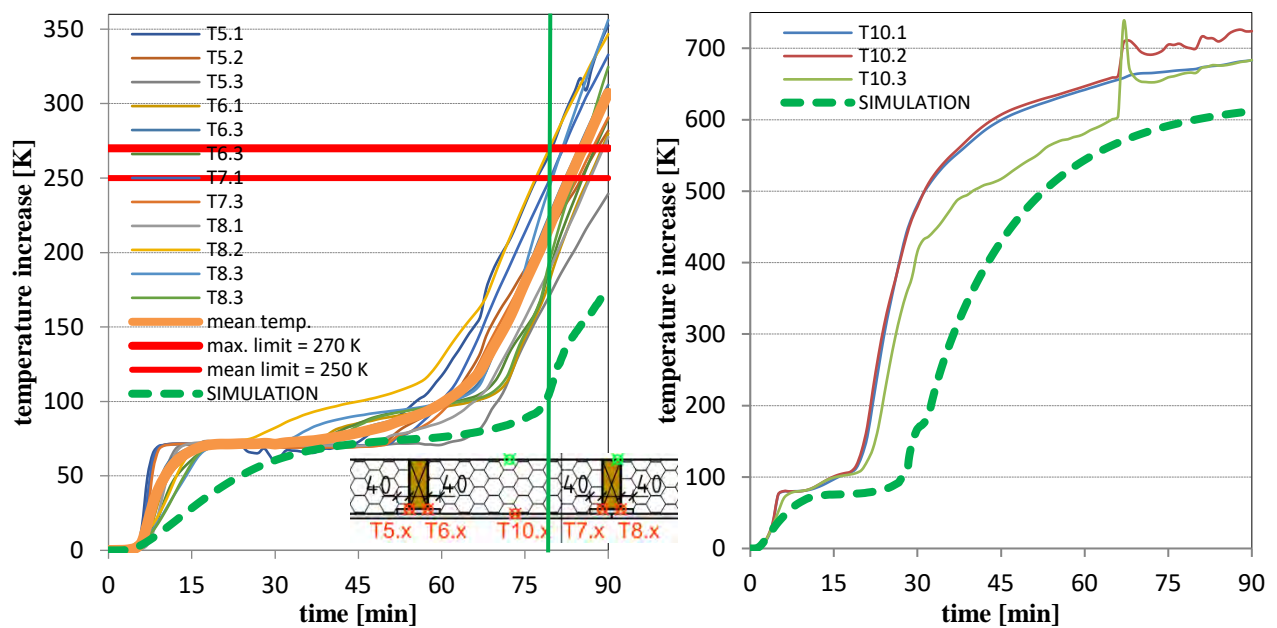


Fig. 6. a) Specimen V2: temperature increase between covering and timber
 b) Specimen V2: temperature increase between covering and insulation

3 NUMERICAL TRANSIENT THERMAL SIMULATIONS

So far, there are hardly information and literature about the fire protection ability of coverings exposed to the external fire curve. Such fire tests were carried out mostly by using the standard temperature-time curve to obtain the classifications. In order to be able to assess the test progress in advance, transient thermal analyses were performed with the software ANSYS. The geometries used for the numerical simulations are shown in Fig. 2. Additionally, a reference test carried out by MFPA Leipzig [18] was numerically simulated and compared to the test results.

3.1 Input parameter

The temperatures on the fire exposed side are defined by equations given in ÖNORM EN 1991-1-2 [10] for the standard temperature-time curve and the external fire curve (Fig. 1a). A constant coefficient of heat transfer by convection of $\alpha_c = 25 \text{ W}/(\text{m}^2 \text{ K})$ is used. On the unexposed side a constant temperature of 20°C and coefficient of heat transfer by convection of $\alpha_c = 9 \text{ W}/(\text{m}^2\text{K})$ are used.

The temperature dependent material properties used in the simulations are shown in Fig. 7. Values given in ÖNORM EN 1995-1-2 Annex B [13] are used for the wooden substructure. Material properties of the Fermacell Firepanel A1 are based on values given in literature [19-23], datasheets and company information [24]. Material properties of the Isover Ultimate mineral wool are based on datasheets and company information [25, 26]. A constant density of $23,5 \text{ kg}/\text{m}^3$ and a constant specific heat of $840 \text{ J}/(\text{kg K})$ are assumed.

3.2 Evaluation

The temperature gradations in the cross sections of specimen V1 and V2 are shown in Fig. 8 after 90 min of fire exposure. The dashed lines in Fig. 5 and Fig. 6 demonstrate the simulated temperature developments in the specimens. It is visible that the calculation results for the specimen V1 (double planked) are slightly below the measured temperatures from the fire test. The differences between simulation and test results are larger for specimen V2. The main reasons for the deviations are listed on following page:

- heat bridges due to butt joints and fasteners (staples) are not considered in simulations. This has a wide influence in higher deviations between specimen V2 (one layer covering) and test results. In specimen V1 this influence is smaller due to two panel layers with offset joints.
- temperature-dependent material properties are based on literature and standards.
- resulting cracks in the gypsum fibre boards are considered in accordance with literature, simplified by an increasing thermal conductivity.
- a constant heat transfer coefficient is assumed.
- in the Austrian national annex ÖNORM B 1991-1-2 [27] is written, *that in case, that acc. to ÖNORM EN 1991-1-2 [10] the temperature of the temperature curve is equated with the gas temperature, the calculation results obtained therefrom with regard to the required thickness of components, to be classified based on the present calculations, naturally will be smaller than it would be based on fire test results. The reason for this lies in the fact that the temperature of the fire chamber is measured and controlled by plate thermometers, which means that the actual gas temperature due to the inertia of the plate thermometer especially in the initial phase of fire tests and possibly in other phases with high temperature change per time is higher than in case of equalization of temperature curve and gas temperature. [27]*

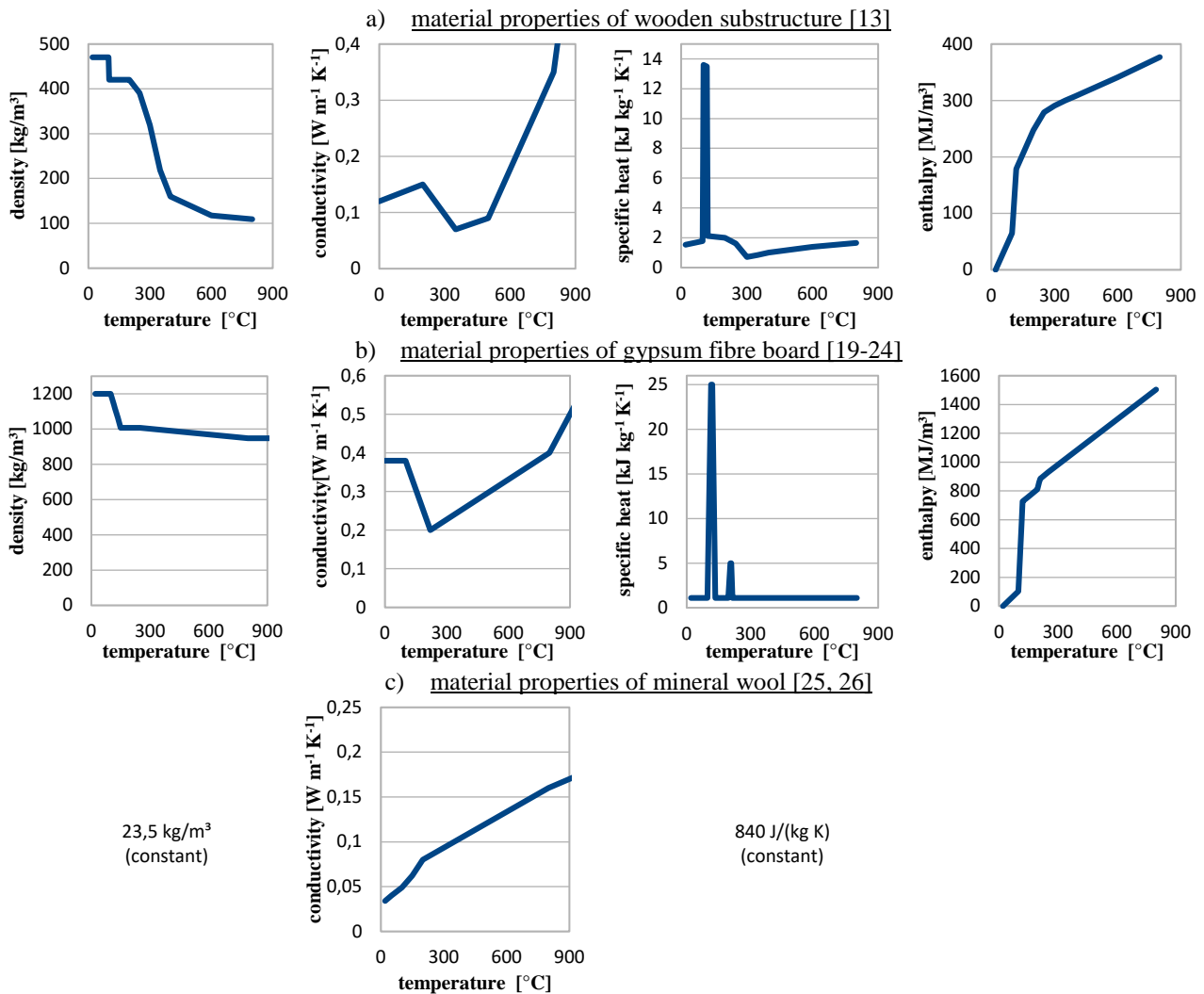


Fig. 7. material properties used in numerical transient thermal simulations of a) wooden substructure [13], b) gypsum fibre board [19-24], c) mineral wool [25, 26]

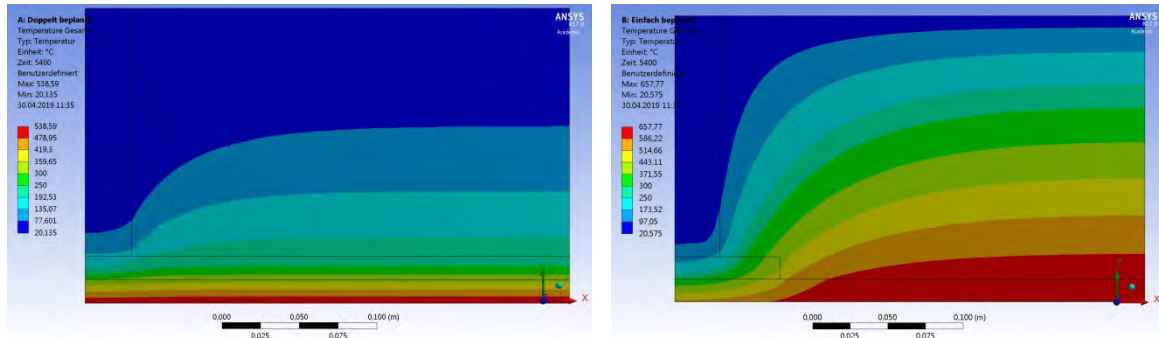


Fig. 8. a) temperature gradation after 90 min in specimen V1
 b) temperature gradation after 90 min in specimen V2

4 COMPARISON STANDARD TEMP-TIME CURVE VS. EXTERNAL FIRE CURVE

Comparable fire resistance tests, performed with the standard temperature-time curve have already been carried out with the same gypsum fibre board by the producer and can be used as a reference [18]. However, it must be pointed out that, apart from the fire exposure, further differences must be considered. The standard temperature-time curve and the external fire curve are approximately the same in the first 10 minutes. While the external fire curve remains constant at 680°C, the standard temperature-time curve continues to rise (about 1000°C after 90 min) (see Fig. 1a).

While specimen V1 has a wooden substructure, the substructure of the reference test has a metal substructure (profiles CW75-06, UW75-06). Another essential difference in the reference test is that no insulation was used between the studs.

Fig. 9 shows that the temperatures during first 60 minutes on the non-exposed side of fibreboards are slightly lower in the reference test (OF9-14,18,21-23) than in specimen V1 (T9.1, T9.2, T9.3). One reason for this is that the wooden substructure and the insulation prevent the heat emission to the non-fire side. After 60 minutes the temperatures in the reference test begin to increase rapidly, approximately 10 minutes earlier compared to the temperatures in specimen V1, which is exposed to lower temperature of the external fire curve and thus a layer of gypsum fibre board can be saved.

A numerical transient thermal simulation was also conducted for the reference test. The temperature developments are shown in Fig. 9 as thick dashed line. Fig. 10 shows the simulated temperature gradation after 90 min. Again, the simulated temperatures are consistently lower than the measured temperatures. The reasons for this are the same as those described in chapter 3.2.

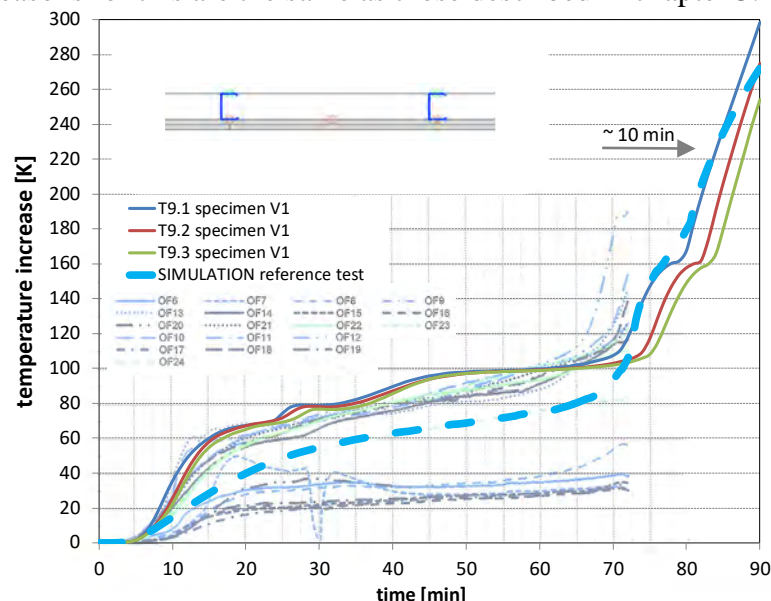


Fig. 9. Temperature increase on non-fire exposed side of coverings. Comparison of reference test (standard temperature-time curve) [18] with test results of specimen V1 (external fire curve) and numerical simulation

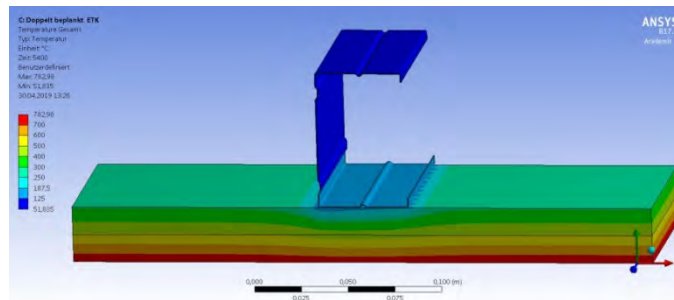


Fig. 10. Temperature gradation after 90 min in reference simulation

5 CONCLUSIONS

In existing Austrian fire safety regulations, the use of timber in exterior wall constructions of high rise buildings is generally not permitted. The results of this research project shall serve as an argumentative basis in an object-specific, coherent fire protection concept.

A fire resistance test and numerical simulations were carried out for the evaluation of the fire protection ability of a gypsum fibre board exposed to the external fire curve. The temperature developments are recorded and evaluated in the oven, between the wooden substructure and the gypsum fibreboard, between the insulation and the gypsum fibreboard and additionally on the non-fire exposed side of the element.

Two different arrangements of the coverings were tested. In both cases, specimen V1 and V2 did not exceed the limit temperature increase of 140 K respectively 180 K. So the fire resistance of the non-load bearing prefabricated façade system is now classified as EI 90-ef_(o→i).

The temperature increase between covering and wooden substructure of specimen V1 remained below the limit temperature increase of 250 K respectively 270 K during the whole test period of 90 minutes. In the wall construction of specimen V2 the maximum temperature increase of 270 K was reached after 80 minutes.

Additionally, the test results of specimen V1 exposed to the external fire curve was compared to a reference test exposed to the standard temperature-time curve exposure and shows that more than 10 minutes could be gained regarding the temperature increase and thus a layer of gypsum fibre board can be saved.

Numerical transient thermal analyses were performed and showed its comparability to the test results. It is evident that the temperature development can be predicted quite well by numerical simulations even if the temperatures of the simulation are consistently lower than in fire tests.

ACKNOWLEDGMENT

This work was financially supported by SINFONIA, a European Unions' Seventh Framework Programme, Wohnbauförderung Tirol, Neue Heimat Tirol Gemeinnützige WohnungsGmbH, proHolz Tirol, Fermacell GmbH and Saint-Gobain ISOVER Austria GmbH.

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FIRE SAFETY OF BIO-BASED FACADES

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ABSTRACT

Architects and engineers are increasingly interested in using wooden facade claddings as an esthetical feature and for sustainability reasons, not only in timber buildings. The introduction of performance-based building codes has generally facilitated the wider use of these materials and products in multi-storey buildings, but the use of visible wood as exterior facade claddings is still limited. Contribution of bio-based façade claddings and insulation materials to fire development and spread can be prevented by using protective methods. Examples of these are protection of insulation products by coverings made of materials with good reaction to fire performance and/or with a sufficient protection capacity and/or prevention of facade cladding fires by hindering flames from a flashover room fire by using projections over windows, fire rated windows, automatic window shutters or sprinklers. Fire stops in ventilation cavities or in order to interrupt a combustible insulation are also effective means of fire protection. Several wooden facade systems do fulfil at least the European reaction to fire class D-s2,d0, but some countries require full scale fire testing. Based on full-scale test results some conclusions and recommendations have been made concerning proper criteria and possible area limits of wooden facades. This paper is based on a recent European guidance document [1].

1 INTRODUCTION

There is at present no European harmonised solution to assessing and quantifying the fire performance of facades as full-scale building elements, but a development has started [2]. Twelve different fire test methods have been identified as being either in use, or referenced in the regulations or guidance documents, throughout Europe. The European harmonised solution to evaluate the fire performance for facades as surface claddings is to use the (harmonised) reaction to fire classes. However, some countries do have additional requirements.

2 FACADE FIRE SCENARIOS AND SPREAD OF FIRE

2.1 Initiation and facade fire scenarios

Key initiating scenarios/events of facade fires are

- A. Exterior fire spatially separated from the external wall system resulting in radiant heat only (fire in adjacent building for example)
- B. Exterior fire directly adjacent the external wall system igniting the wall due to radiant heat and/or flame impingement. It could be an ignited waste container or vehicle placed close to the façade, a fire on a balcony or hot work procedures as e.g. LPG burners used for maintenance.
- C. Interior fire (pre-flashover or post-flashover) spreading to external wall system via external openings such as windows and via internal openings including cavities and concealed spaces. The actual fire scenario is dependent on the building category, the actual fire load, the quality of design of the fire compartment and the design of the façade.

The existing research has identified that exposure to the exterior wall system is generally more severe for internal post flashover fires with flames ejecting from windows, scenario C, than for external fire sources. For this reason, most full scale facade fire tests simulate an internal post

flashover fire. However, it is possible for severe external fires at ground level with fuel loads such as back of house storage areas and large vehicle fires to equal or exceed internal post flashover fires. Although most full-scale facade tests simulate an internal post flashover fire, these tests may also set a suitable level of performance with regards to a limited external fire severity [3]. The fire scenarios A, B and C are illustrated in Figure 1.

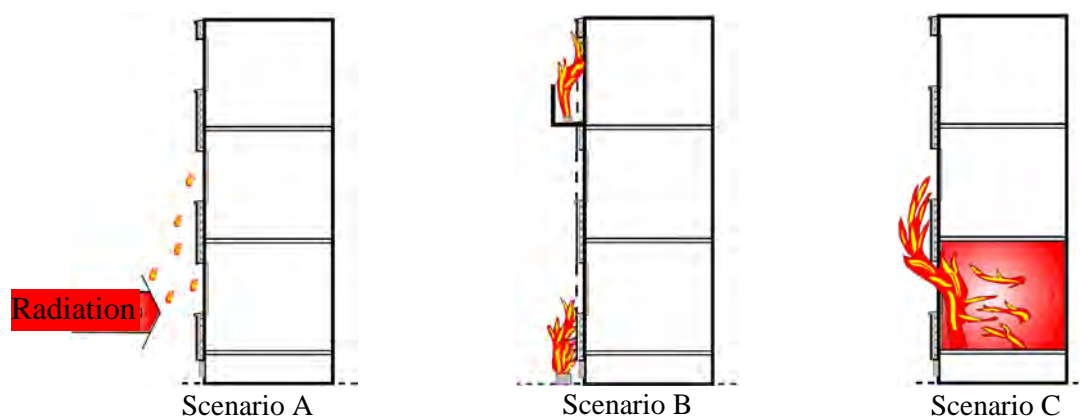


Fig.1. Fire scenarios for exterior walls [4, 5].

2.2 Fire spread along a façade

After ignition of a façade the fire spread may occur along the outer surface, within the facades cavities or as smouldering fire in e.g. the insulation material. The key mechanisms are:

- Fire spread to the interior of level above via openings such as windows causing secondary interior fires on levels above resulting in level to level fire spread
- Flame spread over the external surface of the building
- Flame spread within an internal vertical or horizontal cavity /air gap
- Heat flux impacts cause degradation/separation of non-combustible external skin resulting on flame spread on internal core
- Secondary external fires to lower (ground) levels arising from falling burning debris.

3 LEGAL REQUIREMENTS

3.1 European requirements

The objective of building legislation in terms of fire protection of an exterior wall is to prevent rapid spreading of a fire to floors above. The satisfaction of the European essential requirements "Safety in case of fire" [6] has to be verified for bio-based building products as well as for all other construction products. The regulatory and test based methodology to address behaviour of fires in facades for different facade systems varies significantly for different countries. Fire test methods (full or medium scale) for facades used in Europe are summarised in [1, 2].

3.2 Falling parts at fire exposure

It must also be ensured that emergency workers are not placed in danger by extensive parts of the building's facade falling to the ground. Several European countries (Austria, Denmark, Germany, Greece, Hungary, Norway, Poland, Sweden, Switzerland and UK) have requirements on falling parts at fire exposure in order to secure the safety of rescue personnel and residents [1, 2].

4 MEANS TO PREVENT FAÇADE FIRES SPREADING

Building codes usually allow only limited areas to be covered by combustible claddings, e.g. wood. Some possibilities to prevent facade fires by hindering flames from a flashover room fire to break windows are summarised below. Some of them may allow up to 100 % wooden facade claddings, e.g. projections over windows, fire rated windows and an automatic window shutter. Detailing in facades, e.g. fire stops in cavities, are of utmost importance for the performance of wooden facades, see section 6.

4.1 Fire safety design with sprinkler systems

The use of wooden facades is often facilitated if the building is sprinkled. Sprinklers in apartments will control a fire at an early stage and flashover will not occur. Thus, wooden facades maybe used since the risk of flames out of a window from a fully developed fire is eliminated. The implementation of fire safety design with sprinklers vary between countries. In Sweden following façade related possibilities apply, if sprinklers are installed [7]:

- Combustible facade cladding up to eight storeys
- Decreased requirements on fire spread through windows in the same building

4.2 Projections over windows

The spread of fire can be reduced by extending of flames away from the facade with overhanging fire resistant building components (cantilevers, ledges). A fire shield above the window with horizontal extension of at least 80 cm out from the façade stops the fire spread [1, 8].

4.3 Fire rated windows

Fire rated windows with a fire resistance of at least EI 15 or 30 minutes will limit the risk for upward flame spread along the facade surface. However, such windows need to be locked and are therefore suitable mainly for office buildings.

4.4 Automatic window shutter

An automatic window shutter that closes at fire exposure will also limit the risk for flames getting out of a window and thus allow for more wood claddings to be used [8]. The shutter may consist of a panel hidden behind the facade cladding. It is mounted on a rail and can be moved to cover the window. At fire it closes automatically by a temperature detector inside the window. At normal conditions it may be closed manually to protect from sun, light and noise. Such a device has been tested and got a fire resistance rating of slightly over 30 minutes [9].

4.5 Separation of buildings

Building to building fire spread is considered primarily at risk by an ignited façade in a house that may contribute to ignition of the neighbor house façade. Hence, protection is designed by fire resistance ratings (mostly from EI 30 to EI 60) [10] or distance between buildings (prescriptive rules, usually 6 – 8 meters, or via calculation according to [11], e.g. maximum radiation 15 kW/m²).

4.6 Fire retardant treated wood claddings

Fire retardant treatments may improve the reaction to fire performance of wood products and the treated wood products may reach the highest European reaction to fire class possible for combustible products, class B. Visible wood may then be used more widely in facades. But the long-term durability of the fire properties has to be demonstrated, see section 5.2.

5 FIRE PERFORMANCE OF BIO-BASED BUILDING PRODUCTS IN FACADES

Wood based claddings are widely used in building facades. There is an accepted low fire safety risk with regard to use combustible timber claddings in facades for low-rise buildings up to two floors. But for high rise buildings, timber claddings can lead to an unacceptable fire safety risk and specific fire safety measures have to be implemented to reduce the risk to an acceptable level. The technical guideline for Europe [5] gives the background and design methods for designing timber buildings to have similar fire safety to buildings of other materials. It refers mainly to fulfilling requirements according to the European system for fire safety in buildings [6], but the basic principles are applicable also in North America and elsewhere [13].

The reaction to fire performance of wooden facades has to be determined in accordance with EN 13501-1 [13] in order to arrive at a classification with testing according to Single Burning Item test [14]. The SBI testing requires the entire system, i.e. with cladding, substructure, insulation materials, fasteners and joints, to be determined and tested.

5.1 Untreated wooden claddings

The key factors for wooden claddings, which have influence on facade fire safety level are:

- Cladding type and installation method (tongue-groove or overlapping jointed, ribbon mounting)
- Ventilated or unventilated cladding application
- Substrate (cavity, protective covering, insulation, behind the cladding)
- The thickness of cladding (nominal thickness and minimal cladding profile thickness)
- Fire retardant treatment of wood
- Surface paintings and finishings
- Fire stops.

5.2 Fire retardant treated wooden claddings with long term durability

The long term durability of the fire properties has to be demonstrated, since only few treatments can withstand external weather conditions [15]. A new European standard EN 16755 for testing and classification of the durability of fire retardant treated timber products was recently published [16]. Two interior application classes are included INT1 and INT2 and one class for external application EXT. Service class Durability of reaction to Fire class DRF EXT has to be obtained for facades.

5.3 Insulation materials

Insulation materials and installation methods used in building facades play a significant role in fire safety level of facades. Insulation materials may be either non-combustible (reaction to fire class A1 and A2-s1,d0) – which does not contribute to heat release in case of fire or combustible (reaction to fire class from F to B-s1,d0) – which may contribute to the fire development.

A problem with insulation materials is smouldering combustion. Smouldering combustion is the slow, low temperature, flameless burning of porous fuels. Heat is released when oxygen directly attacks the surface of a solid fuel. It is especially common in porous fuels which form a char on heating [17], like cellulosic insulation, polyurethane foam or peat. Non-combustible insulation materials also can contain organic binders, which may take part in the oxidation process. Smouldering combustion phenomena can spread the fire in all directions from initiation point – upwards, downwards and in sideways. Smouldering combustion of insulation material is very slowly developing fire spread, but also very hard to extinguish.

5.4 Full scale fire tests with wooden façade claddings

Full scale fire tests have been performed according to SP Fire 105 [18] which simulates a three-storey building with a fire from a room at the bottom floor. The fire source is 60 l heptane. The test duration is about 15-20 minutes and the fire exposure exhibits a rise and decay that simulates real fire conditions. This scenario with flames out of a window after flashover is the most severe one for facade claddings. The measurements and the Swedish requirements are given in Table 1. This test

method has similarities with the methods being proposed for a European approach [2] and might give some guidance for the possibility to use wooden facade claddings.

Table 1. Requirements based on data from the facade test SP Fire 105

Measurements in SP 105	Requirements in the Swedish building code
Gas temperature at eave:	< 500°C (excl. 2 minutes) <u>or</u> < 450°C (excl. 10 minutes)
Heat flux at centre of:	
- lower window	< 80 kW/m ²
- upper window	No requirements at present; (< 20 kW/ m ² suggested)
Fire spread (charring) on facade	< lower part of upper window
Falling parts	No major parts, < 0,1 m ² , no burning droplets

5.4.1 Untreated wooden facades

Two series of facade fire tests according to SP Fire 105 have been performed. The first series consisted of partial untreated wood on the facade and the second one of fire retardant treated (FRT) wood. Detailed results are presented [8, 19]. They include partial wood with about 33 and 60 % of untreated wood and a fire shield above the fire window with 100 % wood.

5.4.2 FR treated wooden facades

Two series of facade fire tests with FRT wood was performed [8, 19]. Nordic spruce, 22 mm thick was pressure impregnated by the manufacturers and dried. Panels with a constant retention of FR were selected. The panels were mounted horizontally in the same way as the untreated panels. Three types of fire retardants were included, one at three retention levels.

5.4.3 Conclusions on façade fire tests

The following conclusions could be drawn from the test results:

- The fire damage at the upper window is the main failure criterion for wooden facades
- The damage (charring criterion) is rather subjective and should be replaced by heat flux criterion for the upper window, e.g. 20 kW/m²
- Partial wood up to about 50 % fulfil the requirements, but the exact amount depends on the geometrical configuration of the wood in relation to the windows
- A fire shield above the window with horizontal extension of at least 80 cm out from the façade stops the fire spread and allows for 100 % wood to be used.

5.5 Possible performance criteria for full-scale façade fire testing

Possible reaction to fire requirement criteria for full-scale facade fire test have been developed [10] and are given in Table 2, well in line with [20] and similar to earlier been proposals e.g. [21,22,23].

Table 2. Possible characteristics and requirement criteria for facade fire testing
(at worst case scenario i.e. flames out of a window after flashover)

Facade fire test characteristics:	
- Maximum heat exposure	70-80 kW/m ²
- Burning time	15-20 minutes
Criteria:	
- Heat flux	< 20 kW/ m ² at window 2 storeys up from fire room
- Fire spread	< lower part of window 2 storeys up or not to eave
- Falling parts	No major parts, < 0,1 m ² , no burning droplets

6 DETAILING AND GENERAL RESTRICTIONS

Structural fire protection is a fundamental requirement to facades as the outer layers of external walls of multi-storey buildings (independent of the structural material). A recent review [3] shows that most countries reviewed require fire stopping in gaps at the rear of the external wall at the junction of floors or compartment boundaries, i.e. curtain wall fire stopping [1]. Detailed fire protection measures of wooden facades are given by Lignum [24].

6.1 Fire spreading on cladding surface

The following recommendation can be made:

- Reaction to fire performance of the cladding material; the higher the building the higher the reaction to fire performance should be required. The reaction to fire performance must apply to cladding in their end-use conditions, with the possible impact of underlying layers of materials (e.g. insulation) and their method of fixing.
- Combustible claddings e.g. wood in class D-s2,d0/d1 or d2 without additional passive or active fire protection may be limited to buildings where firefighting with usual extinguish systems is possible e.g. up to 8 storeys.
- A closed cladding surface poses less risk than an open surface.
- By using wood-based materials on the facade the distance between buildings should be minimum 6 - 8 m. As alternative, a calculation should be made to limit the radiation from the fire to the cladding façade to maximum 15 kW/m².

6.2 Fire spread in ventilation cavity

Hidden voids in the construction of a building provide a vertical or horizontal route for spread of smoke and flame to large and inaccessible areas. Hidden facade fires may progress upwards several storeys and may penetrate eave into attic area, which presents higher risks for firefighting.

6.3 Fire stops in facades

The most important technical problem in incorporating fire stops in the ventilation voids behind facades is that the structure must retain its moisture protection functionality and the water draining. Creating a functional fire sealing solution for the ventilation void requires a compromise between the fire protection and moisture protection requirements. Several fire stops are described in [1, 5].

6.4 Fire spreading to attic roof cavities

A cavity fire in the attic area is always highly destructive, as the fire may spread to the entire roof area of the house. The easiest way to prevent a destructive cavity fire is to construct eave structure that do not provide an access route for the fire to enter the attic e.g. by EI requirements.

7 QUALITY OF CONSTRUCTION WORKMANSHIP AND INSPECTION

Quality and inspection of workmanship is vital for high quality buildings, whether of timber or other construction materials. The performance of the building during construction is determined by the quality of workmanship on building site. Formalized fire safety management techniques, including self-auditing of contractors and erectors are required. For larger buildings, a third party control is needed. A new Nordic technical specification is available for such control processes [25]. Although the assembly sequences may differ between countries, the requirements for ensuring adequate performance levels are identical. The appropriate installation of details can be checked only during the construction period, and the quality of workmanship of details should be monitored closely by the responsible contractor.

Self-monitoring by the contractor is an important process and should be mandated and formalised whenever possible. The responsibilities of interacting trades must be clearly stated, and overarching project management processes communicated and enforced at the beginning of a project.

Fire protection documentation should always be produced; normally by a fire consultant. This is mandatory in some European countries and is also forming the basis for the maintenance during service life of the building.

Inspection plans and checklists should also be produced for both design and execution and be communicated to all parties. They should specify in detail the inspection areas and responsibilities. Critical areas, such as interfaces between the various control functions, need special attention.

8 CONCLUSIONS

The behaviour of facades under fire exposure is dependent on the type and architectural features of the facade, on the type and alignment of the cladding, and on the substructure including the rear ventilation opening.

Contribution of bio-based façade materials to fire development and spread can be prevented by using protective methods hindering flames from a flashover compartment to spread over the façade by

- sprinklers inside the building
- projections over windows
- fire rated windows
- automatic window shutters
- separation between buildings
- fire retardant treated wood claddings

The durability of fire retardant treatments at exterior weather conditions has to be demonstrated in addition to the fire behaviour. The new European standard EN 16755 for testing and classification of the durability of fire retardant treated timber products should be used. Service class EXT for external application is needed for facades.

Other important fire preventing means are:

- fire stops e.g. in hidden voids in the construction of a façade to prevent vertical or horizontal spread of fire to large and inaccessible areas
- quality and inspection of workmanship to ensure that all details have been executed correctly, which is important not only for timber buildings

Several wooden facade systems do fulfil at least the European reaction to fire class D-s2,d0. A European full-scale fire test method is under development. In the meantime, available national methods can be used as a useful tool to evaluate the fire behaviour of facade claddings. Based on full-scale test results the following conclusions and recommendations can be made for buildings up to 8 storeys/30 m high buildings:

- The fire damage at the upper window is the main failure criterion for wooden facades, not the temperature at the eave or the heat flux at the lower window
- The damage (charring criterion) is rather subjective and should be replaced by heat flux criterion for the upper window, e.g. 20 kW/m²
- Partial wood up to about 50 % fulfil the requirements, but the exact amount depends on the geometrical configuration of the wood in relation to the windows
- A fire shield above the window with horizontal extension of at least 80 cm out from the façade stops the fire spread and allows for 100 % wood to be used.

ACKNOWLEDGMENT

The cooperation within the COST Action FP1404 *Fire safe use of bio-based buildings products* www.costfp1404.com lead by Joachim Schmid, ETH, Switzerland and the contributions from members to the guidance document on facades are kindly acknowledged.

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FIRE SAFETY OF ETICS WITH BIO-BASED INSULATION MATERIALS

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ABSTRACT

This paper focuses on investigations on the façade application of bio-based insulation materials as external thermal insulation component systems (ETICS). One big challenge, with respect to German building requirements, is the smouldering tendency of bio-based insulation materials. For an evaluation of bio-based insulation materials with regard to their fire behaviour, systematic investigations are carried out, starting with small-scale tests, e. g. Transient-Plane-Source (TPS), coupled Cone Calorimeter FTIR analyses and medium-scale tests, e. g. German standard DIN 4102-15/16 “Brandschacht”, Single-Burning-Item (SBI) test acc. EN 13501-1 ending with large-scale fire tests described in this paper. These large-scale fire tests are conducted acc. to German standard 4102-20 (gas burner) and the German regulation MVV TB A2.2.1.5 (200 kg wood crib fire in the base area in front of the façade). As one result a thick layer lime-cement plaster system (30 mm) for ETICS with wood fibreboards prevented any smouldering for both fire scenarios (DIN 4102-20 and 200 kg wood crib fire in the base area). In addition to the plaster system barriers (200 mm stone wool) were installed around the window and as separation between XPS base and the ETICS with wood fibreboards. Furthermore, standard thin layer plaster systems with other barrier positions are under investigation.

1 INTRODUCTION

Bio-based insulation materials made of renewable resources save the natural resources of our environment. Products made of these bio-based materials are agreeable for the environment and lead an increasing contribution to the reduction of CO₂ emissions. The German agriculture and forestry get an increasing benefit of competitiveness. Regrettably the amount of bio-based insulation materials in Germany is about 7.2 % of the market [1]. One reason for this low value is caused in the building regulations. There is a restricted possibility to use flammable building materials. Flame retardant building materials can be used in a wide range of applications, as long as they fulfil the requirements of non-glowing/ non-smouldering. These flame retardant materials can be used without restrictions for e.g. external thermal insulation composite systems (ETICS) until high rise level. The overall aim of these paper, within the scope of the research projects named in section 5, is to raise the possibilities to use bio-based insulation materials (flammable building materials) by developing fire protection measures to ensure the safety level [2].

2 BUILDING REQUIREMENTS

Germany is a federal republic of 16 independent federal states, each with its own building code. The German building ministers come together in the German ‘Bauministerkonferenz/ building ministers conference’ (BMK) to publish a model building code to be understood as a template for a nearly equal safety level in Germany. These model building code is introduced by law of each federal state, mostly

in the way of the template. In addition to the model building code the BMK introduced several special building codes for buildings with special use or higher safety potential e. g. schools, high rise buildings, industrial buildings, etc. These special buildings are not content of these research and are not discussed further. The model building code of the BMK divides buildings into five classes, as shown in Table 1. The separation of the building classes is based on the building location, single building or build together with others, the height of the highest floor for common utilization areas as well as their area and number. With higher building class the requirements become more and more restricted. These restrictions mostly refer to the building materials and the time duration of fire resistance of the load-bearing structure. With a view to bio-based insulation materials Table 1 shows low requirements within building class 1 - 3, just normal flammable. For higher building classes the requirement is fire retardant. The use of fire retardant insulation based on bio-based materials is difficult because there are further requirements especially that a fire retardant material is not allowed to glow or smoulder. Unfortunately most of the bio-based insulation materials tend to glowing and smouldering.

Table 1. Building classes referring to German model building code (requirements for residential use only; excerpt, no complete overview of all requirements of model building code)

Parameter	Building class					
	1	2	3	4	5	
location	single	non-single	-	-	-	
h [m]	≤ 7	≤ 7	≤ 7	≤ 13	> 13	> 7 +
number uu	2	2	nr	nr	nr	nr
A [m ²]	Together < 400	Together < 400	nr	Each ≤ 400	nr	> 400
lbs walls	nr		30 min ^b	60 min	90 min	
walls between utilization units	nr		30 min	60 min	90 min	
ceilings	nr	30 min		60 min	60 min	
exterior walls	normal flammable			low flammable		
facades ^a	normal flammable			- fire retardant or - sub-construction normal flammable, if burning area is limited		

^a including façade surface, façade cladding and sub-construction and insulation

^b all times are the required time of fire resistance

h ground of highest floor for common room

number allowed number of utilization units (uu)

A Area of Utilization Units

nr no restrictions

lbs load-bearing structure

3 LARGE SCALE FIRE TESTS

3.1 Test Facility and Procedure

The test facility for large scale (LS) Fire Test 1-3 is made acc. to German Standard DIN 4102-20 at iBMB in Braunschweig. The test facility is made of two walls of aerated concrete of about 5 m width together and 6 m high. The two walls are connected in an angle of 90° (L-shape). The ETICS is installed in the inner corner. The described façade constructions 1-3 are made on this facility. In order to save material the specimens are smaller than the test facility. The short side of the specimen is about 2 m and the longer side is about 2.7 m. LS Fire Test 4 was conducted at another institution for

material testing and not at iBMB. The installation was made acc. to DIN 4102-20 respectively acc. to German regulation MVV TB. The test facility is made in an L-shape as well with one side about 4.2 m and the other one about 2.2 m, by a high of about 10 m. The specimen is about 3.4 m x 2 m with a height of about 9 m. To measure the time dependant temperature curves, several thermocouples in different heights are used. The test facility was observed with video camera and thermography camera for all LS Fire tests (1-4).

Acc. to DIN 4102-20 a gas burner is used as fire load for LS Fire Test 1 – 3, see Fig. 1 middle. The named fire scenario is fundamental for certification of ETICS in Germany for building class 4 and 5. The scenario is a model for a fire within a room and with a broken window so the flames and temperature can claim the façade. The gas burner is used with a propane-air-ratio and is installed under the lintel of the ‘window’. The power of the burner is about 350 kW (7.4 g/s). For LS Fire test 4 a wood crib is used as fire load. This fire scenario is described in German regulation MVV TB A2.2.1.5, describing a burning object at the base of a façade. The wood crib is about 200 kg spruce with an area of 1.10 m x 1.10 m and 0.72 m height. The crib consists of several layers of individual rods connected to form a cube-like structure, see Fig. 1 right. Each rod is about 40 mm x 40 mm x 1100 mm connected with nails. The wood-air-ratio is about 1:1 and the wood is conditioned acc. to DIN 50014-23/50-2.

3.2 Test Setup/ Specimen

The tested insulation systems consists of a mineral mortar as glue for a 100 mm thick wood fibreboard. The wood fibreboard is classified as C-s1-d0 acc. to DIN EN 13501-1. It contains about 12 % fire retardants. All façade constructions are made with barriers. For LS Fire Test 3 the distance between the barriers was reduced to investigate the propagation of smouldering to the edges of the system. The stone wool barriers are orientated horizontal and vertical to create different smouldering areas. All constructions are finished with a lime-cement plaster of different thickness for each test. Schematic construction details are shown in Fig. 1, left, and further details to the specimen and the fire scenarios are shown in Table 2, upper section of the table.

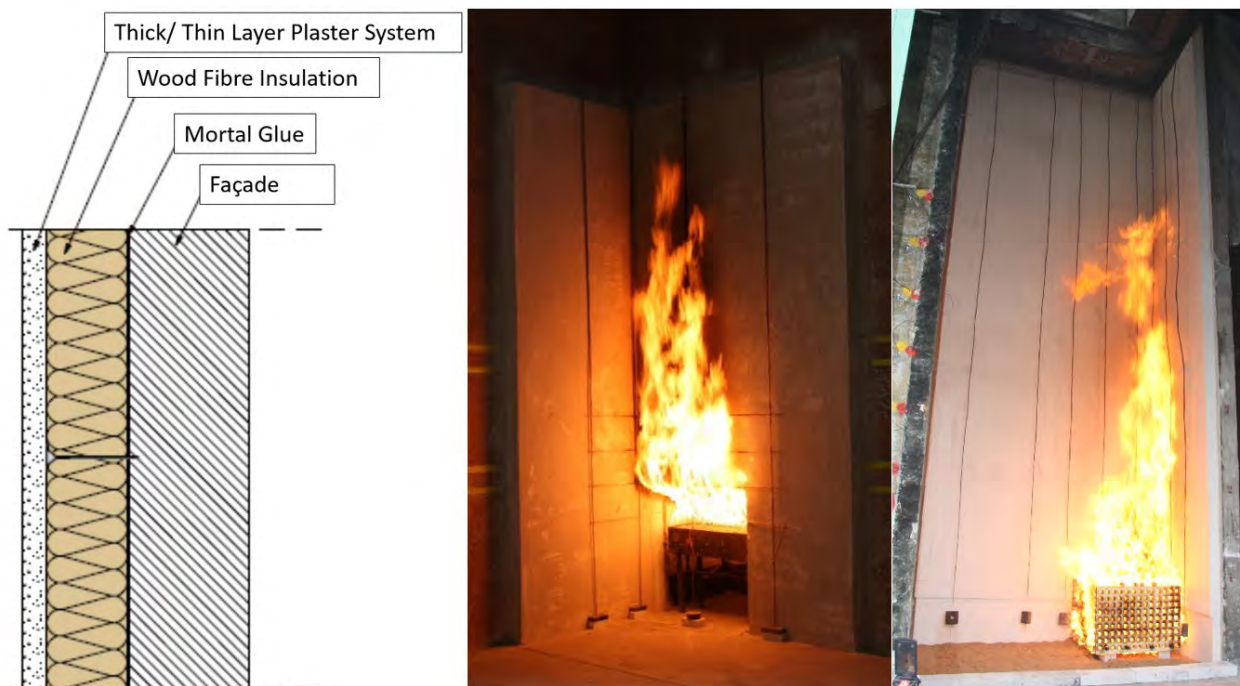


Fig. 1 Left: Schematic construction of the specimen; middle: LS Fire Test acc. to DIN 4102-20; right: LS Fire Test acc. to MVV TB A2.2.1.5

Table 2. Large Scale (LS) Fire Tests 1 - 4 (important construction details)

Detail	Large Scale Fire Test			
	1	2	3	4
insulation	100 mm wood fibreboard, Euroclass C	100 mm wood fibreboard, Euroclass C	100 mm wood fibreboard, Euroclass C	100 mm wood fibreboard, Euroclass C
Soffit protection and/or barriers [mm] (t x h)	200 x 100 (Euroclass A)	200 x 100 (Euroclass A)	200 x 100 (Euroclass A)	200 x 100 (Euroclass A)
plaster	lime cement based	lime cement based	lime cement based	lime cement based
plaster layer [mm]	~ 47	~ 29	~ 6	~ 30
Test szenrio	DIN 4102-20	DIN 4102-20	DIN 4102-20	MVV TB A2.2.1.5
fire source	gas burner	gas burner	gas burner	200 kg wood crib
fire exposure time [min]	20	- 20 + - 23 (till T > 350°C plaster to insulation)	20	~ 30 (ash & embers extinguished)

3.3 Test Results

The results of all LS Fire Tests can be seen in Table 3. LS Fire Test 1 and 4 doesn't show any self-sustained smouldering [3], [4]. Within observation time all thermocouples fell under a temperature of 50 °C. Within the first 20 min and some observation time LS Fire Test 2 doesn't show any self-sustained smouldering as well [3]. After a second flaming of about 23 min or until selected thermocouples raise above a temperature of 350 °C a self-sustained flaming can be detected. The second flaming was just made because of scientific interest, it is not a part of regulation. A self-sustained smouldering can be observed for LS Fire Test 3 with conventional thin-layer plaster system [3]. Exemplary the temperature time curve of LS Fire Test 3 is shown in Fig. 2 (respectively, for all LS Fire Test a T-t-curve is available). There are several temperature peaks raising and falling for different times and locations within the insulation. For this test a collection of thermography images are shown in Fig. 3 to visualize the smouldering propagation as well. For different time steps a moving smouldering front can be observed, starting in the center of the two walls corner moving to the edges of the façade system. For all LS Fire Tests no (burning) droplets can be seen.

Table 3. Results and important observations of LS Fire Test acc. to the different test scenarios and fire sources

Detail	Large Scale Fire Test			
	1	2	3	4
test szenrio	DIN 4102-20	DIN 4102-20	DIN 4102-20	MVV TB A2.2.1.5
fire source	gas burner	gas burner	gas burner	200 kg wood crib
opening of system while fire test	no	no (cracks in area of flaming)	no (cracks in area of flaming)	no
observation time [h]	1.86	70	75	3.5
smouldering 0 – 20 th min	no	no	yes (in area of flaming)	no
smouldering 20 th min – end	no	yes	yes (see Fig. 2 & 6)	no

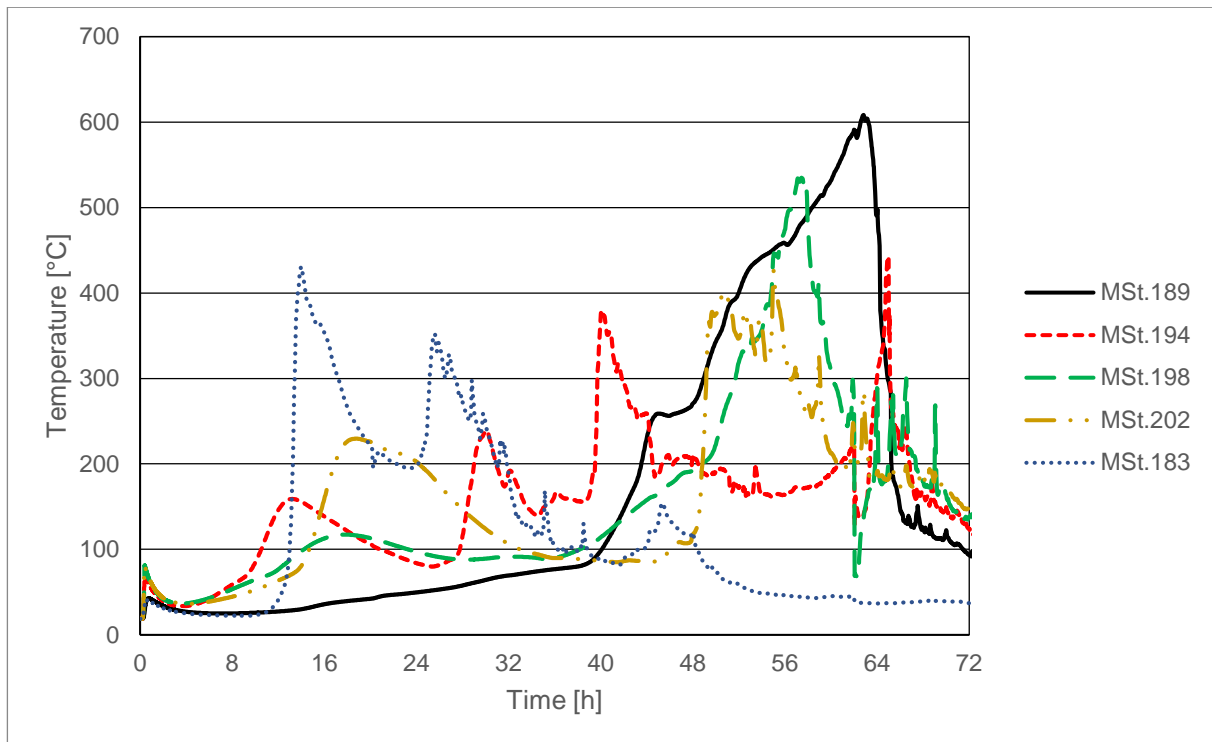


Fig. 2. LS Fire Test 3, Temperature time curve in the middle of insulation, special selected thermocouples of one vertical axis to illustrate self-sustained smouldering

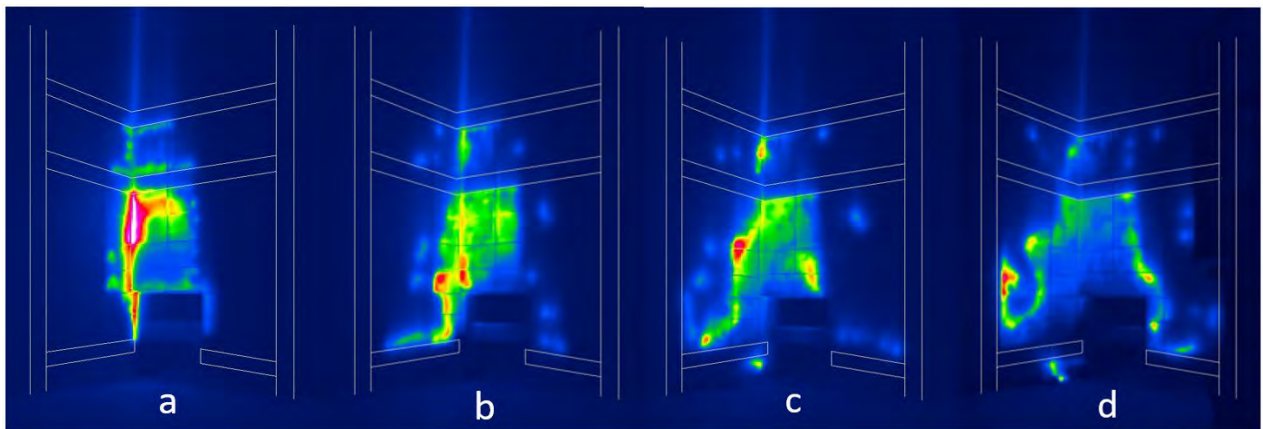


Fig. 3. LS Fire Test 3, Thermography images [some taken from 5], progress of smouldering after end of flaming, a) ~4h, b) ~28h, c) ~52h, d) ~75h; (small white linings represent smouldering barriers, upper edge of specimen not shown because no smouldering beyond)

4 CONCLUSIONS

The following conclusions may be drawn with the LS Fire Tests described above:

- plaster thickness of 30 mm can prevent a wood fibreboard for smouldering with respect to German regulations
- plaster thickness of 30 mm can prevent a wood fibreboard for smouldering without special precautions for lintel and soffit
- stone wool smouldering barriers can prevent of a self-propagating smouldering

- self-propagating smouldering must be assumed by temperatures ≥ 350 °C inside the ETICS/behind the plaster
- an observation by thermography camera can assist in assessment whether there is smouldering or not

To find a limiting thickness to prevent smouldering and investigate other plaster compositions another LS Fire Test with hemp as insulation material will be conducted at iBMB. The ~15 mm plaster layer for this test will be in between the tested 6 mm and 30 mm.

The experimental start temperature for smouldering in LS Fire Test 2 confirm the results of [6]. Steeger et al. investigated different wood fibre boards protected with gypsum boards and discovered non-smouldering by temperatures up to 325 °C and a self-sustained smouldering at 350 °C. As heat source the conical heater from the cone calorimeter was used at different radiation levels.

The results shown in this paper need to be transferred to other bio-based insulation materials. In [7] a first positive transfer acc. to hemp, jute, straw and cellulose is made in small-scale fire tests acc. to German standard DIN 4102-8.

5 ACKNOWLEDGMENT

The fire test described above are related to the research programs “Fire safety of external thermal insulation component systems (ETICS) with wood fibreboards for building-classes 4 and 5” (01.06.2014 - 30.11.2017; founding number KF2178813HF4; Central Innovation Program for Small- and Medium-sized Enterprises (ZIM) of the German Federal Ministry of Economics and Technology) and “More than just insulation - additional benefits of insulating materials from renewable raw materials” (01.12.2016 - 30.11.2019; founding number 22011615; Specialist agency renewable raw materials e. V. (FNR) of the German Federal Ministry of Food and Agriculture).

Furthermore, the authors would like to thank all industry and association partners who have supported the implementation of the fire tests with their expertise and material donations.

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SESSION 2: FACADE TESTING AND FIRE PROPAGATION

- P.38 **Horizontal Deflectors Impact on Vertical Wooden Facade Combustion**
Quentin Jullien, El Mehdi Koutaïba, Pauline Anest Bavoux, Nicolas Pinoteau
Centre Scientifique et Technique du Bâtiment Marne-la-Vallée, France
- P.45 **Effects of Horizontal Projections on the Characteristics of Externally Venting Flames: An Experimental Study**
Christos Kontis, Christoforos Tsihlias, Dionysios I. Kolaitis
Fire Engineering Unit, Laboratory of Heterogeneous Mixtures and Combustion Systems,
School of Mechanical Engineering, National Technical University of Athens, Greece
- P.54 **Influence of the thermal breaks on the behaviour of a balcony under fire external flames experiments, project trepos**
Camille Sautot¹, Amor Ben Larbi², Maël Couchaux³
^{1&2} CTICM, ³ INSA Rennes,
- P.62 **Heat Fluxes to a Facade Resulting from Compartment Fires with combustible and non-combustible ceilings**
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HORIZONTAL DEFLECTORS IMPACT ON VERTICAL WOODEN FAÇADE COMBUSTION

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ABSTRACT

This work presents the experimental results of six large-scale tests carried out to study the fire behaviour of vertical wooden façade combustion. The main purpose of these tests was to study the influence, on the flame trajectory and combustion of a wooden façade, of any projection above a window that has sufficient fire resistance to remain in place when subjected to heating by flames.

During the six large-scale tests have been measured: the temperatures in the fire room in front of it at different levels, the mass loss of wood cribs used as fuel in the room fire as well as the components of combustion gases.

The first two tests were made without any combustible cladding on the calcium silicate board and using two different sizes of inert boards (10 cm and 30 cm) as deflectors above the fire-room opening. The façade of the other tests was composed of a cladding of 18 mm thick plywood mounted directly onto the calcium silicate board. The same flame deflectors used on the inert façade were placed on the plywood cladding. In these tests, two different species of wood are used, Poplar wood and Okoumé (African wood). The aim was to observe the influence of flame deflectors sizes and wood species with different densities on flame propagation. Thus, the present research tries to correlate the thermal stress along the façade to the wood species and flame deflector sizes.

1 INTRODUCTION

Energy economy and heat retention in building lead, nowadays, to a more complex configuration and compositions concerning building façades. Additionally, highly combustible insulating materials are increasingly used to enhance the energy consumption of the building. However, the materials which the façade is made out (timber cladding or CLT) increases the risk of external fire spread along the façade [4,5].

Passive fire protection methods can be used to limit the risk of fire spread [6] such as treating the cladding material or providing horizontal deflector elements with the ability to change the trajectory of the flames and prevent its passage into other compartments (i.e. Figure 1). Indeed, Oleszkiewicz [3] it has been shown that the extent to which a horizontal projection located above flames issuing from a window can be effective in reducing the flame exposure. Other works showed that vertical exterior elements could have a negative impact by increasing the vertical projection of flames along a façade.



Figure 1 Pictures of flames at the façade without a deflector (left) [1,2], with a 10 cm deflector (middle) and with a 30 cm deflector (right)

In this context, large-scale fire experiments were conducted to study the fire behavior of vertical wooden façade combustion and assess the effect of façade geometry on heat flow to the wall. Hence, the aim of the present work is, through the analysis of the results of these tests, to contribute and improve the knowledge of fire spread along a combustible façade.

1. Experiments

Figure 2 illustrates the experimental design. The experimental setup consists of a fire compartment with a vertical façade wall. The fire compartment is a rectangular box made of lightweight concrete of internal horizontal cross-section 1.5 m x 1.5 m and 1.15 m high. The façade wall is 2.5 m wide and 4.9 m high, supported by steel structure and covered by a fire-resistant board. On this board a cladding of 18 mm thick plywood is directly mounted, with no ventilation cavity behind it. In the six tests, four were carried out with two different types of plywood, Poplar and Okoumé (African Wood), the last two were performed without any combustible cladding. Table 1 presents the characteristics of the resistant board and each wood.

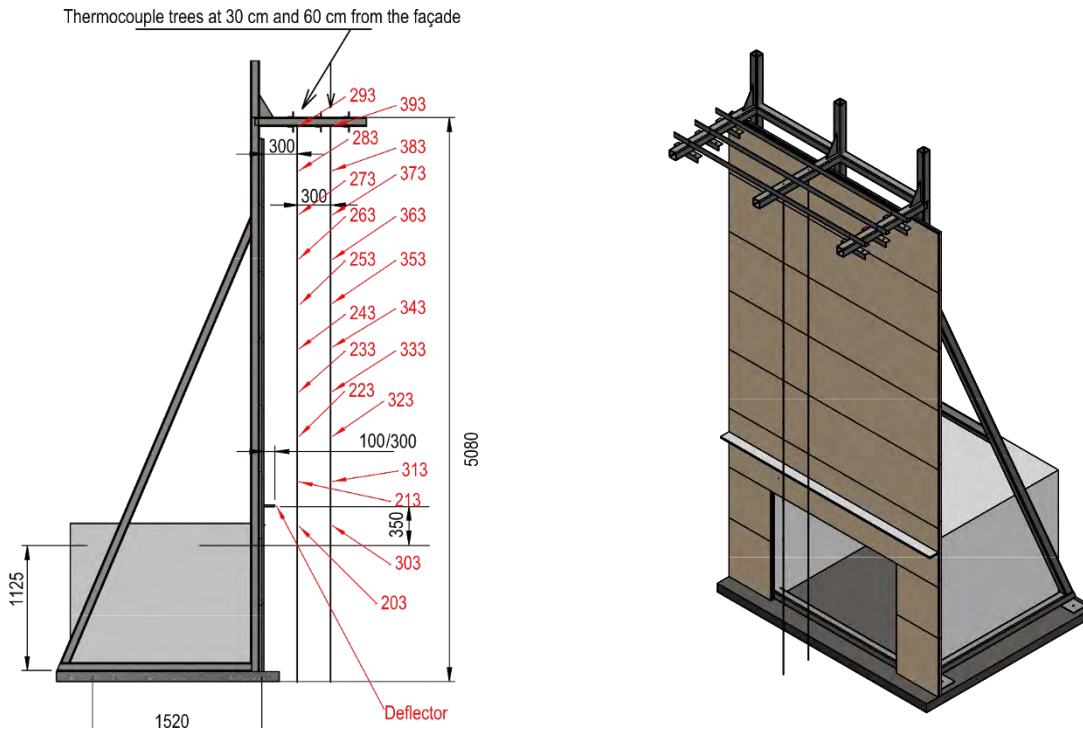


Figure 2 Experimental setup

1.1. Fire source

Inside the fire compartment, a wood crib is used as a fire source. It is constituted with small pine sticks 48x 48 mm² and the average weight of the crib is about 82 kg with a humidity level of 11.5 %. The averaged HRR measured is plotted in Figure 3. Test duration is approximately between 16 and 17 minutes. Fire grows linearly up to its maximum value of about 1.8 MW.

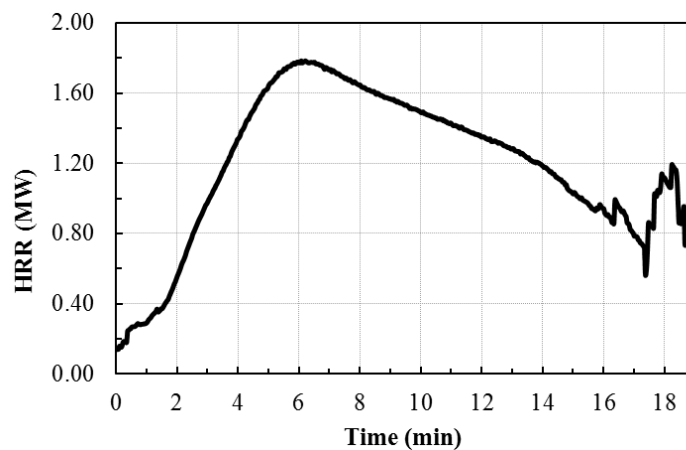


Figure 3 Picture of the wood crib used in the tests and averaged value of HRR calculated from the mass loss rate

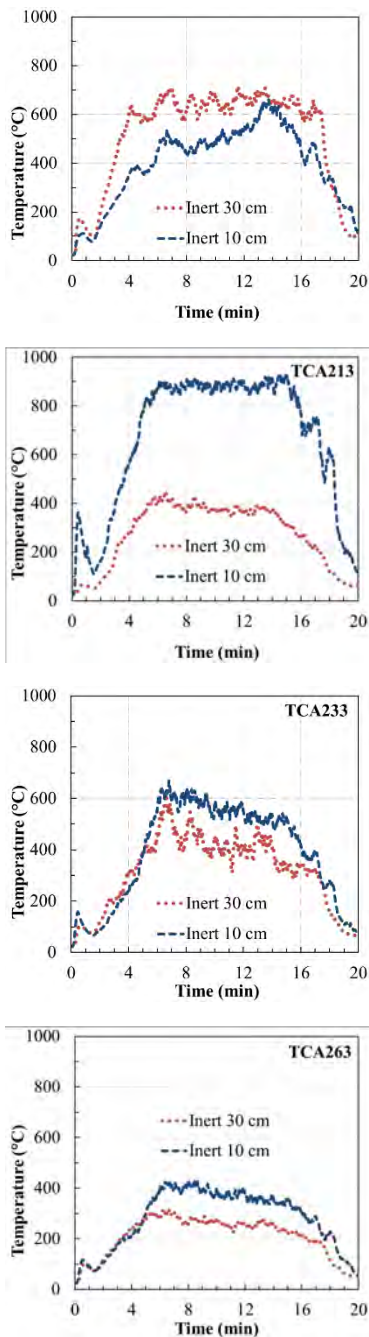
1.2. Measurement

Two series of 10 K-type thermocouples (2mm) with the spacing of 40 cm are located respectively at 30 cm and 60 cm from the façade, the first one being at 1.4 m from the ground. Figure 1 shows the location of the measuring devices.

2. Results and Discussions

Thermocouples are used in order to compare thermal actions depending on the façade nature and the deflector depth. On Figure 4, averaged temperatures for the inert façades are presented to compare the two deflector depths. For both tests (30 cm deflector depth and 10 cm deflector depth) temperatures rapidly increase during the first six minutes, particularly in the lower part of the façade, then a steady state is established between 6 and 16 minutes.

Results at 30 cm from the façade



Results at 60 cm from the façade

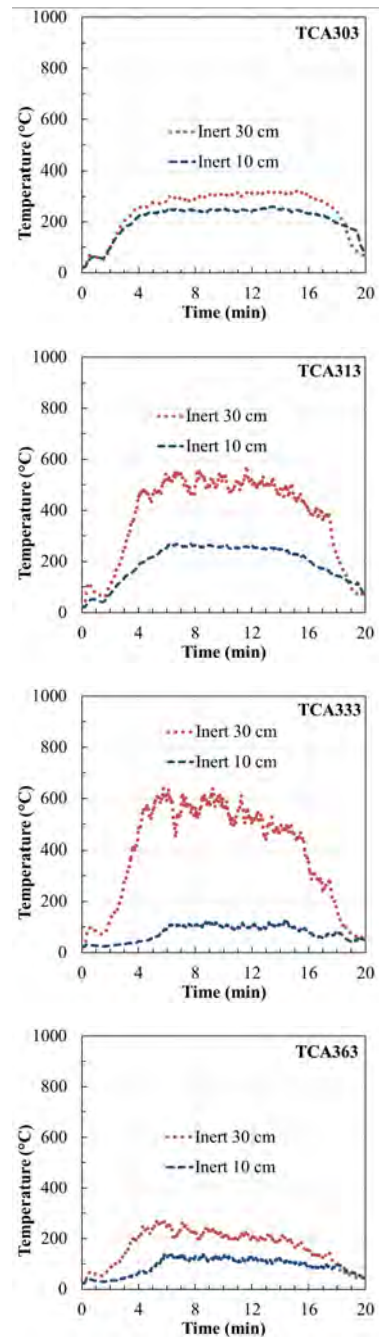


Figure 4 Comparison of temperatures in the centreline at 30 cm from the façade (left) and 60 cm from the façade (right).

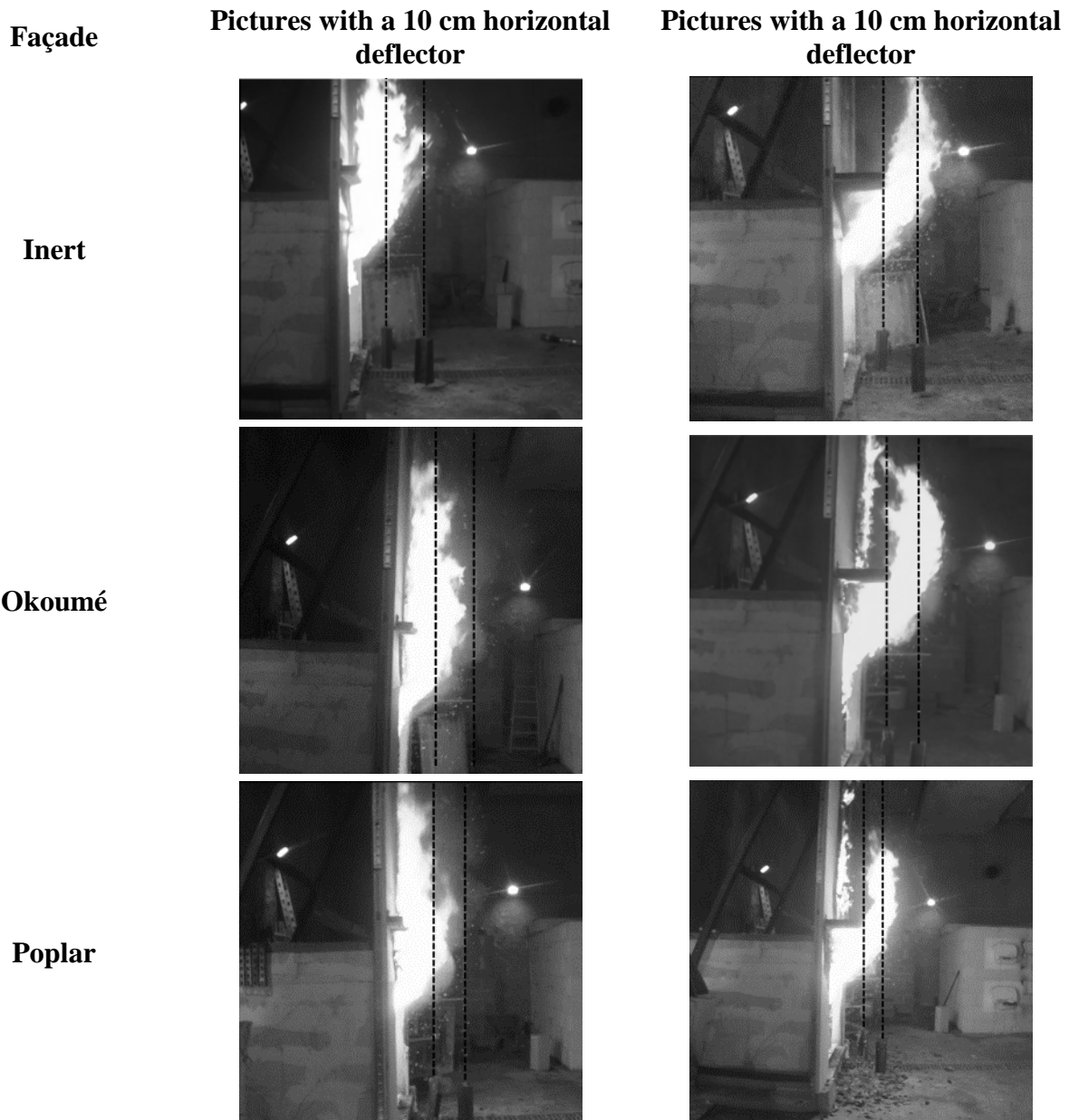
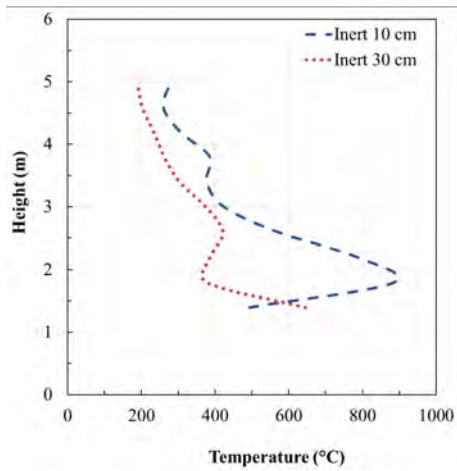


Figure 5 Pictures of flames behaviour for six tests one the HRR peak is reached

We can see that in front of the fire-room opening (TCA203 and TCA303) the temperatures are almost the same for both deflector depths. However, this behavior changes once the flame passes above the deflector position. Indeed, it appears that the temperatures at 30 cm from the façade are significantly higher for the 10 cm depth deflector with temperature values higher than 800 C just above the deflector (more than 400 C difference) which can be explained by the flame presence at this position (i.e. Figure 5). Conversely, the temperatures at 60 cm from the façade show, for their part, higher values for the 30 cm deflector depth. The temperatures begin to decrease from 1.4 m above the deflector to again become similar at 2.2 m.

Results at 30 cm from the façade



Results at 60 cm from the façade

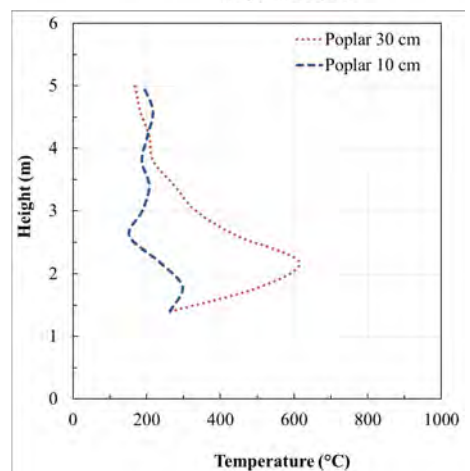
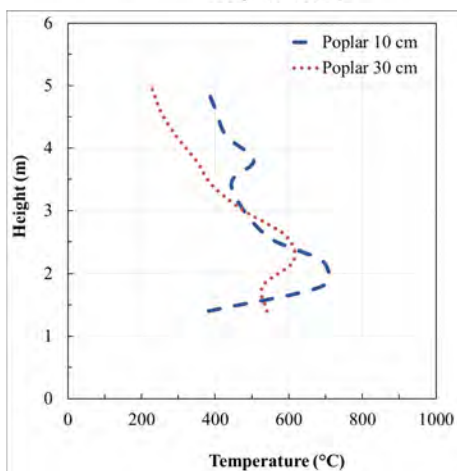
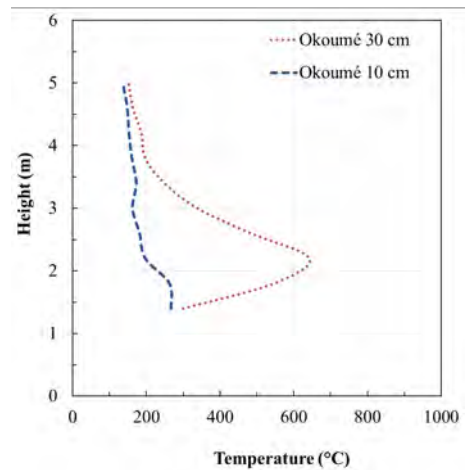
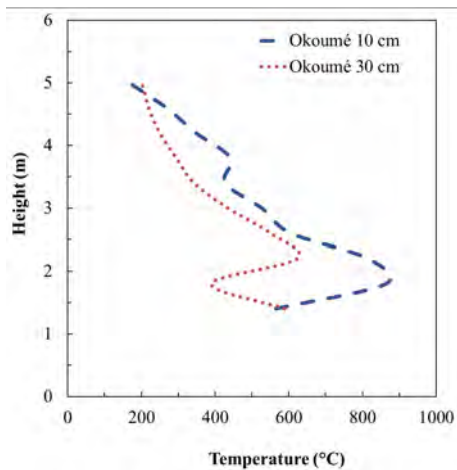
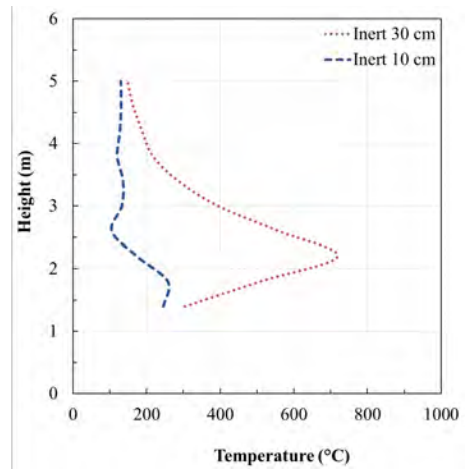


Figure 6 Comparison of temperature profiles with height in the centreline at 30 cm from the façade (left) and 60 cm from the façade (right).

Figure 6 presents averaged temperature profiles with the height at different positions. The temperature is averaged over the pseudo-stationary phase between 8 min and 12 min for each test. It is shown clearly that the tendency mentioned above. For the 10 cm deflector depths and regardless of the façade's nature, temperature values are higher at 30 cm from the façade.

Figure 5 shows clearly that the horizontal projection offered substantial protection to the wall above the window. Those results support the conclusions proposed by Oleszkiewicz [3] and Harmathy [4] who stated that a flame deflector could protect windows from fire plumes issuing from stories below.

3. Conclusion

The thermal aggression induced by a fire façade due to a fire venting through a window depends on multiple parameters: the fire heat release rate, window dimensions and façade geometry and materials. In this paper we investigate, based on fire façade full-scale tests, the influence of the façade geometry and composition and particularly the impact of a horizontal deflector on the flame and plume behaviour.

It was shown that the flame and plume behaviour above the deflector is clearly affected by its depth. Indeed, the temperatures closer to the façade are significantly higher for the smaller of the two deflectors (10 cm).

This work is part of a research project at the CSTB which aims to understand the governing phenomena in a fire façade propagation. Moreover, this experimental campaign supports the French authorities (DHUP) in order to quantitatively estimate the influence of deflector depth on the thermal stress along the façade. Future works will focus on numerically investigating this behaviour using the CFD code FDS (Fire Dynamic Simulator) by adding also combustible materials.

ACKNOWLEDGMENT

This study has been carried out by CSTB division Fire Reaction studies and tests and was financially supported by the DHUP.

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EFFECTS OF HORIZONTAL PROJECTIONS ON THE CHARACTERISTICS OF EXTERNALLY VENTING FLAMES: AN EXPERIMENTAL STUDY

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ABSTRACT

The effects of horizontal projections on the thermal and flow characteristics of Externally Venting Flames (EVF) are investigated by using a 1/4 scale compartment-façade experimental setup to perform five fire tests. A constant 144 kW fire power level was set in all fire tests; the fire source was a methane-fed porous burner, located at the geometrical centre of the compartment. A broad variety of measuring sensors was employed to determine the thermal and flow characteristics of the developing EVF; overall, 109 thermocouples, 4 bi-directional velocity probes, 2 pitot-static tubes, 3 heat flux meters, 1 exhaust gas analyzer, 3 digital flow meters and 2 optical cameras were used. A parametric study was performed, aiming to evaluate the impact of the horizontal projection's "depth" on the EVF characteristics; horizontal projection "depth" values of 0 mm (no projection), 100 mm, 200 mm, 300 mm and 400 mm were used in the performed fire tests. Using an in-house developed image processing software tool, flame intermittency contour plots were produced, allowing the determination of EVF height, horizontal projection and width values. These values were compared to the respective values predicted by correlations proposed in Eurocode; large discrepancies were found, especially for EVF height and width. In addition, Eurocode predictions were found to yield non-conservative values for fire engineering design purposes.

1 INTRODUCTION

When a compartment fire is fully developed, the flames may escape to the ambient environment through the compartment openings, thus creating an Externally Venting Flame (EVF). EVFs usually appear during the post-flashover stage, when under-ventilated fire conditions may develop. In this case, the unburnt volatiles exit through the opening and are mixed with the ambient air, which may lead to their ignition and the establishment of an EVF on the outside of the compartment. It is well established that EVFs may result in very fast external fire spreading along the building's façade, highlighting the importance of this phenomenon from a fire protection design perspective. The geometry and the thermal characteristics of an EVF is influenced by a variety of factors, such as the geometry of the compartment, the geometry and the number of openings, the facade materials etc. In the absence of horizontal projections, an EVF tends to spread vertically upwards due to thermal buoyancy phenomena. However, the presence of a horizontal projection forces the EVF to be diverted outwards, away from the wall, thus delaying its vertical spreading rate and reducing the incident radiation to the upper floors. Therefore, proper fire protection design engineering should take into account the detailed geometry of the opening, the façade system and the balcony. Normally, fire protection codes limit the external fire spreading threats associated with EVFs by imposing a minimum height between two spandrel walls or alternatively a projection over the exposed opening. A typical "balcony" consists of a horizontal projection, perpendicular to the exterior of the vertical

façade wall. In this work, the term "horizontal projection depth" (P), is used to describe the horizontal distance between the vertical façade wall and the edge of the balcony.

The use of horizontal projections as a protection method for the vertical spread of fire in a building façade has been investigated in several experimental and numerical research studies. In general, there is a consensus that increasing the horizontal projection depth P results in a more effective blocking of the vertical fire spreading rate along the façade and also significantly reduces the wall temperatures above the balcony [1-14]. *Table 1* summarizes the main conclusions drawn in the most important investigations relevant to the effects of horizontal projections on EVF characteristics.

Table 1. Main conclusions on the effect of the horizontal projection depth on the EVF characteristics

Reference	Main Conclusions
[1]	Increasing P , the trajectory of the fire plume tends to converge at a higher level.
[2]	A balcony works as a barrier to the EVF vertical spreading rate.
[3]	A horizontal projection with $P = 0.6$ m reduces the heat flux to the façade, at a height of 1.0 m above the opening, by 60%; when $P = 1.0$ m, a 85 % reduction is observed.
[4]	Increasing P results in increasing compartment temperatures and decreasing EVF angle and height; EVF projection does not depend on P .
[5]	Increasing P results in decreasing maximum temperature along the edge of the balcony; the temperature distribution along the façade does not seem to be affected by P .
[6]	A horizontal projection with $P = 0.5$ m is more effective in preventing the EVF vertical spreading rate compared to a 0.9 m high spandrel wall between successive openings.
[7]	Numerical simulations confirmed the experimental results presented in [4]. A horizontal projection successfully blocks the vertical spread of the EVF.
[8]	Increasing P results in decreasing heat flux and temperatures above the horizontal projection.
[9]	The minimum P value required to avoid the critical temperature above the balcony (70°C) is 1.2 m.
[10]	The P parameter impedes the vertical fire spreading rate more effectively compared to other parameters, such as the opening geometry and the horizontal projection height above the lintel.
[11]	The vertical fire spreading rate is gradually reduced with increasing P .
[12]	The ideal P value offering maximum protection is 0.6 m. A further increase to $P = 0.8$ m does not improve the effect on the fire plume; in contrast, it causes an overflow and spread of the fire plume at the top of the opening and in neighbouring buildings.
[13]	Increasing P results in reducing the area, height and width of the flame above the horizontal projection, as well as the heat flux on the facade. The average value of the maximum temperature above the horizontal projection initially reduces and then increases.
[14]	A horizontal projection with $P = 0.6$ m reduces the vertical spreading rate of the EVF and is more efficient than a 1.2 m high spandrel wall between successive openings.

The main scope of this work is to investigate the effects of the presence and depth of the horizontal projection on the EVF characteristics. A thorough analysis of the experimental data allows to determine the impact of P on the compartment (indoor) and EVF (outdoor) temperatures, the compartment wall and façade surface temperatures, the incident heat flux on the façade, the gas velocities (both incoming and outgoing through the opening) and the EVF vertical velocity at a distance of 100 mm from the edge of the horizontal projection. In addition, using cameras and digital image processing tools, the geometric characteristics of the EVF (height, width and horizontal projection) are determined and compared against predictions of the Eurocode correlations [15].

2 EXPERIMENTAL SETUP

2.1 Geometry

The fire tests were carried out at the Laboratory of Heterogeneous Mixtures and Combustion Systems, National Technical University of Athens. The fire compartment dimensions corresponded to a ¼ scale of the ISO 9705 standard compartment, representing a typical room. The compartment's internal

dimensions were 900 mm (length) x 600 mm (width) x 600 mm (height); the door-type opening's dimensions were 200 mm (width) x 500 mm (height). An external façade was added to the south wall where the opening was located; the façade's dimensions were 660 mm (width) x 2100 mm (height). Standard fire-resistant gypsum plasterboards were used for the construction of the test compartment. The horizontal projections used were 20 mm thick and made of a calcium silicate board; the lower surface of each horizontal projection was located 100 mm above the door lintel.

2.2 Fire Source

A porous burner, located at the geometric centre of the compartment floor was fed with 99.95 % pure methane (CH_4). The porous burner was made of aluminium oxide and had holes of 1 mm in diameter all over its top surface, which was located at a height of 150 mm above the floor. The burner dimensions were 125 mm (length) x 175 mm (width) x 55 mm (height). A constant fire power level, equal to 144 kW, was used in all fire tests.

2.3 Sensor Network

Overall, 109 thermocouples, 4 bi-directional velocity probes, 2 pitot-static tubes, 3 heat flux meters, 1 exhaust gas analyser, 3 digital flow meters and 2 optical cameras were used. The spatial distribution of the measurement sensors is depicted in *Fig. 1*. The origin of the coordinate system used was located at the centre of the door, at floor level; all sensors were installed along the symmetry axis of the compartment ($y = 0$ mm).

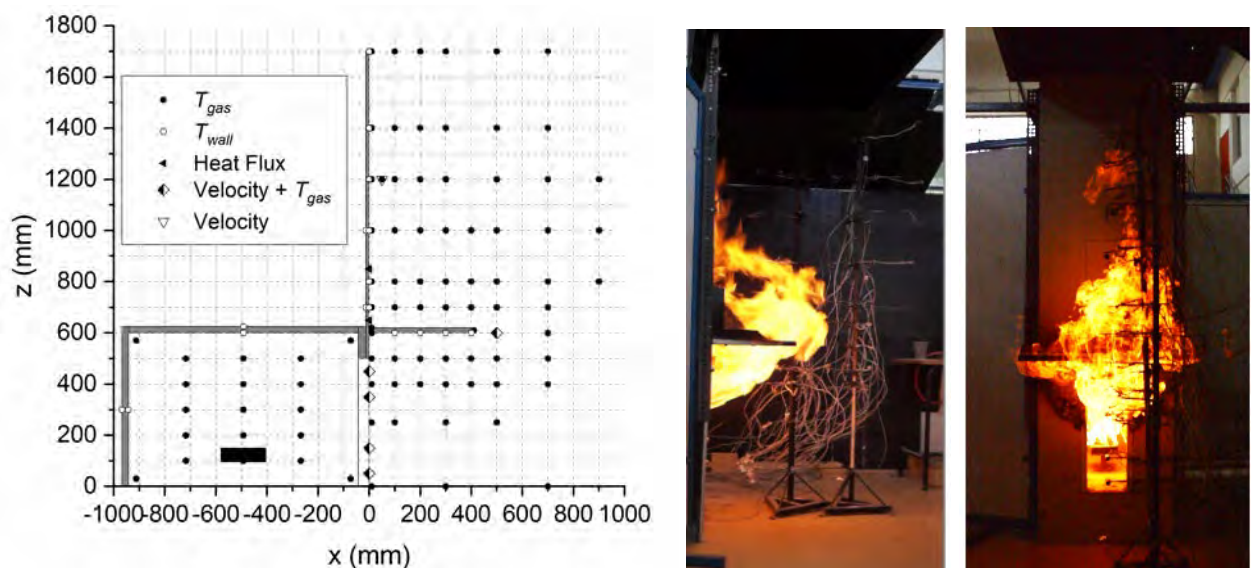


Fig. 1. Spatial distribution of measurement sensors (test case P400); sketch (left) and indicative fire test photos (right).

2.4 Flame Envelope Identification and Flame Intermittency Levels

In order to detect the EVF envelope, an image processing tool was developed in MATLAB. The main steps of the image processing procedure are outlined below:

1. Obtain a series of single frames from the optical camera video streams
2. Import the frame series to the MATLAB tool
3. Define the coordinate system origin to the specific frame series and match to actual dimensions
4. Apply a variety of flame identification criteria (e.g. RGB levels)
5. Calculate flame intermittency values for every pixel
6. Output the spatial distribution of the time-averaged flame intermittency contour levels

2.5 Parametric Study

A “clean” façade configuration, where no horizontal projection was installed, was used as the “base” case (P0); four additional fire tests were performed, where the following horizontal projection “depth” values were used: 100 mm (P100), 200 mm (P200), 300 mm (P300) and 400 mm (P400). The first

case (100 mm) corresponds essentially to a full-scale architectural projection, whereas the latter three cases (200 – 400 mm) correspond to typical balcony geometries.

3 TEST RESULTS

3.1 Compartment Temperatures

Fig. 2 illustrates the variation of compartment temperatures with height at two characteristic horizontal locations, one at the “back” ($x = -717.5$ mm, far from the opening) and one at the “front” ($x = -267.5$ mm, close to the opening) of the compartment. In each location, all curves show similar qualitative trends. At the back of the compartment (*Fig. 2*, left), temperatures gradually increase until a height of $z = 300$ mm, where they reach their maximum value and then decrease again. Lower temperatures were recorded in the P400 case, while for the rest of P values there is no clear trend. For instance, at a height of $z = 200$ mm the highest temperatures correspond to test cases P100 and P300, while at a height of height $z = 300$ mm, the peak temperatures are observed for test cases P0 and P100. Near the front of the compartment (*Fig. 2*, right), temperatures generally increase until a height of $z = 400$ mm, where they reach their maximum value and then decrease.

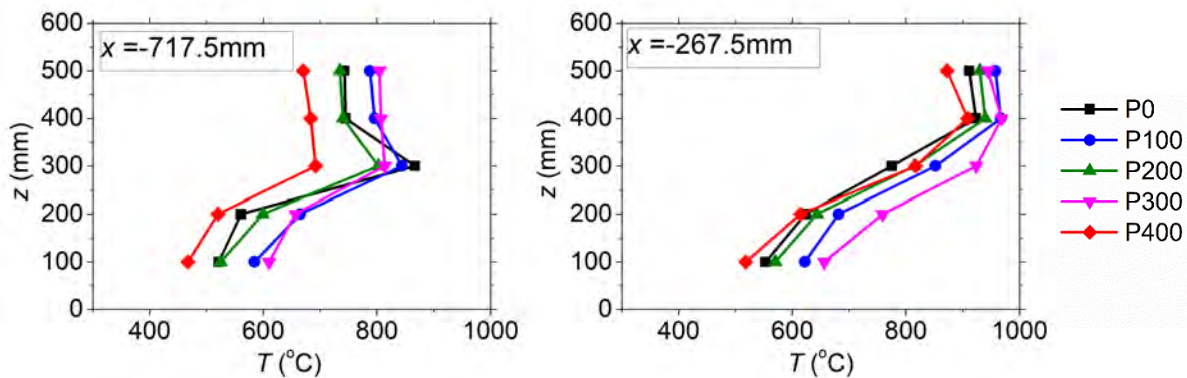


Fig. 2. Compartment temperatures as a function of height, at $x = -717.5$ mm (left) and $x = -267.5$ mm (right).

3.2 Opening Temperatures and Velocities

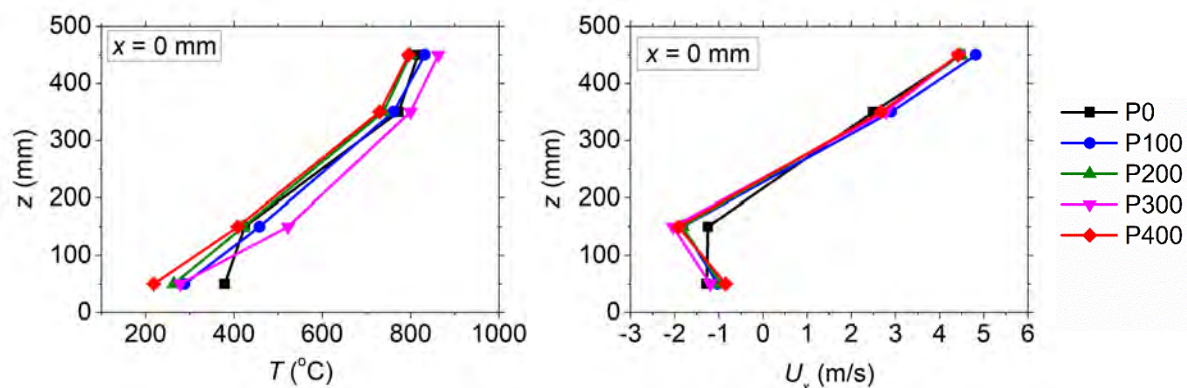


Fig. 3. Opening temperature (left) and horizontal velocities (right) as a function of height.

The vertical distribution of gas temperatures and horizontal velocities at the opening are depicted in *Fig. 3*. In general, the five curves for each parameter are qualitatively similar, shape except for the test case without a balcony (P0). As expected, the opening temperature generally increases with increasing height; the large temperature differences observed between $z = 150$ mm and $z = 350$ mm indicate the presence of the hot exhaust stream in the upper half of the opening and the cold stream of incoming air in the lower half of the opening. Negative horizontal velocity values indicate flow towards the compartment (*Fig. 3*, right). The mean velocity of the hot exhaust gases exiting through

the upper part of the opening is found to be generally higher than the respective mean velocity of the cold ambient air entering through the opening's lower side.

3.3 EVF Temperatures

The variation of EVF temperature as a function of the horizontal distance from the façade (x), for two characteristic height levels, one *below* the horizontal projection ($z = 400$ mm) and the other *above* ($z = 800$ mm) it, is shown in *Fig. 4*. *Fig. 5* depicts the EVF temperature as a function of height, for two characteristic horizontal distances, one close to the façade ($x = 10$ mm) and the other near the EVF centreline ($x = 100$ mm). Below the horizontal projection (*Fig. 4, left*) the peak EVF temperatures are observed close to the façade. However, above the balcony (*Fig. 4, right*) increasing P values result in a drastic reduction of EVF temperatures near the façade, an observation that is in full agreement with similar findings in the open literature [1, 7-10, 13, 14]; in this case, the peak temperature values are observed at increasing horizontal distances. The 400 mm horizontal projection depth is the most effective in reducing the mean EVF temperatures close to the façade (*Fig. 5*); however, a significant outward shift of the EVF trajectory is already observed for a balcony depth of 300 mm (*Fig. 4, right*).

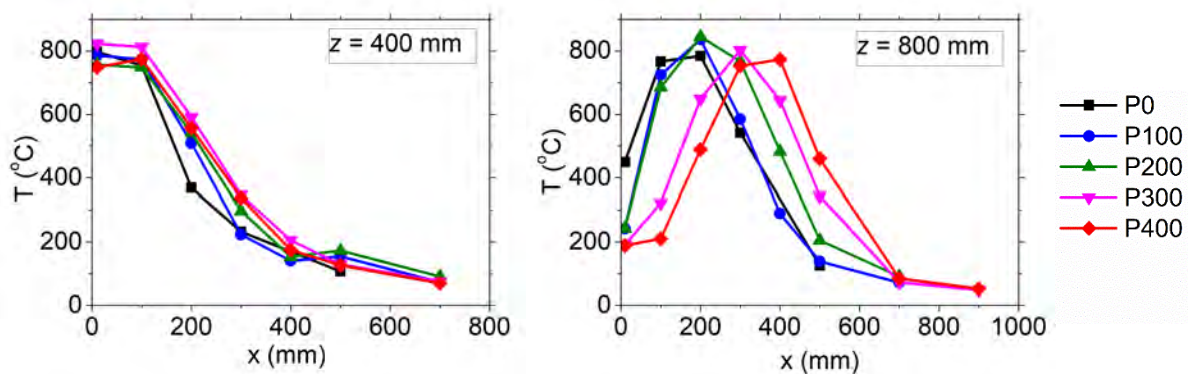


Fig. 4. EVF temperatures as a function of distance from the façade, for $z = 400$ mm (left) and $z = 800$ mm (right).

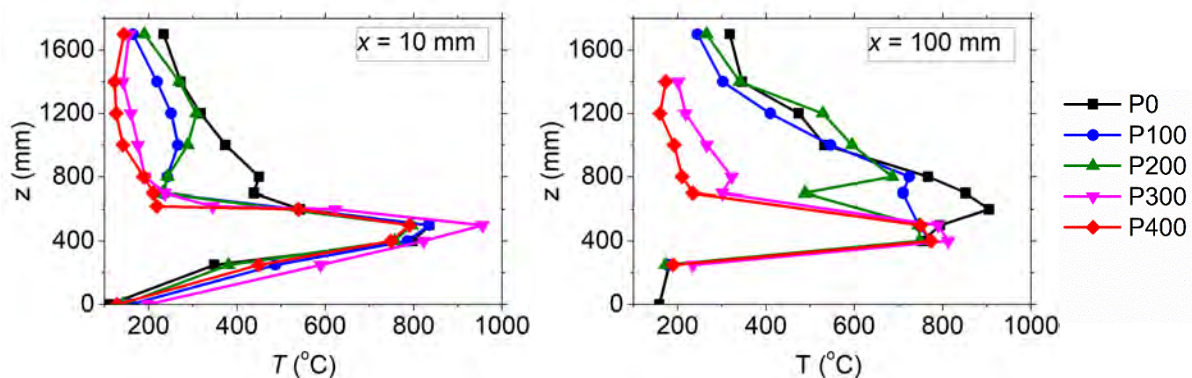


Fig. 5. EVF temperatures as a function of height, at a horizontal distance of $x = 10$ mm (left) and $x = 100$ mm (right).

The spatial distribution of the time-averaged gas temperatures, both inside and outside the compartment, is shown in *Fig. 6* for 3 characteristic test cases, i.e. P0 (*Fig. 6, left*), where no horizontal projection is installed, P200 (*Fig. 6, middle*) and P400 (*Fig. 6, right*). It is evident that the presence of a balcony leads to significantly lower temperatures close to the exposed façade surface. As expected, when P is increased, the EVF trajectory moves away from the façade, resulting in lower thermal attack levels on the wall surface. The temperature field developing inside the compartment exhibit similar characteristics in all test cases.

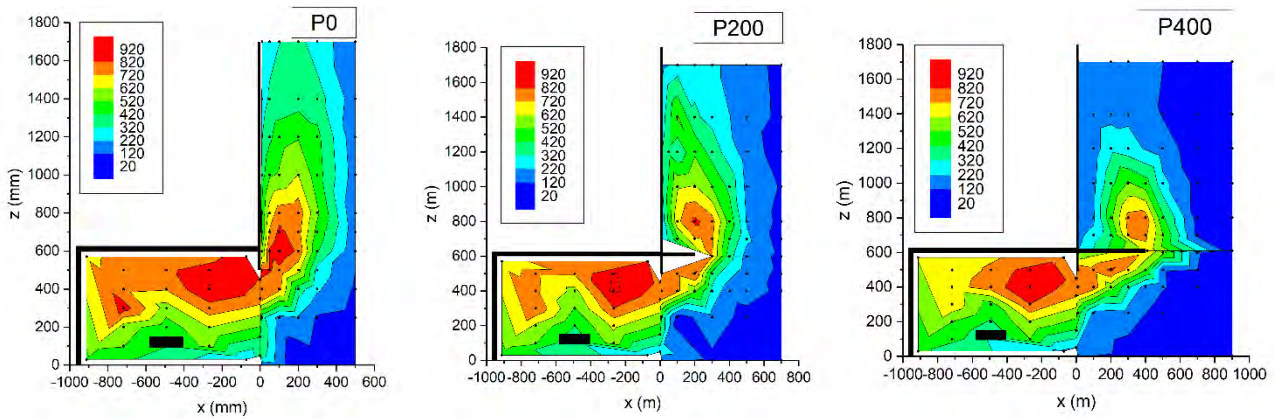


Fig. 6. Spatial distribution of indoor and outdoor temperatures for test cases P0 (left), P200 (middle) and P400 (right).

3.4 Façade Temperatures and Heat Flux

Fig. 7 illustrates the effects of the horizontal projection on the wall temperature (left) and the heat flux (right) on the exposed surface of the façade. A very distinct and sudden drop in façade temperature is observed just above the horizontal projection ($z = 800$ mm). As expected, at all heights, the lowest façade temperatures are recorded for the 400 mm depth horizontal projection (Fig. 7, left). However, the P300 and P400 temperature curves are very similar in shape; above a height of $z = 1200$ mm, they practically coincide. A similar behavior is observed also on the incident heat flux on the façade (Fig. 7, right). Heat flux levels for the P400 case correspond to less than 30% of the respective values when no horizontal projection is installed (P0). It is evident that increasing P results in a gradual reduction of the average heat flux levels, at all heights.

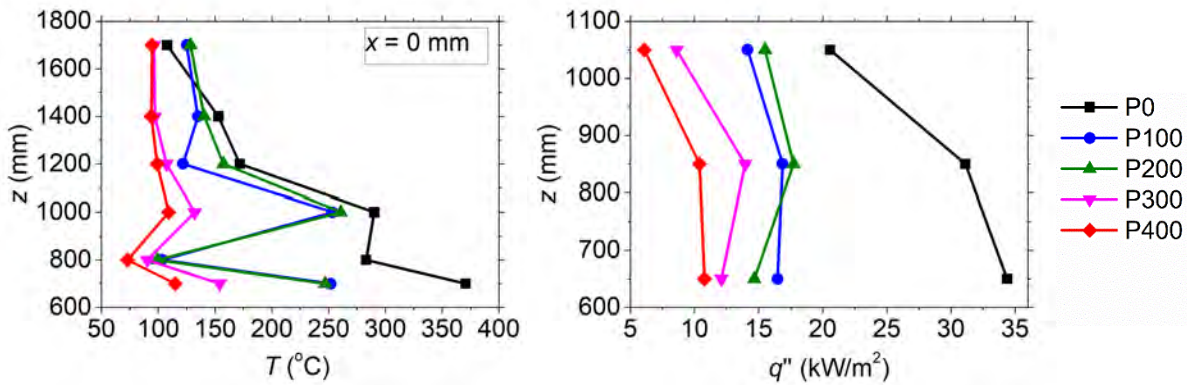


Fig. 7. Façade surface temperature (left) and heat flux (right) as a function of height.

3.5 Horizontal Projection Temperatures

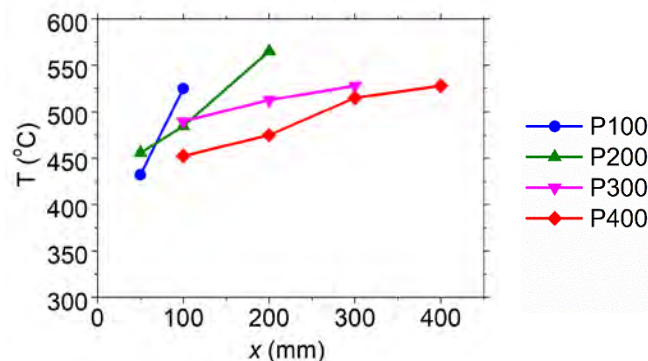


Fig. 8. Horizontal projection exposed surface temperatures as a function of horizontal distance (x).

Fig. 8 shows the recorded temperatures at the exposed surface (lower side) of the horizontal projection. It is observed that for each specific horizontal position, increasing P results in lower balcony temperatures. Once more, the lowest average wall temperatures are recorded for the P400 case. In general, wall temperatures along the lower surface of the horizontal projection are increasing with increasing distance from the façade; in test cases P100 and P200 this trend is more pronounced compare to test cases P300 and P400, which exhibit a more homogeneous temperature distribution.

4 SHAPE OF FLAME ENVELOPE AND COMPARISON TO EUROCODE

Aiming to establish the geometrical boundaries of the EVF envelope, an in-house developed image processing tool was used to determine the spatial distribution of the flame intermittency levels (Fig. 9); the thick black dashed line represents a flame intermittency level of 50%. The effect of the horizontal projection is evident; increasing P results in a more “distorted” EVF shape that gradually moves away from the façade. Overall, increasing P leads in decreasing EVF height, thus significantly reducing the average heat flux impinging on the façade wall above the horizontal projection. However, when the balcony depth is increased, both EVF projection and width are increased as well (c.f. Table 2).

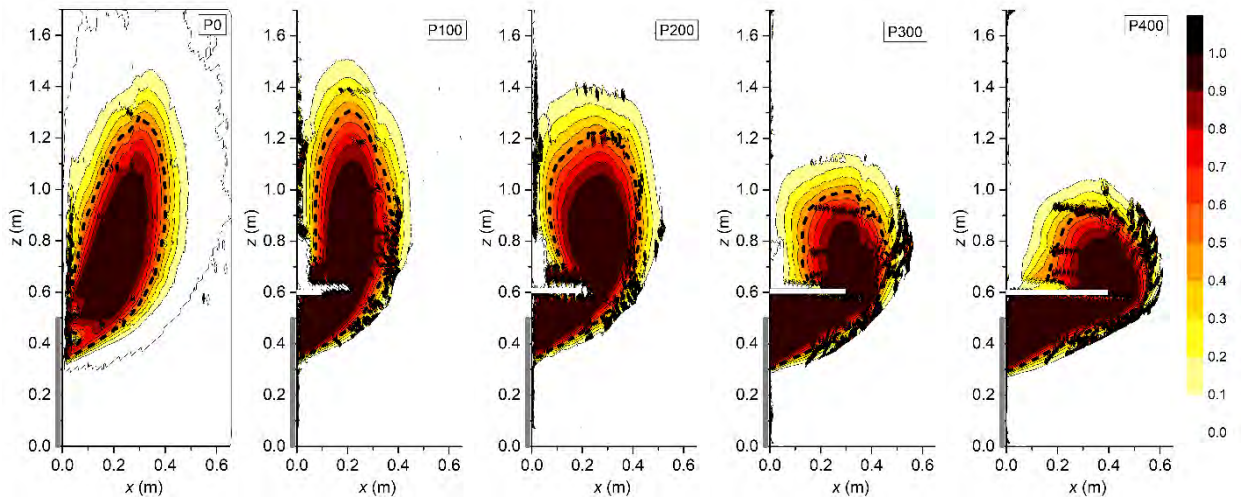


Fig. 9. Spatial distribution of flame intermittency values for all test cases.

A set of fire protection engineering design correlations are given in Annex B of Eurocode 1, Part 1-2 [15], aiming to determine the main geometrical characteristics of the EVF envelope, either without or with a horizontal projection. For the conditions corresponding to the test setup presented in this work, i.e. a door-type opening and a horizontal projection installed on the facade, Eurocode employs Eqs. (1) and (2) to determine the EVF height above its base at the opening ($L_{L,tot}$) and the horizontal distance between the EVF’s envelope projection and the façade ($L_H + h_{eq}/3$), respectively. The main parameters appearing in both Equations are the fire power (Q), the opening area (A_v), the opening height (h_{eq}), the opening width (w_t) and the “depth” of the horizontal projection (P); evidently $P = 0$, when no horizontal projection is present (e.g. test case P0). In addition, in Eurocode it is assumed that the EVF width is equal to the opening’s width.

$$L_{L,tot} = h_{eq} \left[2.37 \left(\frac{\dot{Q}}{A_v \rho_g (h_{eq} g)^{1/2}} \right)^{2/3} - 1 \right] - P + (h_{eq} / 3) \quad (1)$$

$$(L_H + h_{eq} / 3) = 0.3 h_{eq} (h_{eq} / w_t)^{0.54} + P + h_{eq} / 3 \quad (2)$$

Equations (1) and (2) were used to obtain the Eurocode predictions for the EVF height above its base at the opening ($L_{L,tot}$) and the EVF envelope horizontal projection ($L_H + h_{eq}/3$). In Table 2, the Eurocode predictions are compared against the respective experimental values, determined using the 50% flame intermittency isopleth (c.f. Fig. 9) for the EVF height ($L_{L,tot}$) and the 5% flame intermittency isopleth farthest from the façade for the EVF envelope projection ($L_H + h_{eq}/3$). The “deviation” values reported in Table 2 correspond to the relative error of the Eurocode predictions against the experimentally determined values; a negative deviation value suggests that the Eurocode correlations under-predict the respective measured values. It is noted that all EVF height and EVF width values predicted by Eurocode are smaller than the respective experimentally determined parameter and vice-versa for the EVF envelope projection; both cases correspond to “non-conservative” fire engineering design values predicted by Eurocode. In general, increasing P results in increasing levels of discrepancy. It is evident that the Eurocode assumption that the EVF width is equal to the opening width results in a significant under-prediction of the actual EVF width values.

Table 2. Comparison of experimental data and Eurocode predictions for EVF height, projection and width.

	Test Case	P0	P100	P200	P300	P400
EVF Height ($L_{L,tot}$)	Experimental (m)	0.936	0.970	0.874	0.691	0.628
	Eurocode (m)	1.010	0.917	0.756	0.527	0.415
	Deviation (%)	+ 7.95%	-5.42%	-13.49%	-23.75%	-33.95%
EVF Projection ($L_H + h_{eq}/3$)	Experimental (m)	0.483	0.408	0.488	0.516	0.532
	Eurocode (m)	0.413	0.513	0.613	0.713	0.813
	Deviation (%)	-14.47%	+25.72%	+ 25.47%	+ 38.20%	+ 52.79%
EVF Width (w_f)	Experimental (m)	0.325	0.326	0.423	0.639	0.856
	Eurocode (m)	0.200	0.200	0.200	0.200	0.200
	Deviation (%)	-38.37%	-38.56%	-52.74%	-68.72%	-76.65%

5 CONCLUSIONS

In this work, the effects of horizontal projections on the thermal and geometric characteristics of externally venting flames was investigated experimentally, by using a 1/4 scale compartment-façade configuration. Five different fire tests were performed, aiming to quantify the impact of varying the horizontal projection depth (P) on the main EVF parameters. The main conclusions that have been drawn by analysing the obtained experimental data are the following:

1. Compartment gas temperatures are not significantly affected by varying P . In general, gas temperatures at the back of the compartment (far from the opening) were found to be lower than the respective gas temperatures measured close to the opening.
2. Gas temperatures and velocities at the opening were largely unaffected by varying P .
3. EVF temperatures are largely affected by varying P . Increasing the depth of the horizontal projection results in significantly lower temperatures close to the façade wall, since the EVF trajectory moves increasingly away from the façade.
4. Façade surface temperatures and incident heat flux levels are significantly reduced when a horizontal projection is installed; however, increasing the P value further than 300 mm seems to yield a rather modest improvement.
5. Measured temperatures at the exposed (bottom) side of the horizontal projection are generally increasing with increasing horizontal distance from the façade; peak temperature values, of the order of 550°C, are achieved at the edge of the balcony.
6. Increasing the depth of the horizontal projection results in decreasing EVF height and increasing EVF projection and width.

7. Predictions of EVF height, projection and width using the fire engineering design correlations proposed in Eurocode show significant discrepancies with the respective experimentally determined values; it is worth noting that the majority of Eurocode predictions correspond to non-conservative engineering design values.

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INFLUENCE OF THERMAL BREAKS SOLUTIONS ON THE BEHAVIOUR OF A BALCONY UNDER FIRE – EXTERNAL FLAMES EXPERIMENTS, TREPOS PROJECT

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ABSTRACT

The aim of the TREPOS project is to develop and assess the thermal, mechanical and fire performances of simple solutions of thermal break for external steel structures (balconies, passageways) attached on a facade with external thermal insulation.

The studied solutions are composed of a PVC or plywood intermediate layer inserted between the attached steel structure and the support (floor slab, concrete wall, steel column). Thermal performances have been evaluated by numerical simulations and showed a reduction by about 40 to 50% of the heat losses (thermal bridges) at the attached steel structure connections.

Mechanical tests highlight the behaviour of the solution is quite close to that of conventional connections. Moreover, in order to evaluate the influence of the thermal breaks on the behaviour of a balcony under fire, two external flames experiments have been carried out on real balcony attached to concrete structure. These tests are of interest because there are few experimental data of this type on complete and real balconies subjected to fire, and even more so on balconies with thermal breaks.

1 INTRODUCTION

The evolution of requirements, which tends towards the generalization of nearly zero-energy buildings (NZEB) by 2020 (Energy Performance in Buildings Directive (EPBD) - 2010/31/EU - May 2010) [1], requires a judicious treatment of all the singular points (thermal bridges) present in the envelope of the building. The use of simpler solutions of thermal breaks implemented by companies both in the construction of new buildings and renovation, makes it possible to improve the thermal performances.

Thermal breaks are systems used to reduce heat loss through thermal bridges. Linear or point thermal bridges are parts of the building envelope, where the otherwise uniform thermal resistance varies significantly. Point thermal bridges typically occur where an insulated wall is perforated (penetration) by an element with high thermal conductivity. They are characterised by a point thermal transmittance (χ -value in W/K) [2].

The advantages of simpler solutions of thermal break is their reduced costs and ease of erection. Although their thermal performance is generally lower than that of industrial systems (thermal bridge reduction up to about 50% compared with about 80% for industrial breaks), the difference in cost, 7 to 10 times lower.

Many researches have been conducted in recent years to develop solutions reducing thermal bridging in concrete buildings ([3], [4]). However, these researches have concerned linear thermal bridges,

mainly at the junctions between the elements of the building envelope. Few works have been devoted to point thermal bridges due to the implementation of systems and structures on a facade of a building (solar panels, balconies, passageways and so on).

Cleary et al [5] conducted tests on steel connections using filler plates made of Fiber-Reinforced Resin as thermal barrier. Peterman et al [6] performed tests on connections insulated by Fiber-reinforced polymer fillers to characterize their long-term behaviour and to evaluate the modification of the shear resistances of bolts in presence of fillers.

In recent papers, Ben Larbi et al ([7], [8]) studied solution of thermal break with end-plate connection for external steel structures (balconies) attached on a concrete facade with external thermal insulation. This solution consists in the implementation of a rigid PVC plate and an acoustic insulation between the end-plate of each beam and the support (floor slab or concrete wall).

The present paper gives the results of a study assessing the fire performances of solutions of thermal breaks composed of PVC or wood plate for connections between steel structures (balconies...) and a facade with external thermal insulation. The paper gives also a summary of thermal and mechanical performances of these solutions.

2 DESCRIPTION OF THE THERMAL BREAKS SOLUTIONS

The studied solutions of thermal break consist in the implementation of a rigid PVC (20 mm) or wood (30 mm) layer between an end-plate of attached structure (Beam: IPE 200) and a support (concrete facade, ...) (see Fig. 1). The thermal conductivity of PVC and wood is respectively 0.07 W/m.K and 0.13 W/m.K.

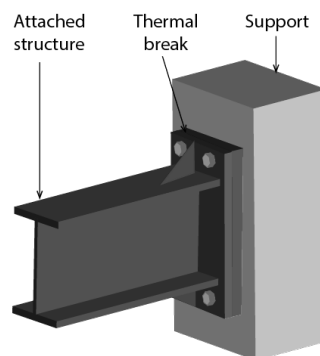


Fig. 1. Thermal break between attached structure and support

3 THERMAL PERFORMANCES

The impact of the thermal breaks on the thermal performances was analysed by numerical simulations according to EN ISO 10211 [2] using software TRISCO. These solutions of thermal breaks reduce the thermal bridge by about 40 to 50% in comparison with a conventional connection (without thermal break). The reduction depends on the facade insulation thickness. The performances of thermal breaks with 20 mm PVC and 30 mm wood are close (see Fig. 2).

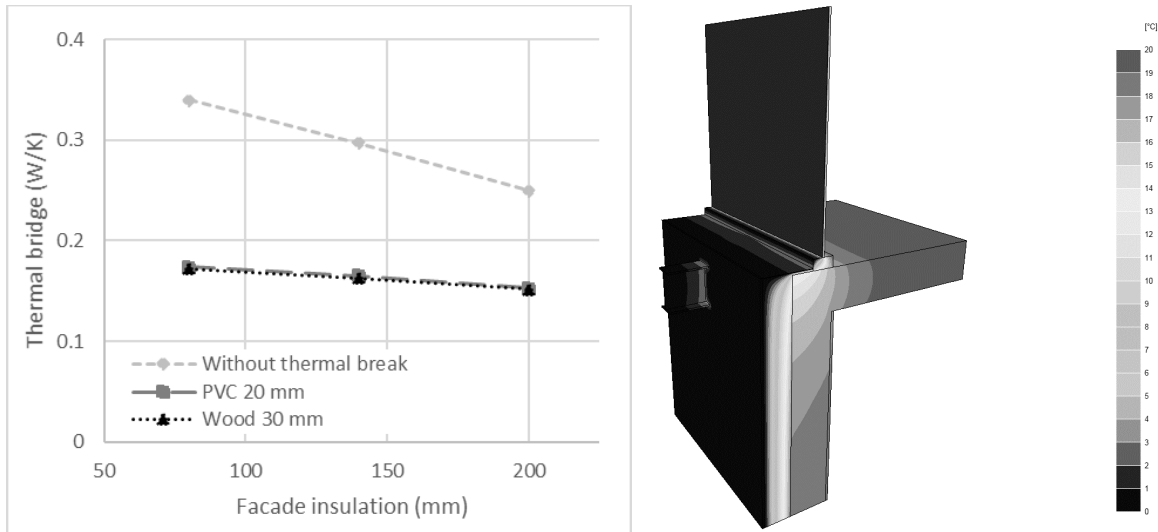


Fig. 2. Thermal performances of a I profile

4 MECHANICAL PERFORMANCES

The connections were firstly tested mechanically at ambient temperature. The test set-up was representative of a balcony attached to a concrete slab and a lintel. A load-jack apply a vertical force to a cantilever beam at 1150 mm from the connection in order to produce the bending moment due to gravity loading that is significant for the connection of a balcony.

The end-plate of 15 mm thickness is connected to the support by 4 chemical post-installed mechanical fasteners M20 and welded to the IPE 200 beam. Two specimens have been tested, a reference one without thermal insulation layer and the second one with a PVC intermediate layer of 20 thickness. The force applied by the load-jack is presented in Fig. 3 as a function of the vertical displacement in front of the load jack. The two specimens with and without thermal insulation layer present similar mechanical behaviour. The ultimate resistance in presence of PVC layer is slightly reduced. The failure corresponds to concrete cone cracking typical of this type of connection and is also not modified by the addition of a thermal insulation layer.

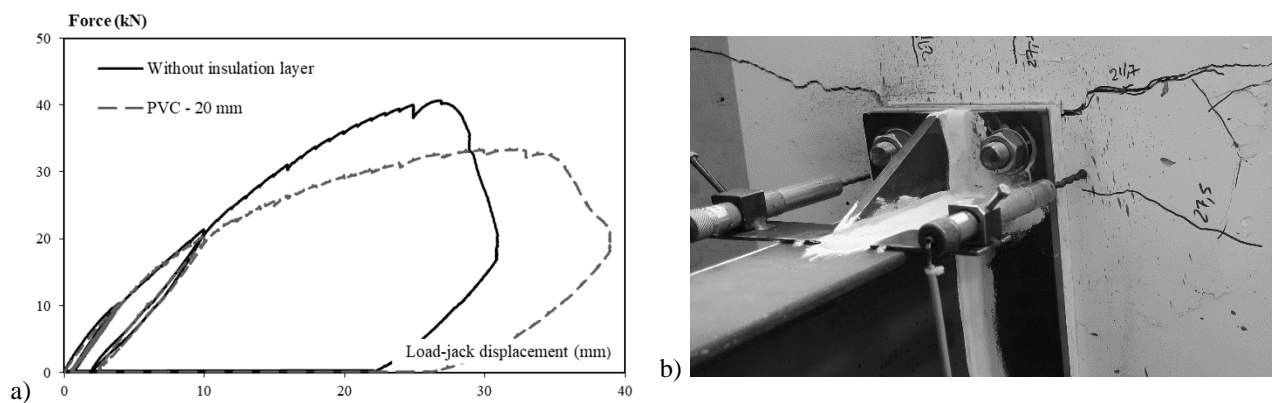


Fig. 3. a) Force-displacement curve; b) Specimen with PVC at failure

5 FIRE PERFORMANCES - EXPERIMENTAL SETUP

5.1 Tested configurations

The TREPOS project focuses a simple solutions of thermal break used in buildings. These solutions should be used in the case of facades with external thermal insulation.

The fire performances are tested in several configurations. A first case without thermal break is the reference case. Then there are two cases, one for each type of breaks, tested in an unfavourable configuration, namely without additional external insulation around the beams. In addition, due to the characteristics of PVC, a final configuration is selected: the PVC thermal break is tested in a realistic configuration, in which the plate beam is surrounded with additional external insulation (see Table 1).

Balcony	Thermal breaks	Additional external insulation
1	No	No
2	PVC	No
3	Plywood	No
4	PVC	Yes



Left: with additional external insulation
Right: without additional external insulation

Table 1. Tested configurations

Thus, four configurations are tested in total. Due to the dimensions of the test cell, two tests are carried out, *id est* two balconies per test. For the first test, the first balcony does not have thermal breaks. This case is considered as the reference case. The second balcony is built with PVC breaks. For these two balconies, no additional external insulation is added around the connection. This configuration is a critical case: the fire exposition of the beams is maximum. For the second test, the first balcony is built with wood breaks, without additional external insulation. The second balcony is built with PVC breaks, as the first test, but with additional external insulation.

5.2 Test facility

The fire testing is done by exposing the balcony to external flames generated by a generalized fire in a furnace. The internal dimensions of the furnace are 2850×4850×2700 mm. The front face is closed with a 200 mm thick concrete block, and at the top, the reinforced concrete slab is 250 mm thick, with a lintel 600 mm high. The front face had an opening of dimensions 2000×1500 mm, located at 950 mm from the ground. This size allows (and was chosen) to have two balconies per test and also to have one of the beams of each balcony highly exposed to fire. The rear face had an opening of dimensions 2750×360 mm. The external insulation of the facade is made of 140 mm stone wool. The fire load in the furnace consists of two wood stacks of 300 kg each composed in the same way as for a LEPiR II test (see Fig. 4). This is also consistent with recommendations in EN 1991-1-2 [9].

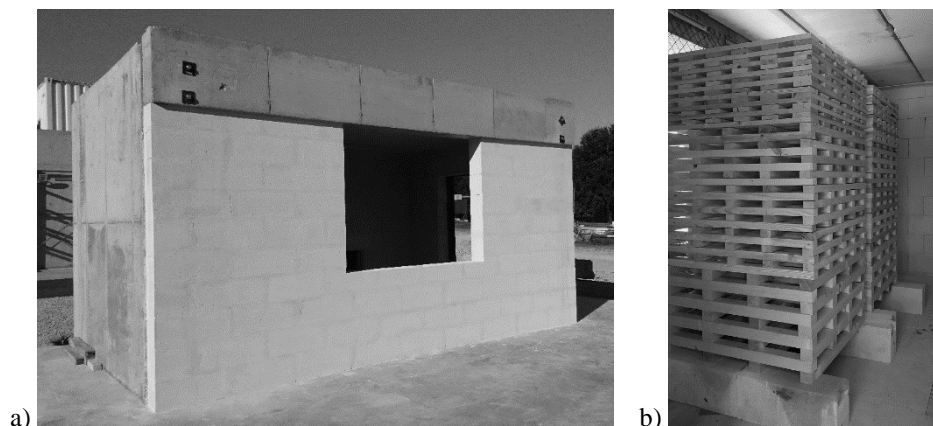


Fig. 4. a) Test cell; b) Wood stacks

5.3 Structure

The balconies tested have a range of 1.40 m and are supported by two consoles separated by a distance of 1 m. The consoles are installed on a reinforced concrete lintel 600 mm high. The support beams are composed of an IPE 200 S275 welded to an end-plate of 340×160 mm² in S235. The consoles are connected to the lintel with four chemical post-installed anchor bolts M20. The balcony slab is in cellular concrete with a thickness of 125 mm and a density of 550 kg/m³. Both structures are exposed to flames coming out of a single aperture whose width allows maximum exposure of the two central beams and reduced exposure of the other beams. Fig. 5 gives an overview of the test setup.



Fig. 5. a) Complete test setup; b) Slab loaded

The load applied on each balcony, is close to 570 kg, and thus 285 kg per beam. The weights are distributed on the upper face of the cellular concrete slab, on the same line, at the end of balcony. This load have been designed based on a permanent load of 120 kg/m² and operating load 175 kg/m².

5.4 Measurements

The objective being to validate the steel structure with thermal breaks, it is necessary to measure the mechanical resistance of console subjected to fire. Moreover, to carry out the post-test numerical simulation campaign, it is necessary to measure the temperature of steel and gases. Thus, between 25 and 30 thermocouples are placed on each beam to measure steel temperature, lintel-break interface temperature, and break-plate interface temperature. Other thermocouples are positioned to measure the external insulation temperature. Moreover, temperatures in the test cell are measured and 6 thermocouples are placed under the front opening to measure external flames temperature.

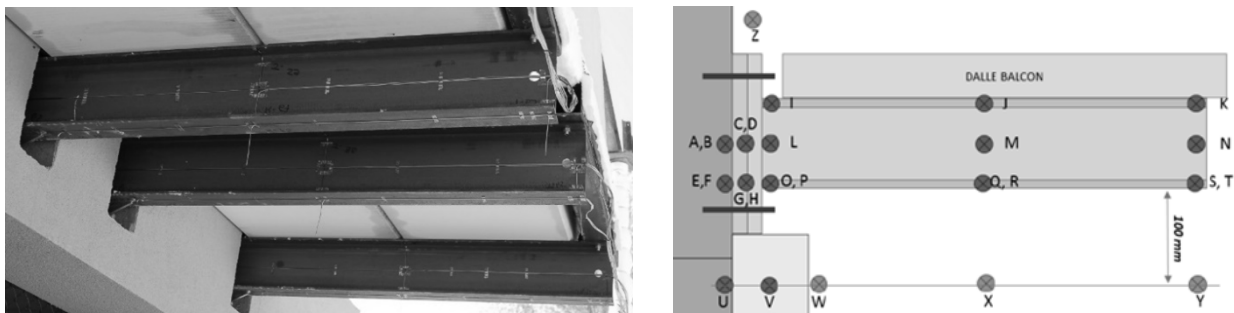


Fig. 6. Location of the thermocouples

A measurement of vertical displacement at the extremity of the beams is performed, as well as a measurement of rotation of the console with an inclinometer. In addition, a flowmeter of range 0 to 50 kW/m² is positioned 3 m from the front, and a conventional camera records one video of each test.

6 RESULTS

6.1 Global description

Each test lasts approximately 45 minutes and proceeds as follows. The firing is done using fuel tanks placed under the wood stacks. The smokes exit through the opening of the facade one minute after ignition. After 5 minutes, we observe the first external flames. At 10 minutes, the fire is fully developed and the flames reach their maximum length. They leave the opening at an angle of 45° , thus only half of the console is directly impacted by these flames. From 15 minutes, the fire gradually decreases, and the stacks have partially collapsed. At 20 minutes, the wood stacks are collapsed and no flame is visible outside. Hot gases come out again through the opening of the facade, and the temperature under the balcony remains high for another 20 minutes. Measurement acquisition is cut off after 45 minutes. There is no longer any observable flame above the rest of the wood stacks.

In terms of temperature, the temperature in the test cell reaches 900°C at the measurement points in the full development phase of the fire. The temperature of flames and gases coming out through the front opening is close to 800°C and can reach up to 1000°C under the consoles directly above the opening.

The temperature in the external insulation of the facade above the opening increases progressively during the test. It reaches 600°C in the heart of the external insulation (thermocouple Tc V), but only 100°C at the interface between the insulation and the concrete support (Tc U). These measures highlight the importance of external insulation and its proper implementation around beams, even in case of exceptional fire situation.

The central beams located directly above the opening are the most exposed. The temperature of their steel section closest to the facade are lower than the temperature at mid-range or at the beam extremity. This is due to the shape of the flames coming out through the opening. The distance between the top of the opening and the bottom of the metal elements guarantees a flame free zone. The maximum temperature of the end-plate is about 500°C , while the mid-range temperature reaches almost 900°C , and the temperature at the beam extremity is 750°C (see Fig. 7). Note that these unprotected steel elements have a fire-resistant behaviour.

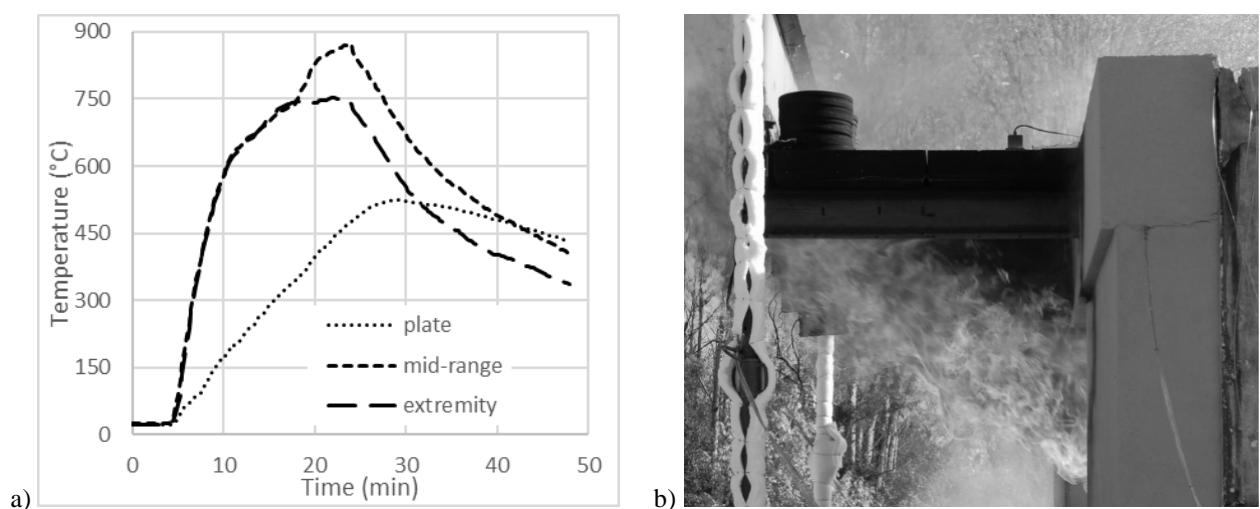


Fig. 7. a) Temperatures reach (first test); b) Shape of the external flames

6.2 Thermal break behaviour and temperature

By comparing configurations 2 and 4, the influence of the additional external insulation is strong: the decrease between the air temperature ($T_c L$) and the plate-break interface temperature ($T_c C$) is higher from 320°C (800°C-480°C) to 580°C (740°C-160°C). The thermal break plays also a role in the temperature decrease at the lintel interface ($T_c A$). For the second test, the temperature observed under the balconies is lower than the temperature of the first test. Indeed, the fire developed differently in the two cases with wind in the second test. Thus, the steel end-plate temperature is lower for the configurations 3 and 4, and the temperatures of plate-break interface and break-lintel interface are lower than the temperatures of the first test. The use of plywood layer leads to a better insulation comparatively to PVC layer. Nevertheless, in all cases the thermal break (with or without additional external insulation) allows a high degree of insulation for the lintel.

Thermal break	Additional external insulation	Air temperature (°C)	Plate-break interface temperature (°C)	Break-lintel interface temperature (°C)	ΔT (°C)
1- No	No	830		375	/
2- PVC	No	800	480	280	200
3- Wood	No	670	320	50	270
4- PVC	Yes	740	160	30	110

Table 2. Temperatures of plate-break and break-lintel interfaces

The temperature of the break-lintel interface in the configuration 2 was about 280 °C and is high compared to the other temperatures observed at the break-lintel interface. This increase of the temperature is due to the fact the PVC break burned. Part of the thermal break is consumed and the hot gases are introduced under the plate. The temperature of the break is therefore much higher. The partial consumption of the thermal break causes the rotation of the end-plate that returns in contact with the lintel at the bottom. This rotation induces a vertical displacement of 14 cm at the extremity of the beam, compared to the 5 cm for the other configurations. The three thermal breaks tested are presented by Fig. 8.



Fig. 8. Thermal breaks after test (left to right: configurations 2, 3 and 4)

Despite the high temperatures at the thermal breaks, the integrity of the balconies attached to the facade of the building subjected to fire is preserved. While the absence of external insulation was very favourable, the tests show that the presence of the thermal breaks does not affect the overall stability of the balconies during fire.

7 CONCLUSION

The aim of the TREPOS project is to assess the behaviour of simple thermal break solutions for steel structures attached to the facade of a building. The mechanical tests performed on the proposed solutions shown that the behaviour is not far from that of conventional connections in terms of resistance and stiffness. Fire tests have been carried out on balconies typically used in practice. The temperature measurements of the various elements of the structure during the tests allow a thorough analysis of the assemblies' behaviour during the fire. It is noted that the presence of thermal breaks in wood or PVC does not compromise the overall stability of the balconies.

The tests also demonstrate that the unprotected steel elements subjected to fire do not have a critical behaviour which could compromise their stability. Moreover, their behaviour remains good even in the presence of thermal breaks that weaken the structure.

In order to complete these experimental tests for different structures and fire situations, a numerical parametric study will be conducted. The purpose of the study is to validate the use of simple thermal break solutions for other steel beam sections and other building dimensions. It is expected that the study will be done in three stages: CFD modelling of external flame tests, finite elements modelling of the different structures evaluated, and proposal of a simplified design method for steel construction practitioners.

ACKNOWLEDGMENTS

The TREPOS project was partially funded ADEME (Environment and Energy Management Agency) as part of the call for research projects "Toward responsible buildings by 2020". The society PERRAUD & ASSOCIES carried out the implementation and the assembly of the tested structures, and advised the design of the experiments.

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HEAT FLUXES TO A FAÇADE RESULTING FROM COMPARTMENT FIRES WITH COMBUSTIBLE AND NON-COMBUSTIBLE CEILINGS

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ABSTRACT

Exposed structural timber elements pose a particular fire hazard due to their combustibility, which means that they will generate additional fuel which will burn in the event of a fire. Burning within a building compartment is limited by oxygen availability, which is controlled primarily by the opening geometry. Under ventilation-controlled conditions, any unburned pyrolysis products will vent via the opening and burn outside the compartment. The resulting external fire plume will radiate heat to the façade and surrounding buildings – this has implications for fire spread.

As part of the Épernon fire tests programme, six large-scale compartment fire experiments were undertaken to interrogate this issue – three with a precast concrete ceiling, and three with an exposed cross-laminated timber (CLT) ceiling, with three different ventilation factors. All compartments had non-combustible walls and floor. Heat fluxes were recorded opposite the opening and on the façade to attempt to quantify the potential increased risk(s) of fire spread induced by an exposed timber element in the compartment. During experiments with a smaller opening factor ($4.64 \text{ m}^{-0.5}$) the peak heat flux recorded opposite the opening was approximately double when a CLT ceiling was introduced ($\sim 45 \text{ kW/m}^2$ versus $\sim 22 \text{ kW/m}^2$ with a concrete ceiling, at a standoff distance of 3 m). Experiments with a larger opening factor ($14.2 \text{ m}^{-0.5}$) showed a $\sim 50\%$ increase ($\sim 17 \text{ kW/m}^2$ versus $\sim 25 \text{ kW/m}^2$) when a CLT ceiling was introduced.

1 INTRODUCTION

Cross-laminated timber (CLT) is becoming increasingly popular as a construction material due to its environmental, economic, and aesthetic appeal. Increasingly, architects wish to leave some of this timber exposed, to better realise its aesthetic benefits. This is known to result in fundamental changes to the fire dynamics when compared to non-combustible building materials. In the event of a fire, exposed timber surfaces will generate additional pyrolysate, which ignites and burns alongside the compartment's "imposed" fuel load (e.g. furniture and other combustible contents). When the quantity of pyrolysate generated is greater than that which can react with the available oxygen, unburned gases will vent through the compartment opening. These will then mix with available oxygen outside the compartment and burn as an external plume. The energy released in this plume will radiate to the façade above the opening. This paper will explore the additional hazard generated by the presence of an exposed timber ceiling compared to an inert (concrete in this case) ceiling.

2 EXPERIMENTAL REGIME

Six compartment fire experiments were undertaken as part of the "Épernon Fire Tests Programme". Each compartment had the same internal dimensions, being 6 m x 4 m in plan, and 2.52 m in height. Three different opening geometries were tested, with one test with a CLT ceiling and one test with a concrete ceiling used for each geometry. The geometries used are listed in *Table 1*. The opening

factors are given as defined by Thomas [1] as $A_T/A_v\sqrt{h_v}$, where A_T is the total internal area (excluding openings and floor), A_v is the opening area, and h_v is the opening height. Equivalent opening factors according to the definition in the Eurocode [2] are also included in the table.

Table 1. Opening geometries in compartment fire experiments

Scenario #	Number of openings	Height of opening [m]	Width of opening [m]	Opening factor [$m^{-0.5}$]
1	2	2	2.5	4.64 (0.14*)
2	3	1.2	1.25	14.2 (0.05*)
3	1	2	1.1	23.2 (0.03*)

*Equivalent opening factors according to the Eurocode definition [$m^{0.5}$]

In each experiment, the external fuel load was supplied using wood cribs, with six cribs, each with 12 rows of five sticks. Each stick measured 90 mm x 90 mm x 1 m, and weighed approximately 3.5 kg. The cribs were ignited using a 3 L heptane pool fire beneath each crib. Thus the total imposed fuel load, including heptane, was approximately 891 MJ/m².

2.1 Instrumentation

Temperature was recorded next to each crib using Type K thermocouples. In addition, plate thermometers were installed below the ceiling slab. Opposite the opening(s), water-cooled heat flux gauges were positioned at 3 m from the compartment and at a height of 1.5 m to compare heat fluxes during the experiments.

For Scenarios 2 and 3, a screen made of six panels of calcium silicate boards (Promatect T – 25 mm thick) representing a façade was installed above the compartment, instrumented with thermocouples and thin skin calorimeters (TSCs). Six TSCs were installed in two columns – one in line with the centreline of the opening, and one 1475 mm to the right (not presented here). The TSCs were positioned at heights of 200 mm, 1200 mm, and 2200 mm above the top of the compartment. Each TSC had a Type K thermocouple positioned 100 mm below it recording the gas-phase temperature.

Thin skin calorimeters were developed as a robust, low-cost alternative to traditional water-cooled heat flux gauges [3]. They consist of a thin Inconel disc of diameter 9.6 mm and thickness 0.7 mm embedded in a vermiculite core. The disc is welded to a type K thermocouple, and an energy balance on the disc can be solved as in Eq. (1) to approximate the incident heat flux.

$$\dot{q}''_{inc} = \frac{1}{\alpha_{disc}(1-C)} \left[\gamma \frac{m_{disc}}{S_{disc}} c_p \frac{dT_{disc}}{dt} + \varepsilon_{TSC} \sigma T_{disc}^4 + h_c (T_{disc} - T_{\infty}) \right] \quad (1)$$

where \dot{q}''_{inc} is the incident radiative heat flux,
 α_{disc} is the absorptivity of the disc, taken as 0.8 [4],
 C is the experimentally determined calibration factor,
 γ is a transient compensation factor, taken as 0.8 [3],
 $\frac{m_{disc}}{S_{disc}}$ is the mass to surface area ratio,
 C_p is the specific heat capacity of the disc,
 $\frac{dT_{disc}}{dt}$ is the rate of change of temperature of the disc,
 ε_{TSC} is the emissivity of the disc,
 σ is the Stefan-Boltzmann constant,
 T_{disc} is the disc temperature,
 h_c is the convective heat transfer coefficient,
 T_{∞} is the gas phase temperature.

The TSCs were calibrated according to a methodology given by Hidalgo et al. [3] over a range of heat fluxes from 5 kW/m^2 to 90 kW/m^2 . This gave a calibration factor of $C = -4.1723 \times 10^{-4}T + 0.5098$, with T in $^{\circ}\text{C}$. This calibration factor was shown to calculate the heat flux accurately within the range $5 \text{ kW/m}^2 < \dot{q}'' < 45 \text{ kW/m}^2$ when comparing against values from the heat flux gauge. Since Eq. (1) explicitly accounts for the convective exchange between the disc and the gas, it is important to consider accurate gas temperatures. For this reason, the readings from the thermocouples positioned 100 mm below the TSCs were used as the gas temperatures. This methodology has been shown to give good agreement with water-cooled heat flux gauges in small-scale façade fire experiments [5].

3 EXPERIMENTAL RESULTS

3.1 Gas-Phase Temperatures

The plate thermometer temperatures inside the fire compartment for each experiment are shown in Fig. 1. The thick lines indicate average temperatures, and the thinner dotted lines minima and maxima.

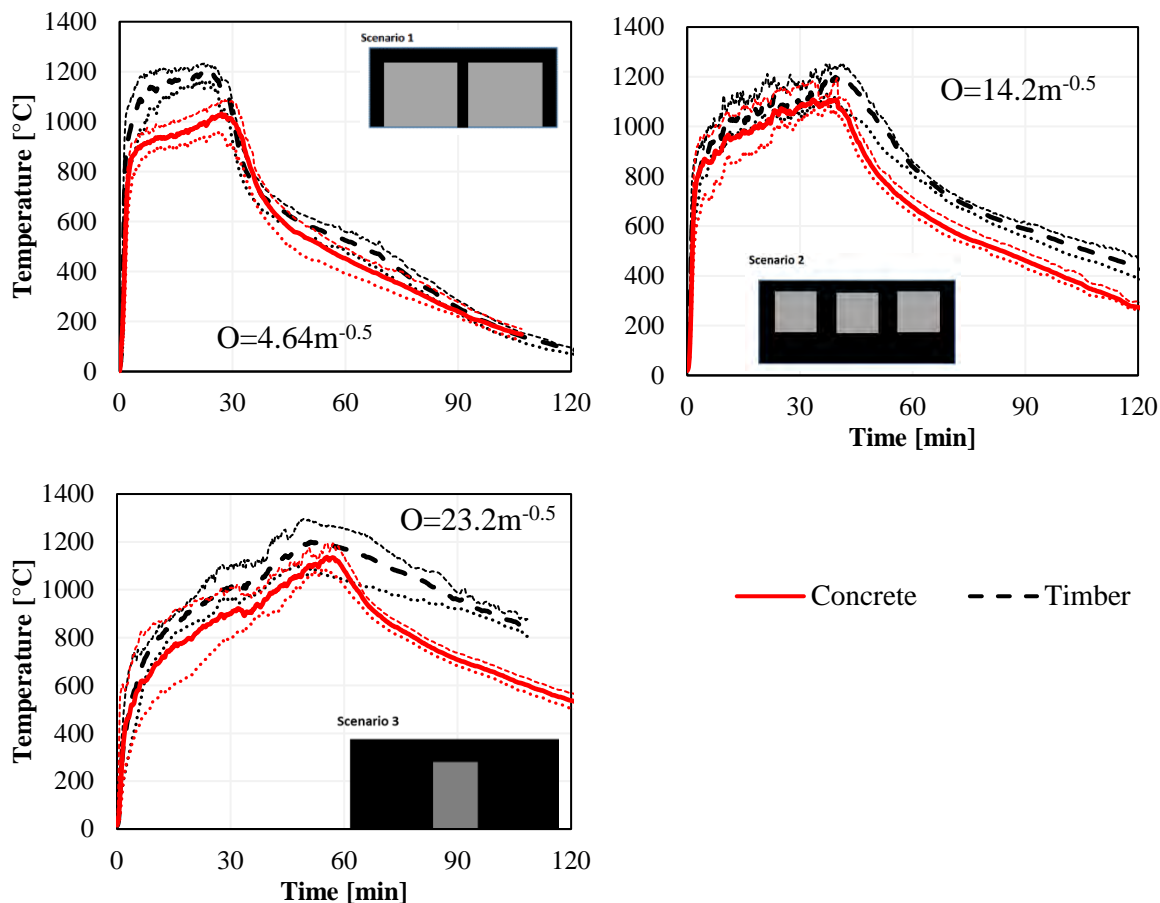


Fig. 1. Averaged plate thermometer temperatures during compartment fire experiments, with minima and maxima shown. Top-left: Scenario 1 (two large openings), top-right: Scenario 2 (three small openings); bottom-left: Scenario 3 (single small opening).

It is evident that in most cases the presence of a combustible ceiling increases the average temperature and/or burning duration. Scenario 1 corresponds to a *Regime II* (fuel-controlled) post-flashover fire. This means that the ventilation is sufficient to burn all the available fuel inside the compartment, and thus introducing additional fuel will result in greater burning *inside* the compartment (as there is available oxygen), rather than forcing the extra pyrolysate to burn *outside* the compartment in an external plume. This is evident from the clearly increased gas-phase temperatures associated with the

timber slab for Scenario 1 in *Fig.1*. Scenarios 2 and 3 corresponds to a *Regime I* (ventilation-controlled) post-flashover fire. This means that the amount of burning inside the compartment is limited by the available oxygen, and thus some additional burning will occur outside the compartment in an external plume. As such, introducing additional fuel will not result in a greater burning rate *inside* the compartment (as there is insufficient oxygen for it to burn), but will instead result in more unburned gases exiting the compartment and burning in an external plume, and may also result in a greater burning duration. This is evident from the similar gas-phase temperatures for Scenarios 2 and 3. The slightly higher temperatures observed in the timber tests can be attributed (at least in part) to differences in the thermal diffusivity of the two materials.

3.2 Heat Fluxes to the Facade

The façade instrumentation was installed only for Scenarios 2 and 3 due to wind conditions on testing days – thus the heat flux to the façade is not available for Scenario 1. The heat fluxes to the centreline of the façade, 200 mm, 1200 mm, and 2200 mm above the top of the compartment ceiling slab are shown in *Fig. 2*. It should be noted that, as mentioned above, heat fluxes above 45 kW/m² may not be accurate due to the limitations of the TSC calibrations.

The methodology for heat fluxes to external elements of structure provided in Annex B of Eurocode 1 Part 1-2 [2] was used as a comparison. This method calculates the heat release rate based on the compartment geometry, and from this calculates the flame height and temperature. The full method is presented in Annex B of Eurocode 1 Part 1-2 [2]; key aspects are summarised here. The heat release rate (HRR) is calculated from *Eq. (2)*:

$$Q = \min \left(\frac{A_f \cdot q_{f,d}}{\tau_F}; 3.15 \left(1 - e^{-\frac{0.036}{O}} \right) A_v \sqrt{\left(\frac{h_v}{\frac{D}{W}} \right)} \right) \quad (2)$$

where A_f is the compartment floor area,
 $q_{f,d}$ is the fuel load per unit area,
 τ_F is the free burning fire duration (assumed to be 1200 s),
 O is the inverse opening factor $A_v \sqrt{h_v} / A_{tot}$,
 A_{tot} is the total internal surface area, *including* openings and floor,
 D is the compartment depth,
 W is the compartment width.

In both cases (Scenario 2 and Scenario 3), the second term in *Eq. (2)* was found to be the lower, and thus the heat release rate is independent of fuel load, and adjusting the fuel load to account for exposed CLT would not change the calculated HRR. This HRR was then used to calculate the flame height above the top of the opening by *Eq. (3)*:

$$L_L = 1.9 \left(\frac{Q}{w_v} \right)^{\frac{2}{3}} - h_v \quad (3)$$

where w_v is the total width of all openings.

This is added to the flame exit length, L_1 , calculated as $\frac{h_v}{2}$, to get the total flame length, L_f . The temperature along the axis can be calculated from *Eq. (4)*:

$$T_z = \left(\frac{520}{1 - 0.4725 \left(L_f \cdot \frac{w_v}{Q} \right)} \right) \left(1 - 0.4725 \left(z \cdot \frac{w_v}{Q} \right) \right) + T_0 \quad (4)$$

where z is the height along the axis, taken as $L_1 + 1.7$,
 T_0 is the ambient temperature.

The view factor to the TSC is assumed to be equal to one – i.e. the flames are engulfing the façade. The emissivity is calculated as:

$$\varepsilon = 1 - e^{-0.3d_f} \tag{5}$$

where d_f is the flame thickness, given by $\frac{2}{3}h_v$.

The incident radiative heat flux is then calculated; these values are plotted alongside the experimental data in Fig. 2 for each of the centreline TSCs. Due to a misplaced gas-phase thermocouple beside the lowest TSC in CLT Scenario 3, it was not possible to calculate the heat flux for this position. Therefore, this comparison has been omitted.

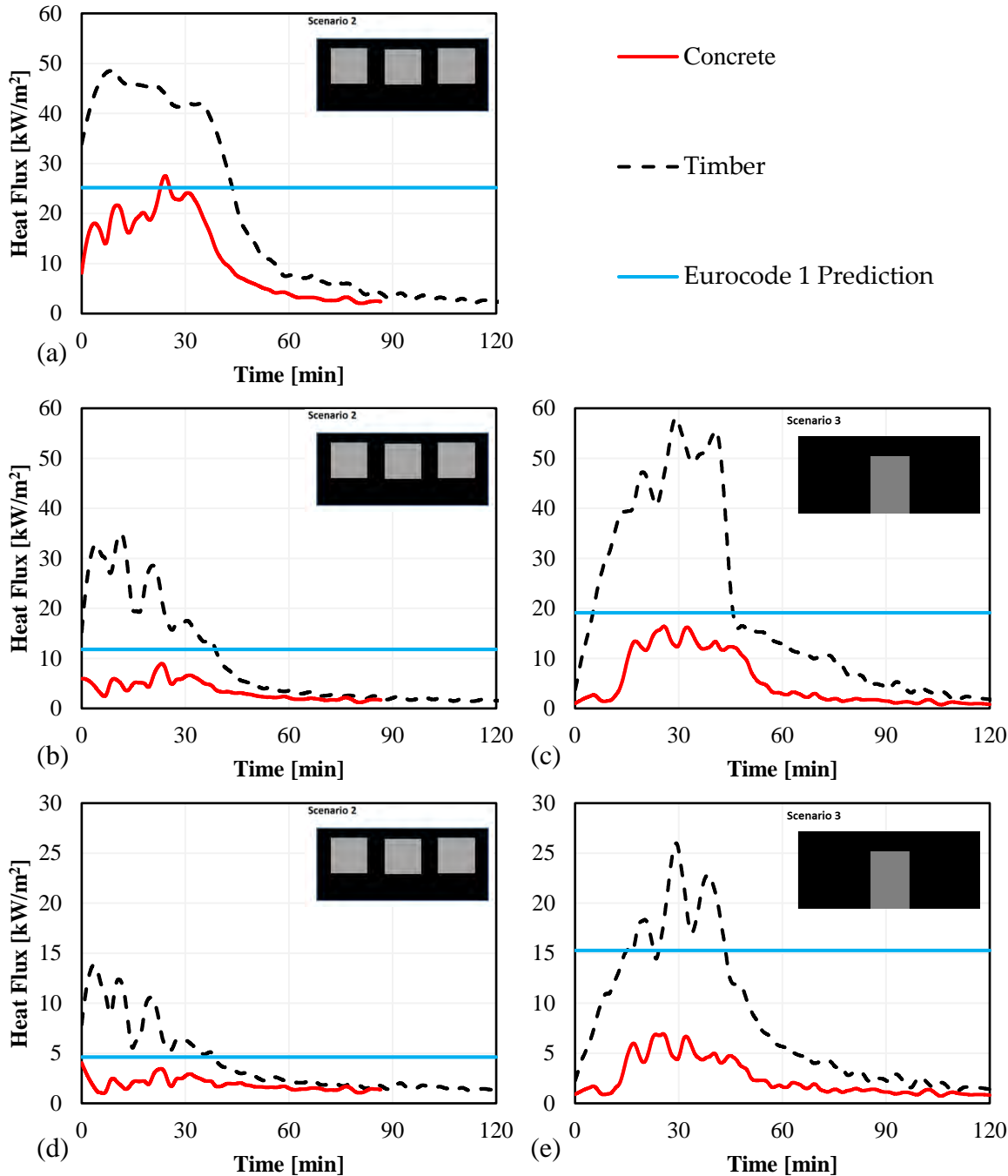


Fig. 2. Incident heat flux to the centreline of the façade above top of opening for (a) 200 mm above the top of the compartment, Scenario 2; (b) 1200 mm above the top of the compartment, Scenario 2; (c) 1200 mm above the top of the compartment, Scenario 3; (d) 2200 mm above the top of the compartment, Scenario 2; and (e) 2200 mm above the top of the compartment, Scenario 3.

It is evident that the incident heat flux to the façade is significantly ($\sim 3\times$) greater when a timber ceiling is used instead of a concrete ceiling – a maximum increase of $\sim 30 \text{ kW/m}^2$ for Scenario 2 and $\sim 40 \text{ kW/m}^2$ for Scenario 3. This is a much more significant difference than was observed for the gas phase temperatures shown in *Fig. 1*. This is due to the extra pyrolysate produced by the burning timber slab burning in the external plume due to insufficient oxygen entrained into the compartment. The Eurocode method provides a reasonable (and slightly conservative) estimation of heat flux to the façade for the case of a non-combustible ceiling in Scenario 2, but significantly overestimates the heat flux at 2200 mm for Scenario 3. In the case of a combustible ceiling, the method does not account for the additional fuel load provided by the exposed CLT, and thus severely under-estimates the peak heat flux to the façade. These data are shown in *Fig. 3* as a function of height – the maximum heat fluxes recorded at each location are shown for the timber and concrete tests, and are again compared against the Eurocode predictions. It is again evident that the presence of an exposed timber ceiling significantly increases the maximum heat flux to the façade compared to a non-combustible slab or the Eurocode calculation methods.

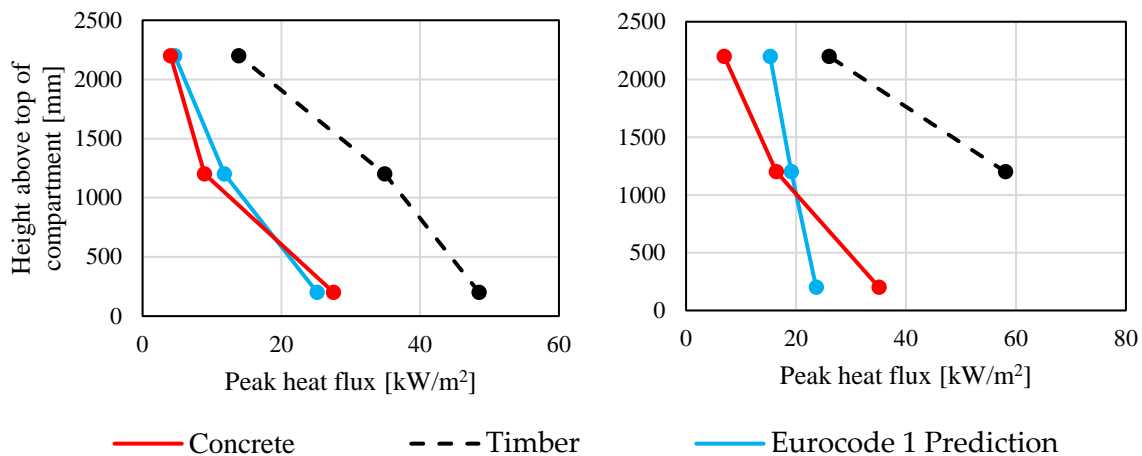


Fig. 3. Maximum heat fluxes as a function of height for Scenario 2 (left) and Scenario 3 (right).

The gas phase temperatures above the openings are shown in *Fig. 4*. As with the heat fluxes, it is clear that an exposed timber ceiling significantly increases the temperatures in the external plume. *Fig. 4* also shows how the gas phase temperatures reduce as a function of height – the data are plotted for the thermocouples located 0.2 m, 1.2 m, and 2.2 m above the top of the opening. (Note that the 0.2 m thermocouples are not shown for Scenario 3 due to an error in their placement).

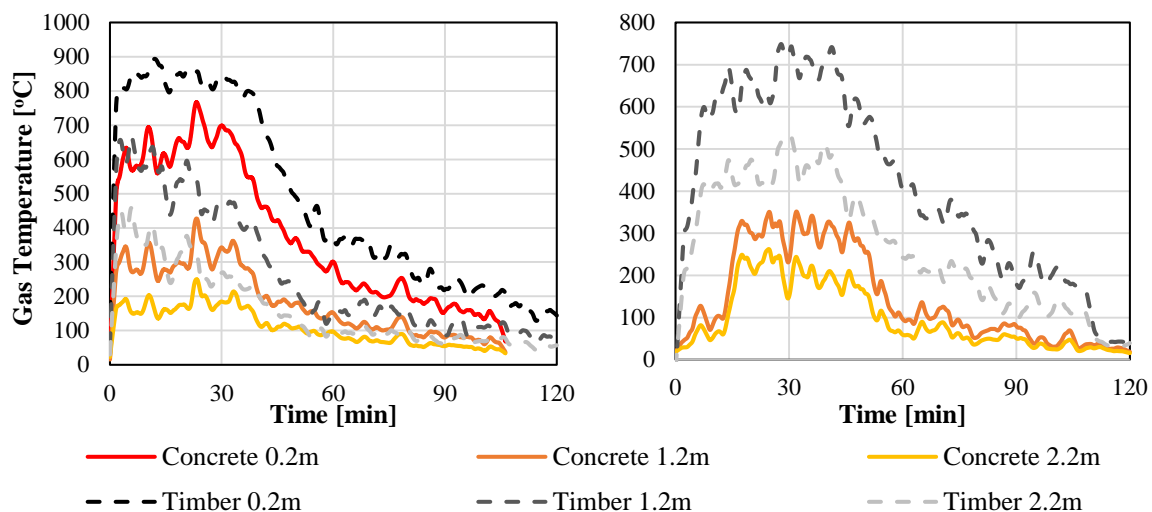


Fig. 4. Gas temperatures at the centreline of the façade for Scenarios 2 (left) and 3 (right).

3.3 Heat Fluxes opposite the Opening

Water-cooled heat flux gauges were installed opposite the façade for all experiments, enabling comparison of the external heat fluxes across all six experiments. The heat flux data directly opposite the opening (the centre opening for Scenario 2) at a standoff distance of 3 m are shown in Fig. 5 as functions of time.

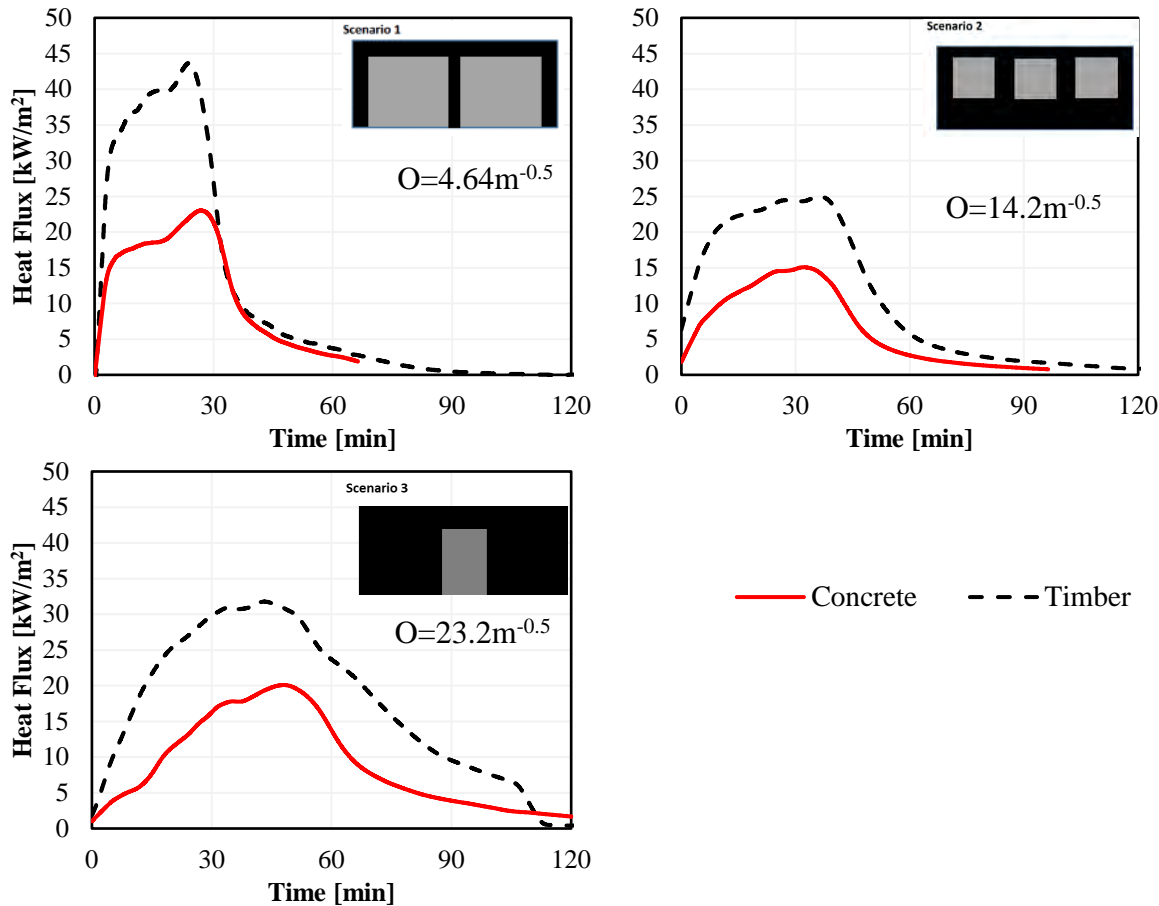


Fig. 5. Incident heat flux opposite opening for all experiments. Top-left: Scenario 1 (two large openings), top-right: Scenario 2 (three small openings); bottom-left: Scenario 3 (single small opening).

The peak heat fluxes for each concrete test are similar, with a minimum for Scenario 2 ($\sim 15 \text{ kW/m}^2$), and a maximum for Scenario 1 ($\sim 23 \text{ kW/m}^2$). The larger heat flux for Scenario 1 can be attributed to the size of the openings, resulting in a larger physical flame area (i.e. view factor *into* the compartment) and significantly higher internal compartment temperatures with a timber ceiling. In each case, there was a notable ($\sim 10\text{-}20 \text{ kW/m}^2$) increase in the heat flux when a timber ceiling was introduced. This can again be attributed to the increased flame area and gas phase temperatures.

4 CONCLUSIONS

A series of six compartment fire experiments has shown (or rather confirmed) that:

- opening geometry has a significant effect on the fire dynamics, and the resulting external fire plume;
- the presence of a timber ceiling results in a heat flux to the façade around three times that when a non-combustible ceiling is used – this will result in an increased risk of vertical fire spread up the building of fire origin; and

- the presence of a timber ceiling results in heat fluxes opposite the opening around one-and-a-half to two times that when a non-combustible ceiling is used – this will result in an increased risk of horizontal fire spread to neighbouring buildings.

ACKNOWLEDGMENTS

We gratefully acknowledge ongoing support from the project partners: CERIB, Fire Testing Centre; the School of Engineering, The University of Edinburgh; Bordeaux University; Brandskyddslaget AB; the Institute of Building Materials, Concrete Construction and Fire Safety of Technische Universität Braunschweig, Division of Fire Safety; and Liège University. Bartlett would like to gratefully acknowledge the support given to his position by EPSRC under the grant *Fire Spread from Mass Timber Buildings* (EP/R012296/1).

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SESSION 3: FACADE TESTING AND ASSESSMENTS METHODS

- P.71 **The Material Library for Cladding Materials in Queensland, Australia**
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- P.78 **Fire exposure on facades of buildings with exposed cross-laminated timber / Fire safety risks and measures**
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- P.86 **Preliminary study on the round robin proposals for assessing fire performance of facades**
Istvan Moder, Markus Eichhorn-Gruber
IBS, Linz, Austria
- P.95 **Different Standard Tests of Facade Fire Spread Applied for Identical Aluminum Composite Panel Specimens - MSZ 14800-6 (full-scale) and JIS A 1310 (intermediate-scale)**
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THE MATERIAL LIBRARY FOR CLADDING MATERIALS IN QUEENSLAND, AUSTRALIA

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ABSTRACT

Fire engineers require the means and knowledge to adequately assess the fire risk associated with façades. An engineering framework has been developed in Queensland to provide the necessary material data for competent fire engineers to perform appropriate analyses and make informed decisions. This is comprised of two testing protocols and forms a Cladding Materials Library which is made publicly available. The first protocol consists of material identification (part A) and thermal decomposition (B) which is performed on all samples extracted from buildings. The second protocol adds a more detailed characterisation including the heat of combustion (C), ignitability (D), flammability (E) and flame spread (F) for specifically selected samples. Cross-referencing of these protocols allows a thorough characterisation of a wide range of materials including aluminium composite panels, high pressure laminates, insulations, sarking materials, etc. This reports on the results of parts A and B applied to 1,059 samples of publicly owned buildings in the state of Queensland. Furthermore, it reports on data for a total of at least 20 materials for which complete testing has been performed (parts A to F). The framework thus delivers key data for fire safety engineers to conduct a comprehensive engineering assessment of fire spread for façade systems.

1 INTRODUCTION

Jurisdictions around the world are developing responses to evaluate the level of fire risk associated with the cladding on buildings. In the state of Queensland, Australia, the Non-Conforming Building Products (NCBP) taskforce was established and tasked The University of Queensland (UQ) with proposing a suitable testing response to investigate existing buildings. This has led to the development of the publicly available Materials Library for Cladding Materials with the aim of providing hazard classification through characterisation of the fire performance of façade system components. Qualified fire engineers can use the library as a tool to make informed decisions on the design of a building under review.

The approach taken in Queensland is unique in that it is holistic and wide-reaching, and systemically assesses every single material. It is not limited to only ACPs (Aluminium Cladding Panels) where most of the focus lies but is also used to assess underlying insulation, sarking (waterproof/protection membranes), high pressure laminates (HPLs), timber-based products, cementitious boards, and others. A complete overview of the library and the framework is described elsewhere [1].

2 BACKGROUND

The Material Library is based on two testing protocols. The first is a screening testing protocol where small-scale samples (10–100 mm) are taken from every building and tested to identify and quantify the chemical composition, and to provide insight into the thermal degradation. This can be run quickly, at low economic cost and with as little damage to an existing building façade as possible. The second part of the library is the detailed testing protocol. A key sub-section of the products identified in the screening protocol then undergo further fire science testing to obtain the heat of combustion, key ignitability and flammability metrics, and flame spread assessment. This requires small- to intermediate-scale samples (100–1000 mm) which are slightly more costly and time consuming, and so are not run for every building. Cross-referencing of the two protocols allows the characterisation of fire performance of cladding materials without having to run these small- to intermediate-scale test methods on every building. As a result, the testing is cheap and effective but delivers a high throughput of data. Materials identified using the screening protocol may already be in the Library and thus the data can be used directly, or otherwise the closest conservative alternative (i.e. more hazardous) can instead be used. The Material Library is designed to be updated and incorporate future data analyses to identify parameters that may be used in fire engineering assessments and models.

At present, the screening testing protocol has been run on 1,059 samples, of which there are 88 unique products, and 20 of these are currently included in the Material Library having undergone the detailed testing protocol. A portion of the unique products will never be included in the library due to the fact that the hazard posed is extremely low, for example, inert or non-combustible materials. The library is nonetheless conservative and thus materials which have a relatively low hazard level will still be included so that engineers can give the proper quantified data to back their assessment.

The engineer must know the exact materials which are used in a building and their flammability characterisation to be able to properly assess the building's fire safety strategy. Even in cases where the design and build are well documented, there is not a sufficient level of detail available to be able to properly investigate the buildings and deliver a qualified assessment. For this reason, it is necessary to test every cladding material in the building to be sure of the materials and their performance. Philosophically this is in line with the approach recommended decades earlier by Emmons [2].

The approach of the library is that every building should be assessed individually. There are no right or wrong materials, and materials which have relatively poor performance may be justified in cases where the fire safety strategy in the remainder of the building is robust and that there is adequate protection in place. This also means that in some instances – for example, high-risk buildings or specific geometric configurations – there are products which are otherwise safe but may need to be removed due to the hazard that they pose in this specific scenario. Thus, the response should be tailored to the building, its specifics and performance and functional requirements.

The Materials Library is at its core fundamentally a material-level approach. This gives a conservative assessment and identification of the materials used in a building but does not allow the interpretation of complex system-level interactions at this stage. Further research and large-scale testing is possible to allow this, and still include the data from the Library to clearly identify the materials used in the testing. The Library additionally ensures that the costly and time consuming large-scale testing is only performed on systems where the results will be useful, and not on systems which are sure to be unsafe for most or all buildings. The Library therefore provides the foundations to perform effective intermediate- and large-scale testing.

Finally, the Materials Library is publicly available and can be used by any competent engineers who have skills to interpret the data within its limits of applicability. This promotes transparency, and provides an important tool for the fire engineering community. New products or materials that are encountered are free to be submitted and uploaded to the Library once they have been suitably vetted.

3 ENGINEERING FRAMEWORK

The Material Library is fundamentally a framework to deliver the needed data to engineers. The key components are outlined below and the test methods which have been used to achieve each part are also described. Nonetheless, the framework has flexibility in that other test methods (or combinations of methods) which provide the same data can equally be used and the results will be consistent. The test methods described below are therefore just one example of the combinations that can be used to deliver the necessary data to provide a robust identification and flammability characterisation.

Testing is performed according to standardised methods to ensure that the framework can easily be exported and adopted elsewhere, and that it is already based on well-established and accepted means. Inevitably, some materials are not well suited to the test methods often due to highly complex behaviour but once identified these can be dealt with individually. One example of this type of material is EPS (expanded polystyrene) or ETICS (external thermal insulation composite systems) where softening, shrinking and melting of the material raises challenges in extracting fundamental properties in the detailed testing protocol.

The descriptions given below are short to give an overview of the framework, and the full details can be found either in the corresponding standards or in the Material Library framework document [1].

3.1 Screening testing protocol

The screening protocol is performed on all samples which are received. It is comparatively quick, easy and cheap to identify the product and can then be cross-referenced against the established library. It is comprised of Part A – chemical composition and Part B – thermal decomposition. Part A is further split into parts A1 and A2 to reflect the two test methods which must be used together to ensure correct results. A single sample required is approximately 40mm in diameter, and most of the material is retained thus allowing repeat testing to be performed if needed. Any samples removed from buildings should have an effective replacement material or stop, such as a sealant.

3.1.1 Part A1 – Material identification (ATR-FTIR)

Qualitative material identification is possible using Attenuated Total Reflectance Fourier Transform Infrared (ATR-FTIR), ASTM 1252 [3]. This enables identification of the polymer(s) and any additives such as fire retardants, minerals, or fillers. There can be some limitations in the ability to detect individual components in materials with complex composition but this can be alleviated in part through identification using the other micro-scale methods detailed below in Parts A2 and B. This testing requires only a thin slice (<1 mm) of the sample to perform testing, although extra samples are taken to ensure representative results.

3.1.2 Part A2 – Material quantification (EDXRF)

The quantification of the components identified in Part A1 is performed using Energy Dispersive X-Ray Fluorescence [4]. This quantifies the elements in a material, which in tandem with the material identification results allows highly accurate quantification of the compounds in a sample. For example, if a product contains a polymer and an aluminium based fire retardant, then the quantity of

these two components can easily be quantified. The testing requires a 40 mm disc and is completely non-destructive.

3.1.3 Part B – Thermal decomposition (TGA)

Thermal decomposition using Thermogravimetric Analysis (TGA), ASTM 11358 [5] is increasingly common in the field of fire science. The thermal degradation is analysed in both oxidative and non-oxidative environments up to a temperature of 800 °C. The samples tested are all 10.0 mg to ensure the best results for heterogeneous materials, and are tested at a heating rate of 20 °C min⁻¹ with a gas flow of 150 ml min⁻¹. Samples are taken from the centre of the material where possible to be representative, and are cut into small flakes to reduce thermal lag. Repetitions are performed where it is clear there are issues in the results but otherwise only a single test per atmosphere is required, for a total of two TGA tests.

Reactions across a range of temperatures can be identified and the inorganic residue at the end of the test is also obtained. This gives essential data to the engineers, and can supplement the material identification and quantification. In many cases, the TGA results are used to help identify and quantify the material composition and acts as a check. This ensures that the Material Library is robust and future-proof, and will not be prone to gaming the system as new products are released.

3.2 Detailed testing protocol

The detailed testing protocol is performed to give key performance data on materials beyond the micro-scale. The functionality of the library is such that the assessment should not be based solely on the screening protocol, and instead the corresponding detailed protocol data should be obtained so that a complete dataset can be used. The quantity of material required is approximately 1 m square, to ensure that there is sufficient for all parts. The screening protocol (Parts A and B) are repeated before performing the more detailed testing below (Parts C to F).

3.2.1 Part C – Heat of combustion (bomb calorimeter)

The heat of combustion is a key material property which is the amount of energy released per unit mass. This is obtained using the bomb calorimeter (ISO 1716 [6]), and forms a part of many standardised frameworks around the world. The value given is based purely on an ideal case, and does not give the amount of energy released under practical conditions. Furthermore, it does not provide an indication of the rate at which energy is released, and so other Parts are required in the protocol to describe this.

3.2.2 Part D – Flaming ignition (cone calorimeter/mass loss calorimeter)

Key ignitability metrics including critical heat flux and associated heat transfer coefficient, ignition temperature, time to ignition and apparent thermal inertia are all measured or calculated. This is done using either a mass loss calorimeter or a cone calorimeter (ISO 5660 [7]) where the sample is tested at different heat fluxes until the critical condition required to achieve flaming ignition is found. It is not feasible to run full-length tests for every heat flux due to the number of materials tested, and so the test is stopped after ignition occurs. The calculation of the corresponding heat transfer coefficient, ignition temperature and apparent thermal inertia are all according to the common flaming ignition theory of solids [8].

3.2.3 Part E – Flammability (cone calorimeter)

Materials are tested in the cone calorimeter (ISO 5660 [7]) for three different incident heat fluxes – 35, 50, and 60 kW m⁻² – to investigate their burning behaviour. The peak heat release rate, total energy released and remaining mass residue are all recorded, and the plot of heat release rate over time is also given. Finally, the effective heat of combustion is calculated, which gives an indication

of the combustion efficiency when compared with the heat of combustion obtained from the bomb calorimeter earlier in Part C. Together, these parameters give key insight into the fire performance of each of the materials in the Library and act as an important basis for the decision making of engineers.

3.2.4 Part F – Flame spread (LIFT)

Finally, materials are tested according to a modified Lateral Ignition and Flame Spread (LIFT) apparatus (ISO 5658 [9]). In this test, long samples (600mm x 100mm x thickness) are exposed to a radiant heat panel positioned at an angle to deliver a specific heat flux distribution lengthwise. The heat flux is set to be 5 kW m⁻² above the critical heat flux obtained in Part D and the sample is ignited at the leading edge once the surface temperature reaches equilibrium. This is based on the original methodology proposed by Quintiere & Harkleroad [10] tailored for research needs due to the fact that it allows more focus on the flame spread behaviour below the critical heat flux. The positioning of the panel is such that the flame spread velocity can be obtained as a function of the incident heat flux. From this, it is possible to obtain a flame spread parameter to describe its behaviour as well as a minimum heat flux required for flame spread which will be lower than the critical heat flux for ignition obtained in Part D.

4 MATERIAL LIBRARY

4.1 Screening testing protocol

At present, all publicly owned buildings in the state of Queensland, Australia have run the screening testing protocol for a number of samples chosen from each building. This has resulted in 1,059 samples from approximately 54 sites or buildings. The breakdown of the unique materials or products encountered so far are as follows:

- 32 ACPs
- 10 insulation
- 16 sarking (membranes)
- 6 timber-based or HPLs
- 9 metallic discs
- 3 cementitious or gypsum materials
- 12 other uncategorised samples

It is clear from the number of samples encountered that it is not possible to assume the materials based on their naming or from their datasheet. This also shows disproves the idea that there are only three different types of ACP, and that each within those categories behaves in a similar manner. Additionally, the screening protocol in Queensland identifies all non-ACP materials, which are 55% of the samples received. This differentiates from many of the other screening and cladding investigation tools used elsewhere in the world which are only focused on ACP cores.

Screening of the private sector is now underway using the same method. It is expected that the majority of materials will fall into the above unique products but that additional samples will also be encountered. There is some bias in the data from publicly owned buildings since the government has a tendency to pick specific contractors for the public buildings whereas in the private sector there will be a wider variety. Nonetheless, the materials already included in the library provide a wide scale and the new products will still within this range of extremes.

4.2 Detailed testing protocol

A total of 20 materials split across ACPs, insulation and sarking have been selected for the initial version of the Library. These have been chosen to give a broad spectrum of products in the library to

start with and are based both on the samples encountered in the public sector as well as a selection of materials expected to be common elsewhere. Additional products will be added to either fill gaps between existing materials, or to cover new areas where there is currently no data in the Library.

The breakdown of the number of samples in the Library which have undergone detailed testing are as follows:

- 9 ACPs
- 6 insulations
- 2 sarking materials
- 3 HPLs or timber products

A further 5 ACPs have already been identified and will proceed to detailed testing to help reduce the gaps and to illustrate the effect of minor variations without having to make assumptions. A number of materials have been rejected from the library based on the screening protocol since they were deemed to not provide sufficient worth for the time and money required. This includes the 9 metallic discs, 2 wool-based insulations with low organic adhesive content, and 3 cementitious materials. Some of these materials may still be run to obtain representative mass loss and heat of combustion but other new materials are given a higher priority to be added to the library first.

5 CONCLUSIONS AND FUTURE WORK

The following conclusions are drawn:

- The holistic approach for the investigation and remediation of claddings developed in Queensland has been detailed. This has the benefit of assessing all materials in the exterior envelope of a building, and has already been successfully implemented on all publicly owned buildings in Queensland.
- The Library is a publicly available resource which contains a wide selection of cladding materials and a characterisation of their fire performance to enable hazard classification.
- There have been 32 ACPs encountered so far which is more than the often quoted 3 types, and of those which have undergone detailed testing there has been highly distinct behaviour which cannot assumed to be the same.
- Intermediate- and large-scale testing can be performed on those specific materials and configurations which are shown to be of the most interest, and can ensure that the products used are properly known.

ACKNOWLEDGMENT

The Queensland Government Department of Housing and Public Works are gratefully acknowledged for funding the project Material Library for Cladding Materials. All those who have contributed to the library and to the project are also thanked. In particular, Tam Do, Janal Numapo, Ruby Fritz, Angela Solarte, Camilo Montoya Giraldo, Mohamed Lutfi Ramadhan, Samuel Barker, Stewart Matthews, Alvaro Rubio Gomez, Sohan Roopra, Vinny Gupta, Hangyu Xu, Jaime Cadena Gomez, Stanley Yap and Brendan Garvey are thanked for their tireless work in performing the testing and other associated activities.

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FIRE EXPOSURE ON FAÇADES OF CROSS-LAMINATED TIMBER BUILDINGS – A REVIEW

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ABSTRACT

Cross-laminated timber (CLT) used as structural elements in buildings are increasing in popularity due to their high degree of prefabrication and environmental benefits. However, there are still knowledge gaps regarding the fire performance of the buildings and construction details to prevent fire spread. This paper is a review of experiments and research on the fire exposure on façades of buildings with CLT structures partly exposed inside the building, and the risk of fire spread to adjacent buildings. Both partly and fully exposed CLT surfaces on the walls, floors and ceilings inside the buildings have been studied, in addition to fully protected CLT. The review reveals that when one surface of CLT inside the building is unprotected, the fire exposure on the façade is similar to a situation with fully protected CLT or other structural materials. However, if more than one surface is unprotected the fire exposure on the external façade and on adjacent buildings might be more intense and extensive. This is because the flames protruding from the windows can be larger and the heat flux towards the façade higher. More than one unprotected CLT surface might therefore require additional or other fire safety measures than for façades of buildings with sufficiently protected CLT or other structures. These findings can be used to design façades with less risks of fire spread to large parts of the façades, and to define safe distances between buildings with exposed CLT.

1 INTRODUCTION

The focus on environmentally friendly and sustainable buildings is increasing, and accordingly the competitiveness of timber as a construction material. The use of timber in buildings has several advantages compared to for example steel and concrete. Timber constructions have a low carbon footprint, local manufacturing contributes to shorter transport distances and less pollution, and prefabrication of elements reduces the construction period and enables better quality control. There is currently an increasing motivation to extend the application areas of innovative timber constructions, such as cross-laminated timber (CLT), to larger and taller buildings, as substitute for more traditional construction materials. However, such applications are still in the cradle, and despite extensive research on the topic, the literature is still pointing at knowledge gaps related to fire safety. Timber is a combustible material, and although the fire performance of wood-based materials is well elucidated, the implementation of combustible construction elements in large and tall buildings is in general limited by perceived fire risks, regulations, and advanced fire safety analysis for fire design requiring special expertise. Furthermore, existing fire design models may not be applicable to the new products or they may be conservative.

Fire safety engineers of large and tall timber buildings must consider that the timber construction may contribute to the fire, and the fire design is therefore of high importance and must be considered in the early design phase. Several studies show that exposed CLT structures or insufficient protection can cause a fire to develop faster, be more intense and last longer than in compartments where the CLT is well protected. It is further shown that the amount of unprotected timber in a compartment may have impact on the extent and duration of a fire, as well as fire spread through windows to the façade materials and to windows above the fire compartment. The fire can also spread horizontally to other parts of the building and to other buildings. According to Brandon et al. [1], the most frequent mode of significant fire spread is via the façade, which is confirmed by the devastating fire in Grenfell Tower in London and other recent façade fires. A recent literature review conducted by Reitan et al. [2] pinpointed that fire spread via the façade to other parts of the building and to adjacent buildings is one of the scenarios that must be considered in buildings with CLT structures. The objectives of this review are therefore to summarize the recent research on fire exposure on façades of CLT buildings, study the exposure on the façades, identify knowledge gaps and recommend future research needs.

2 RESEARCH RESULTS

Only a handful of large research projects on the use of CLT in buildings, including full-scale fire experiments, have been performed the last two decades [3-7]. This review summarizes research results of fire exposure on the façades of buildings with CLT elements. Both partly and fully exposed CLT surfaces on the walls, floors and ceilings inside the buildings have been studied, in addition to fully protected CLT. Literature from sources like scientific journals, research institutes and fire test laboratories are included, and systematically mapped. The findings are mainly based on a literature review on fire safety of CLT buildings, by Reitan et al. [2].

Five projects including large-scale experiments were found in the literature, and information about them are given in *Table 1*. Some of the research projects included experiments on both CLT and light steel frame (LSF) or light timber frame (LTF) structures. The protection on the structures was *type A* standard gypsum boards, and *type F* (including North-American type X) fire rated gypsum boards, according to EN 520. The fire compartments varied in size, with floor areas from 4.5 m x 3.5 m to 9.14 m x 9.14 m, and ceiling heights from 2.44 m to 2.8 m. In some of the tests a façade mock-up was built above the opening on the external wall to enable measurements of heat flux towards the façade above the opening. In addition, the heat fluxes at horizontal distances from the centre of window openings were measured in some experiments to determine the exposure on adjacent buildings. The fire loads were based on common fire loads in apartments, ranging from 211 to 550 MJ/m² floor area, while in [3] it was 900 MJ/m². In most of the experiments the fuel was common furnishing, but n-Heptane and pallets were used in some experiments.

One of the first studies in which exposure on the façade of heavy timber structures is mentioned was Hakkarainen [3], who performed four experiments to study the gas temperature development and the charring of timber constructions. Glue-laminated wall elements were used, and in Test 1 all walls were exposed. In Test 2 the elements were protected with 1 layer 12.5 mm type A gypsum, and in Test 3 and 4 the structure was protected with 1 layer 12.5 mm type A plus 1 layer 15.4 mm type F gypsum. A heat flux gauge was fixed 2.2 m above the upper edge of window opening, centred on the façade, on the surface of a façade mock-up above the window. Flashover was reached after 4.5-5 minutes in Test 1 and 2, and after 6 minutes in Test 3 and 4. During Test 1 and 2 the heat flux continued to increase throughout the experiment, see *Fig. 1*. Hakkarainen found that, due to the lack of oxygen, a larger part of the pyrolysis gases burnt outside the fire compartment in Test 1 with exposed timber elements compared to Test 2, 3 and 4 with protected surfaces.

Approximately 50% of the pyrolysis gases burnt outside the compartment in Test 1, compared to only 15% in Test 3. The combustion of gases outside the compartment resulted in lower maximum temperatures inside the compartment in Test 1, but higher exposure on the façade.

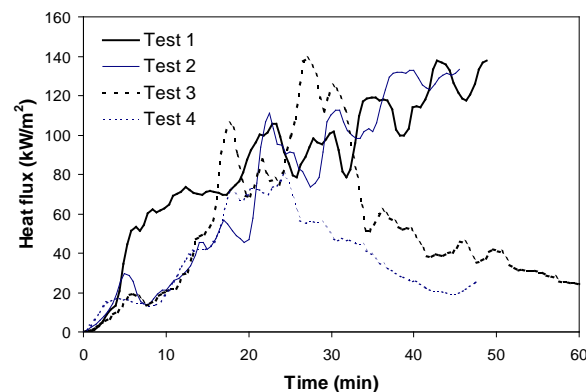


Fig. 1. Heat flux measurements on the façade 2.2 m above the opening from the four tests [3]

Frangi & Fontana [4] studied the influence of combustible surfaces on the fire growth and fire spread inside and outside the compartment, and the efficiency of different fire safety concepts for multi-storey timber buildings. Six tests were performed, see *Table 1*, but only the BÜ-series, where the influence of the combustible surfaces on the fire development and external burning was measured, is included here. The compartments were made of LTF structures protected with combustible or non-combustible lining. In the BÜ bb-test all surfaces were combustible, while in the BÜ nbb-tests the walls and ceiling were protected with gypsum boards. Flashover was reached after 4.5 minutes in BÜ bb, and after 6 to 7 minutes in BÜ nbb. It was observed that the external flames were much larger after flashover in the tests with combustible lining than with non-combustible lining. The window in the upper module broke after 40 mins for the tests with non-combustible lining, and after only 7.5 mins for test with combustible lining.

Su & Lougheed [6] summarized four large-scale apartment tests. The research was undertaken to develop information to be used as the basis for alternative, acceptable solutions for mid-rise construction with wood structural elements. The four apartments consisted of a bedroom, bathroom, small entrance, and a combined living room and kitchen. Three different structures were tested; light timber frame (LWF1, LWF2), LSF and CLT. In compartment CLT and LWF1 the protection on all walls, ceiling and floors was 2 layers 12.7 mm type F gypsum. In compartment LWF2 and LSF the protection on the inside of the exterior wall was 1 layer 12.7 mm type F gypsum, and for LSF the protection of the ceiling was only 1 layer 12.7 mm type F gypsum. The results are given in *Table 1* and show that the max heat flux on the façade above compartment LSF was higher than for LWF1 and CLT. This was caused by the fall-off of the gypsum boards on the inside and sheathing on the outside of the exterior wall. The duration of the max heat flux was longer for the compartment with CLT, but this might be caused by the damaged wall and increased ventilation factor in the LSF test.

Five full-scale tests on fires in an apartment were performed by Zelinka et al. [7] to observe the performance of a two-level apartment-style structure of CLT. The apartments had a bedroom, bathroom, small entrance and hall, and combined living room and kitchen. 2 layers 15.9 mm type F gypsum were used to protect the CLT. In Test 1 all surfaces were protected, in Test 2 parts of the ceiling in the bedroom and living room were exposed; Test 3 had one wall in bedroom and living room exposed, and in Test 4 and 5 one wall and ceiling in both bedroom and living room were exposed. The heat flux measurements are given in *Table 1*. The measurements at distance 2.44 m during Test 1 were disrupted because the limit of the transducer was reached at one of the points,

while the data connection was lost at the other point. The duration of the heat flux exposure was 15-20 minutes in Test 1, 2 and 3.

Through 6 tests of full-scale, one room apartments, Su & Lafrance [5] studied the CLT structures' contribution to the fire development. The apartments included bedroom, kitchen and living room areas. Two variables were incorporated; the ventilation openings and the size and position of the exposed CLT surfaces, see *Table 1*. In addition, the number of 15.9 mm thick type X gypsum boards on the fire protected surfaces varied between 2 layers in Test 1-2 and 1-3, and 3 layers in the other tests. Su & Lafrance found that the fully developed fire lasted longer and therefore also the exposure on the façade and adjacent buildings. The duration of the exposure was 30-40 minutes in Test 1.1, compared to only 10-20 minutes in Test 1-2. With one exposed CLT surface and small opening the duration increased to 40-80 minutes, while it was only 30 minutes in Test 1-3 with large opening.

Table 1. Overview of experiments

Reference	Name of exp.	Floor area of comp. (m ²)	Opening size B x H (m) Opening factor (m ^{1/2})	Exposed surfaces Surfaces	Vertical flame spread		Horizontal flame spread		
					Area of exposed CLT surfaces (m ²)	Distance above opening (m)	Heat flux on façade ¹⁾ (kW/m ²)	Distance from opening (m)	Heat flux towards adjacent buildings ¹⁾ (kW/m ²)
Hakkarainen [3]	Test 1	15.75	2.3 x 1.2 0.042	All	55.75	2.2	140	-	-
	Test 2			None	0	2.2	130	-	-
	Test 3			None	0	2.2	140	-	-
	Test 4 (LTF)			None	0	2.2	80	-	-
Frangi & Fontana [4] (LTF)	BE bb g	20.46	1.5 x 1.7 0.041	All	92.69	-	-	-	-
	BE bb o I			All	92.69	-	-	-	-
	BE bb o II			All	92.69	-	-	-	-
	BÜ nbb			Floor	20.46	-	-	-	-
	BÜ bb			All	92.69	-	-	-	-
	BÜ nbb demo			Floor	20.46	-	-	-	-
Su & Loughheed [6]	LWF1	55.74	2 pcs 1.5 x 1.5 0.031	None	0	3.5	25 / 26	2.4 4.8	23 / 21 7 / 7
	LWF2			None	0	3.5	-	2.4 4.8	28 / 25 10 / 10
	CLT			None	0	3.5	18 / 25	2.4 4.8	25 / 23 9 / 7
	LSF			None	0	3.5	35 / 23	2.4 4.8	25 / 33 9 / 10
Zelinka et al [7]	Test 1	83.53	2 pcs 3.66 x 2.44	None	0	0.4 3.315	Not found	2.44 4.88	74 ²⁾ / 65 ²⁾ 32 / 29
	Test 2			Two ceilings	16.714	-	-	2.44 4.88	62 / 64 24 / 25
	Test 3			Two walls	16.714	-	-	2.44 4.88	58 / 60 25 / 23
	Test 4 ³⁾			Two ceilings, two walls	41	-	-	2.44 4.88	0.2 / 0.3 0.2 / 0.3
	Test 5 ⁴⁾			Two ceilings, two walls	41	-	-	2.44 4.88	1.1 / 5.0 0.7 / 1.0

Su & Lafrance [5]	Test 1-1	1.8 x 2.0	None	0	1.5	70	2.4	40
		0.03			3.5	20	4.8	20
	Test 1-2	3.6 x 2.0	None	0	1.5	105	2.4	65
		0.06			3.5	37	4.8	22
	Test 1-3	3.6 x 2.0	1 wall	24.57	1.5	115	2.4	65
		0.06			3.5	45	4.8	25
Test 1-4	1.8 x 2.0	Ceiling	41.86	1.5	120	2.4	45	
	0.03			3.5	30	4.8	17	
Test 1-5	1.8 x 2.0	1 wall	24.57	1.5	120	2.4	40	
	0.03			3.5	30	4.8	15	
Test 1-6	1.8 x 2.0	Ceiling and 1 wall	66.43	1.5	190	2.4	55	
	0.03			3.5	60	4.8	20	

¹⁾ Heat flux measured above, or in horizontal distance from, an opening. In case of two openings, the heat flux above or in front of the opening in the fire start room is given first.

²⁾ The heat flux reached the max limit of 75 kW/m² of one transducer and the data connection failed for the other.

³⁾ Windows installed. Sprinkler active

⁴⁾ Windows installed. Sprinkler active, delayed 20 min

3 DISCUSSION

This review aimed at summarizing the current knowledge on the fire exposure of façades on buildings with exposed CLT structures inside, analyse research results, identify knowledge gaps and recommend future research needs. Results from recent research reveal that exposed CLT in the building may, in some cases, contribute to the fire development, increase the fire exposure on the façade and the heat flux towards adjacent buildings, as discussed below. However, this is not always the case, exposure of the CLT on only one surface, for example, might be insignificant to the fire development.

3.1 Fire development

Recent research has found that the contribution of exposed CLT to the fire development is, among other factors, determined by the number of exposed surfaces, the configuration and size of the surfaces, and the ventilation factors. The fire resistance of the cladding on protected CLT is crucial to prevent contribution from the CLT. In compartments with exposed CLT or insufficient protection on the CLT the time to flashover can become shorter than if all CLT is protected [2-5]. The results also suggest that the fully developed fire phase might have a longer duration [2,5], and that the temperature can continue to increase through the duration of the experiment [3]. Exposed CLT may also delaminate when the char line reaches the glue-line and cause a second growth and flashover. However, if only one CLT-surface is exposed or radiation between exposed surfaces is prevented, the effect on the fire development might be negligible [2,5,7]. In addition, Su & Lafrance [5] found that larger ventilation openings accelerated combustion of the room contents, intensifying the exterior exposure, while shortening the duration of the fully developed fire. Smaller openings delayed the onset of the decay phase, thereby extending the duration of the fully developed fire phase. The findings of [4,5] suggest that extensive use of combustible claddings on LTF or non-combustible structures inside the compartment also can contribute to the fire development and increase the flaming outside the compartment.

3.2 Exposure on the façade above the fire compartment

The heat flux on the façade above the window opening was measured in three of the research projects reviewed [3,5,6], see *Table 1*, at a vertical distance of 1.5 m, 2.2 m and 3.5 m above the upper edge of the windows. Hakkarainen [3] found that the heat flux on the façade above the window opening in the compartment was considerably higher in the tests with exposed or insufficiently protected CLT, causing the CLT to char and contribute to the fire load. This is supported by the findings of [4] and

[5]. Exposed CLT or insufficiently protected CLT can also cause a prolonged duration of the fully developed fire which can lead to a longer duration of the fire exposure on the façade [6].

Su & Lafrance [5] found that larger ventilation openings intensified the exposure on the façade above the window but shortened the duration of the exposure. Outside the compartments with small openings and only one exposed CLT surface, the duration of the exposure was 10-50 minutes longer than for compartments with large openings. The heat flux 1.5 m above the opening in a compartment with small opening and one exposed CLT wall was similar to the compartment with the same exposed wall, but with a large opening. However, the heat flux was considerably higher than for the compartment with no exposed CLT. At 3.5 m above the opening the heat flux was higher for the compartment with large opening. This suggests that the flames reached higher up on the façade. If one wall or ceiling is exposed and the compartment has a small opening factor ($0.03 \text{ m}^{1/2}$), this might result in a much higher heat flux on façade 1.5 m above window compared to the same compartment without exposed CLT. But 3.5 m above the opening the heat flux was only slightly higher than a compartment without exposed CLT. This suggest that the flames might not reach considerably higher even though some CLT is exposed. For compartments with large opening factors ($0.06 \text{ m}^{1/2}$) the heat flux might become very high, whether only one wall is exposed, or all are protected CLT [5]. The results from [5] indicate that the heat flux on the façade above the window in compartments with three exposed CLT-surfaces might be as much as 3 times higher than for a compartment without exposed CLT. This is supported by the findings in [2], which suggest that with three exposed surfaces the fire duration might be very long and with no decay phase. Measurements by Su & Lougheed [6] showed similar heat flux results for compartments with different structural materials, but the same gypsum board protection. This indicate that sufficiently protected CLT might not cause higher heat flux on the façade above the window. In the test with combustible linings by Frangi & Fontana [4] the window broke much earlier than in the tests with non-combustible linings. This might result in a longer fire exposure on the façade.

At NRC in Canada, a façade fire test was performed, where the heat flux at different distances from the window opening was measured [8]. The gas flow to the burners was manually adjusted to follow the prescribed heat input required by the standard [9]. The max heat flux on the façade 3.5 m above the upper edge of the window opening was 20 kW/m^2 at the centre of the wall. At horizontal distance 2.4 m from the window, 1.16 m above the window, the heat flux was max 9.9 kW/m^2 . At horizontal distance from 3.0 m from the centre of the window, the heat flux was 17.8 kW/m^2 . Since the results from the other reviewed experiments show a quick reduction of heat flux with increasing horizontal distance from the window, the results from [8] are not directly comparable with the results in *Table 1*. The heat flux on the façade above the window, however, were measured at the same distance. The heat flux at 3.5 m above the window opening in the standard test is slightly lower than the results from natural fire test for compartments with gypsum board protection on CLT, LTF or LSF [6], and identic with the natural fire test of a compartment with protected CLT and small opening factor in [5]. However, in the experiment with natural fire exposure, large ventilation openings and/or exposed CLT the heat flux was higher, ranging from 30 kW/m^2 for compartments with small opening and only one exposed CLT-surface, to 60 kW/m^2 in the compartment with exposed ceiling and one wall. Due to the limited number of test results available it is not possible to determine the expected heat flux above windows in compartments with one or more exposed CLT-surfaces. It is obvious, however, that it can be considerably higher than in current standard test methods, and that these test methods are probably not applicable to such façades.

3.3 Heat flux towards adjacent buildings

The heat flux towards adjacent buildings was measured in three of the reviewed research projects [5-7], see *Table 1*, at a horizontal distance of 2.4 m and 4.8 m from the centre of the window opening. In almost all tests the heat flux was reduced by 1/2 to 2/3 from 2.4 m to 4.8 m distance from the

opening. Su & Lougheed's [6] results indicate no significant difference in the heat flux towards adjacent buildings between compartments with protected CLT, LTF or LSF. Zelinka [7], on the other hand, found that the heat flux above the window of the compartment with no exposed CLT was higher than for the compartments with exposed CLT. This might be caused by insufficient protection of the CLT or other factors but is not explained in the report [7]. The results from Su & Lafrance [5] indicate that there is no difference in the heat flux from compartments with no exposed CLT compared to compartments with exposed CLT on one wall or ceiling, and the same opening factor. The results also suggest that a large opening factor might result in higher heat flux towards adjacent buildings than smaller opening factors [5,7], but the duration of the exposure might be shorter. One exposed wall or ceiling, although different surface areas, can result in the same heat flux when the opening factor is the same, and be similar to the heat flux outside a compartment without exposed CLT. For compartments with three exposed CLT-surfaces, the heat flux towards other buildings at a distance 2.4 m was slightly higher than for one exposed surface and small opening factor, and slightly lower than for compartments with a large opening factor, regardless of whether the compartment had an exposed surface or not. While at distance 4.8 m the heat flux was identical with compartments without exposed CLT or with one exposed surface. According to the measurements, the heat flux was reduced by more than 50% with a doubling of the distance from 2.44 m to 4.88 m [5,7].

Many parameters affect the fire exposure on the façade and towards other buildings. The reviewed research projects suggest that the fire exposure on the façade above windows of compartments with exposed CLT inside the compartments can, in some cases, be more intense with higher heat flux exposure and longer flames. Due to a higher production of pyrolysis gases and the lack of oxygen in the compartment, combustion of a considerable larger portion of the pyrolysis gases may take place outside the compartment if the CLT is involved in the fire. However, results indicate that if only one surface is exposed, i.e. one wall or the ceiling, the heat flux on the façade might be similar to buildings without exposed CLT inside.

4 CONCLUSIONS AND FURTHER RESEARCH

A literature review has been conducted to gather knowledge on the fire exposure on the façade of buildings with exposed CLT inside the fire compartments, and the heat flux on adjacent buildings. The results found in the literature have been compared to buildings without exposed CLT to enable better understanding of the specific risks related to fire spread to the façade of CLT buildings, and the need for novel measures to reduce the risk. CLT elements are combustible, and can, if directly exposed, contribute to the fire and cause a more rapid growth, longer duration of fully developed fire, more combustion outside the compartment, and thereby higher heat flux on the façade and towards other buildings. Several parameters that may affect the intensity and duration of the fire exposure on the façade have been revealed:

- the number of exposed CLT-surfaces and their configuration in relation to each other,
- insufficient protection on CLT structures,
- the opening factor, and
- the fire resistance of windows.

The reviewed research suggests that if the CLT structure in the compartment is sufficiently protected, the heat flux exposure on the façade above the windows and towards neighbours will be similar to buildings with other types of structures, including light steel and timber frames, and perhaps other non-combustible structures. Exposure of CLT on one surface, whether this is a wall or ceiling, may also give heat fluxes towards other buildings similar to a sufficiently protected structure. However, one or more exposed surfaces in the compartment might cause a severely increased heat flux on the façade above the window. The opening factor of the compartment may also influence the heat flux

on the façade and towards adjacent buildings significantly. The exposure can be higher on the façade for large opening factors, while the duration can be shorter, compared to small opening factors. A comparison with the heat flux conditions occurring in a standard test method [9] reveals that the intensity of the exposure on the façade of buildings with exposed CLT might be considerably higher than the test conditions. The design of the façade is therefore crucial to prevent fire spread to the façade, to other compartments in the building, or other adjacent buildings. Based on the research reviewed in this paper, there is need for a fire test method for façades which incorporates more intense, further reaching flames, and higher heat flux on the façade. Ongoing work to develop a European standard test method for façades should consider the results in the current review paper, and the possibility of including specific test conditions for buildings for which the external fire exposure can be more extensive [10]. Two projects have recently been performed, where different measures to prevent spread of fire via the façade have been studied, amongst others [1,11]. The possibly increased heat flux on the façade due to exposed CLT is not specifically addressed, but the research can form background for future research.

Future research is needed in order to:

- gather more reliable knowledge on how the number and configuration of exposed CLT, and the opening factors, affect the fire exposure on the façade and towards adjacent buildings,
- establish guidelines for sufficient fire protection of CLT to prevent premature charring,
- gain knowledge about necessary measures to prevent fire spread via the façade for buildings with significantly larger heat flux than the current standard test methods impose on the façade, including evaluation of current common measures, and
- develop a façade fire test method that incorporates the relevant heat flux levels.

ACKNOWLEDGMENT

This paper is completed as part of the Fire Research and Innovation Centre, FRIC, partly financed by the Research Council of Norway, project 294649.

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PRELIMINARY STUDY ON THE ROUND ROBIN PROPOSALS FOR ASSESSING FIRE PERFORMANCE OF FACADES

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ABSTRACT

The paper follows the logic described and the tasks listed in the “European approach to assess fire performance of facades” [1] but it extends the published content by providing inputs and solutions for each given cornerstone of round robin proposals. The study starts with a short introduction to the ‘proposed’ and ‘alternative’ test methods, which is followed by a list of potential goals of the round robin. The paper differentiates between the robustness and round robin phases. The predicted factors influencing the robustness testing are listed (such as fuel source, thermo couple mounting etc.). A risk analysis is carried out on the factors influencing the repeatability and reproducibility which is followed by three options regarding the test rig. The paper provides four possible calibration elements that might be used during the robustness testing and the round robin as well. Possible mathematical solutions are collected and suggested that might be used during the evaluation of the round robin results. For the experimental round robin, a list of possible product types is given, meanwhile for the theoretical round robin a handful of suggestions on data sheets are described. The paper serves the interest of the European Commission, Member States, expert groups and fire laboratories.

1 INTRODUCTION

In the “Development of a European approach to assess the fire performance of facades” (DEAFPF) two main solutions were provided, one is the so called “proposed method” and the other one is the “alternative method” [1]. Both methods are based on the DIN 4102-20 (medium scale test/medium fire exposure) and BS 8414-1 and -2 (large scale test/large fire exposure); from the SP FIRE 105 the falling parts were adopted. The proposed method offers small modifications to the already published standards. Even though the alternative method is based on the DIN and BS standards, it takes into account another national test methods and scientific studies as well – for example the appearance of the secondary window or new temperature measuring locations. Classification possibilities of the two methods, due to many reasons, is limited to four main classes, such as LS1, LS2, LS3, LS4. The authors of this paper suppose that the reader is familiar with the aforementioned methods in more details, therefore, the methods are not precisely described here. The DEAFPF offers round robin (RR) options for the proposed and alternative test method as well. In our paper we revisit these chapters and extend the content of it, adding alternative views or providing alternative solutions to them.

2 SETTING UP THE GOALS OF THE ROUND ROBIN

At first, as with any project, precisely formulated series of goals shall be set for the round robin, which might be many. Round robins or interlaboratory comparisons are widely used to evaluate laboratory performance which is highly required from Accreditation Bodies of Member States. As a consequence, this involves quality improvement policies within laboratories, obviously, if they are

needed. According to Visser, further goals might be added to this list, such as the evaluation of trueness and training of personnel [6]. As the document DEAFPF declares, the aim shall be “professional input for the standardization work” [1]. We would add the following goal to the list, allowing fire laboratories and Regulators to gain first-hand experience would help the Member States to understand the test and classification methods described in DEAFPF and gain first-hand experience that these methods work. Therefore, the implicit goal shall be to involve as many participants and Member States as possible in the full scope of the RR project or in many parts of it.

3 PROFESSIONAL INPUT FOR STANDARDIZATION WORK

Validation of a test method is carried out in two phases, such as robustness testing phase and round robin phase. The robustness testing shall focus on individual criterion/step/measurement of the test method and on the whole test method as well. The second phase is carried out to determine the repeatability (“goodness” of a laboratory) and reproducibility (“goodness” of a test method) as well. [8]

3.1 Robustness testing – Proposed method

Robustness testing of individual criteria/steps/measurements for the proposed test method is not considered to be necessary as it is based on already issued and in force test standards. If the standardisation committee requires such tests, then the list given for the alternative method shall be followed. Robustness testing of the whole test method might be advantageous to carry out, these steps are identical with the steps given in the alternative method.

3.2 Robustness testing – Alternative method

Robustness testing is necessary for this method as it is considered to be a ‘new’ method. As robustness testing is usually carried out by the most experienced laboratories of the test method, which in this case it cannot take place. Robustness testing shall focus on both the individual criteria/steps/measurements and the total test method as well.

3.3 Robustness testing – Alternative method – List of influencing factors

In the following chapters a proposed list of influencing factors in the test methods are given - with a potential testing method - which ones shall be taken into account during the robustness testing and the standardization work as well. Where it is not stated elsewhere, the suggested test plan shall be carried out on large scale and medium scale tests as well.

3.3.1 Fuel source

Most significant parameters that influence the fuel source: density and moisture content of the crib, however, other physical properties (such as growth rings etc.) of the timber crib shall be neglected. As D.L.Chamberlain wrote “The higher the moisture content, the greater the amount of energy required to remove the bound water and the longer the exposure time required before pyrolysis is initiated.” [9]. When it comes to moisture content assessment of a timber crib, it would be advantageous to revise the moisture content rate and introduce the target moisture content with a specific range ($12 \pm 1,5\%$), where the readings have a high confidence level (75 %). EN 14298 standard provides a good, “ready-to-use” method [10]. This paper uses further on the nomenclature given in DEAFPF.

Medium scale cribs shall be tested with two densities (400 and 500 kg/m³), and with a target moisture content of 10%, 15% and with an uncontrolled one. Large scale cribs shall be tested also with the minimum and maximum allowed density (400 and 650 kg/m³), and with a target moisture content of 10%, 15% and with an uncontrolled one. All configuration shall be tested on three sets of identical cribs. Cribs shall be tested own their own (not within a test rig). Measurements during the test shall

be mass loss, time, temperature in the crib and at an agreed distance away from the crib. To provide input for further analysis, heat release rate shall be determined at least on one crib from each variation.

Measuring flame height during the test might be for scientific purposes advantageous, as flame height and heat release rate are in relation with each other. Many flame height calculation formulas are available, one of the most trusted one is the McCaffrey formula [11].

$$\dot{Q} = \left(\frac{Z_i}{0.20} \right)^{5/2} \quad (1)$$

where, Z_i intermittent height of flame [m];
 0.20 intermittent flame variable [m/kW];
 \dot{Q} Heat Release Rate of fire [kW].

Due to the nature of the fire source, a control tool for the fire laboratories shall be developed during the standardization work. Flame height measurement might be too scientific for everyday use, but it provides an approximate value of the heat release rate which is one of the most important parameters of the fire source. Details and applicability shall be evaluated later on. Flame height measurement does not only serve the purpose of the scientific world but also the fire laboratories. If the tests shall be carried out indoors, the hazard of the “open-fire” test affecting the surroundings of the test crib and the roof of the test hall shall be assessed as well.

A study [12] on BS 8414 reported a flame height of 6,25 m from a standard timber crib. It is unclear in the study if the flame height is measured from the bottom of the timber crib or from the top edge. In the latter case, the heat release rate calculated with the McCaffrey formula results in a 3530 MW, which is in correlation with the given HRR in the standard “a nominal total heat output of 4500 MJ over 30 min at a peak rate of (3 ± 0,5) MW” [2]. The study reports as well that during the crib test the temperature of the roof of the testing hall was over 100°C. This fact shall be taken into account on the necessary hall design to accommodate the test rig(s).

3.3.2 Location of the test (outdoor and/or indoor)

The location of the tests involves three main sub criteria which shall be considered; these are weather, wind speed and conditioning. Allowing only indoor testing would result in eliminating two out the three criteria, but conditioning shall be worked out irrespectively, but it would result in a problem to accommodate the test rig(s). Allowing outdoor testing would encourage testing laboratories (and indirectly Member States) to easily adapt the new test methods, but it brings a big amount of “uncalibrated-able” factors into the test method. Humidity sensitive kits might show big variation in test results depending on the weather before and during the test. Finding pure and “calibrate-able” values of the weathering effect might be very time and cost consuming – taking into account humidity, weather before the test, during, season and the variability of the product. Therefore, an agreed consensus might solve the problem without heavily investigating the problem, acknowledging that the test method contains significant variability. Wind speed might be simulated by applying fans and setting them to different velocities. Conditioning methods shall be worked out during the standardization work for both methods and testing locations as well remembering that 28-day conditioning results in maximal 13 tests per test rig in a year.

3.3.3 Secondary opening

Although, the secondary opening is only present at the large-scale test method, the influence of it shall be checked. The robustness testing shall focus on determining the effect of the secondary opening, if it has an influence on the results in a positive or negative way or it has no influence at all – in respect of temperature rise, damage, falling parts etc. – at all. The effect of the secondary opening

might be screened with tests on an inert face with and without secondary opening, a chosen ETICS system without secondary opening, the same ETICS system with a not fully detailed secondary opening and finally with a fully detailed secondary opening.

3.3.4 Thickness of tested materials

The effect of test specimen thickness shall be checked during the robustness testing phase. As it is stated in the DEAFPF, the fire chamber shall be shifted with the tested total material thickness. The thermo couples for assessing horizontal fire spread shall be located 2.75 m from the corner of the main face and 1.45 m from the corner of the wing (as the text does not refer to the “finished face”, these vertical lines should be considered as a fixed location independently from the thickness of test specimen). Robustness testing shall focus on finding out whether the potential failure of the test specimen is due to the increased material thickness or due to the shift of the fire chamber, meaning bringing the fire source closer to the vertical row of TCs. Other phenomena may be that the thick insulation material (especially the non-combustible ones) diverts the fire plume and flame more to a vertical direction.

Test variations shall contain medium and large fire exposures as well. Suggested materials to test are ETICS with combustible insulation core and ETICS with non-combustible insulation core, the thickness of insulation material shall contain an average (150 mm), an increased (300 mm) and an extreme (450 mm) thickness as well. To gain more information on the test method, all test variations with the shifted fire chamber shall be checked as inert faces as well. These tests might be a great input for determining the direct field of application in respect of changing of thickness of tested material.

3.3.5 Further effecting factors

Due to nature of this paper, in the following only the effecting factors and a brief reasoning/background is presented.

Table 1. Further effecting factors

Effecting factor	Reasoning / Background
Blow speed / forced ventilation	It is only present in medium scale tests. Vertical and horizontal deviation from the horizontal plane might cause the fire plume and the flame zone to influence the test results in negative-positive way. Suggested test set up: $\pm 10^\circ$ vertically (up and down) and $\pm 10^\circ$ horizontally (left and right)
Location of thermo couples	Inserting the TCs into layers which the operator cannot visually observe might carry a big uncertainty within itself; this temperature measurement procedure is not common in the general EN fire resistance standards. An informative annex in the future standard on this item might be useful.
Fixation of thermo couples	Fixation of the thermo couples and stiffness of thermocouple wires are not clearly written down in the DEAFPF. If a layer, which supports the TCs, is burned out then the location of the TCs might change from the original position due to gravity (bending down). Stiffness of the wire of the type K thermocouples shall be indicated.
Minimum number of thermo couples	As in all fire resistance test malfunction of TCs are expected. A minimum number of TC shall be set that under which the test results shall be classified as invalid.

Data acquisition system	The robustness testing shall be run by a data acquisition system with a recording interval of 1 s interval, in order to evaluate the correctness of 10 s (30 s) recording intervals.
Start time and extinguishing timber crib	Even though, the assessment methods neglect the time criterion, the test methods are requiring measuring time in respect of starting the data acquisition system and knowing the time of extinguishing of timber crib. The start time is connected with the ignition of the spirit-soaked strips along its full length. That requires visual observations and response time. Written safety instructions of extinguishing timber cribs during fire tests may be necessary. Also, a maximum duration of quenching shall be stated.
Remodelling main faces of test rigs	ETICS systems might be sensitive to discontinuities and unevenness of the faces of the test rig. Heavily used and damaged faces shall be avoided. Advise on the acceptable face surfaces shall be worked out during the robustness testing.
Determining thickness of layers	Where the test specimen (kits) consists several layers (like ETICS), determining the actual thickness of the individual layers might be impossible. During the robustness testing a method of verification of test specimen, as solution a best practise guide shall be worked out.

If any of the above listed problems can be verified by confidential and/or non-confidential reports, they shall be made available to the standardization body and the RR organizing team to reduce the cost of the research.

4 ROUND ROBIN ON FACADES – TEST METHODS – REPEATABILITY AND REPRODUCIBILITY

When the robustness testing is finished the results are evaluated, the next step of validation would be the round robin on the test methods, which one is focusing on the repeatability and reproducibility of the test method.

4.1 Risk analysis

Table 2 presents, in a tabulated form, a brief risk analysis of the repeatability and reproducibility effecting risks.

Table 2. Risk analysis of factors influencing the repeatability and reproducibility testing

Description of risk	Background information	Action to take
Laboratories have no experience with the given test method	Misinterpretation can lead to major differences among test results	Kick off education is needed
Laboratories have a huge experience with a former test method that might not be in line with the new test method	The basic standards behind the large scale and medium scale methods have respected history	Kick off education is needed
Laboratories have no experience installing the round robin element	Usually sponsors of the tests install the test specimens	One brigade shall install on all testing locations

The chosen material or kit to test in the RR may show high variability	The more components a product / kit have, the higher deviation is expected	The number of components shall be limited to the bare minimum
Correctness of expected value	Boundary conditions are expected to have high impact on the test result (see above)	The chosen RR product or kit shall be heavily tested before the RR can take place
Precision of test method	A widely used method is needed	Mandel's k and h consistency test [13] shall be applied
Determining the outliers in the dataset	Variation between laboratories can be calculated	Grubb's test [14] might provide mathematical method
Boundary conditions are not kept	Boundary conditions are expected to have high impact on the test result (see above)	Precise description of boundary conditions shall be given to participants

4.2 Test rig

Independently from the final test method (proposed or alternative) the following three options are available concerning the test rig(s) of the round robins. The first one that each participant erects its own test rig, which has many disadvantages – such as very high costs to the participating lab, high and not harmonised installation time and necessity of early dedication to the test method. The second option to erect only one test rig – hopefully covered by the budget of the RR – and participants perform the necessary tests on that location. This solution has the advantage of low installation time, however, on the other side it requires high travelling time from the participants and performing test according to a not daily used test method on an unfamiliar location. The third option is when one test rig is transportable among members. This method is suitable to involve more participants, but it requires a special test rig and very detailed mounting and dismantling instruction, the transportation costs would be high, and the scheduling would be challenging, even impossible without serious delays. All options described above have their own advantages and disadvantages, choosing the right solution depends on the budget available to the project, the involvement of fire labs and Member States and their dedication to the test method.

4.3 Calibration element

The authors of this paper consider the temperature readings the most critical criterion in the test methods. The real value of a temperature reading (v_{real}), to simply put, equals of the measured value ($v_{measured}$) and errors (e_i).

$$v_{real} = v_{measured} \pm e_{method} \pm e_{product} \pm e_{system} \pm e_{human} \tag{2}$$

The error related to the measuring system (e_{system}) can be calibrated by the everyday methods applied in the fire laboratories. The human error (e_{human}) relates to the staff of the laboratory and the brigade installing test specimen. All products contain some manufacturing error ($e_{product}$) that are within the tolerances. The test method itself carries some deviations (e_{method}), which shall be assessed by the robustness testing phase, from these the fire source is considered to be the most critical one. For these reasons in the following four calibration elements are suggested to be applied during different steps of the robustness testing and/or round robin phase, short description of three of them are described in Table 3.

Table 3. Calibration elements

1	Steel tray	
	Location	On the top of the fire chamber
	Material	Steel tray filled with CaSi boards and/or stone wool
	Function	Temperature increase measurement in the fire chamber

		Location of applied TCs are on non-exposed side of the steel plate under the CaSi boards It functions as a “big” plate thermo-meter
2	Steel rod	In almost all test configurations are applicable
	Location	Lintel area of the fire chamber
	Material	Steel rod
	Function	Temperature distribution of the exiting plume from the fire chamber Location of applied TCs are along the steel rod
	When to use	In almost all test configuration applicable, but it could be especially useful to detect the effect of the orientation of blow speed
3	Steel rod	
	Location	Inside the timber crib
	Material	Steel rod
	Function	Temperature “map” of the timber crib Location of applied TCs are along the steel rod
	When to use	In almost all test, but it could be especially useful during the robustness testing of timber cribs

Due to the degradation of these elements in the fire test, the possibility of multiple usage of them shall be analysed beforehand. To eliminate or to minimize the number of errors, the calibration of the test bench shall be carried out on an inert façade with increased number of thermo couples. The fourth calibration element can be a uniformly distributed thermo couple mesh, with a grid with of 500 mm, which shall be applied on the faces of the test rig during a test. By this way the temperature pattern of a test can be determined. This uniform mesh might be suitable for multiple usage in different locations; obviously the details shall be worked out later on.

4.4 Materials / Kits to test in the RR

Aspects of choosing the right kit: it should be moisture resistant and have the least number of components, especially water-based ones should be avoided, the mounting of the product/kit should not require special experience, the opportunity to make observations during the fire test shall be available (avoiding forming of a pall of smoke and observing visible burning droplets). Timber based kits carry a negative effect of moisture content sensitivity; even though it was widely tested [15-17], due to the nature of the material and the complexity of the project, timber-based kits shall be neglected. An ETICS system would be really interesting to test in a RR, however due to the numerous components and possible deviations in the installation, it is not advised. Inert faces are expected to always pass all criteria, a properly chosen rain screen would be advantageous to test , a polycarbonate wall provides the possibility to visually follow the effect of the flames vertically and horizontally, observing burning droplets and detecting temperature increase.

5 ROUND ROBIN ON FACADES – THERORETICAL ROUND ROBIN

A theoretical round robin (TRR) shall involve at least one participant from each Member State. As the TRR would take place before the issuance of the official test and classification standard, the main question to be solved is the basis of the theoretical round robin. A finalized ‘standardization-ready’ report shall be circulated with the questionnaire. The TRR shall contain both test methods (medium and large scale) with two test configurations at least and it shall focus on the tasks taking place before the test (preparation) and after the test (evaluation). Since the evaluation is based on not just temperature rise readings, full videos shall be provided to the participants (these ones might be

recorded during the robustness / screening tests). The following topics shall be part of the TRR: location of thermo couples and fire chamber, fire source (geometry, amount etc.), conditioning, determining the start of a test. On the other hand, the TRR focusing on the assessment the reached fire propagation class(es) and the direct field of application, if any is available at the time of the TRR.

6 CONCLUSION

- The aims of robustness testing and round robins shall be set; it shall include that first-hand experience in a fire lab and, indirectly, in Member States might increase the acceptability of the new test method(s).
- The most important robustness influencing factors are: fuel source, location of the test, secondary opening, thicknesses of test materials.
- Mandel's h and k consistency test method and Grubb's test might provide adequate mathematical solutions to evaluate the data set of repeatability and reproducibility.
- During the robustness testing phase the calibration elements shall be applied for measuring the temperature in and around the fire chamber, while during the round robin phase a thermo-couple mesh might be used to measure the face temperature.
- Possible round robin materials are the following: inert face, rain screen, polycarbonate wall.
- Theoretical round robin should focus on preparation of test and evaluation of test results.

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DIFFERENT STANDARD TESTS OF FAÇADE FIRE SPREAD APPLIED FOR IDENTICAL ALUMINUM COMPOSITE PANEL SPECIMENS -MSZ 14800-6 (FULL-SCALE) AND JIS A 1310 (INTERMEDIATE-SCALE)-

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ABSTRACT

Authors from Hungary and Japan performed their tests using identical “aluminum composite panel” specimens provided by the same supplier. Test results were discussed: to evaluate the fire spreading behaviour of façade models with comparative analysis, to point out similarities and differences of the methods finding a correlation between data measured and performance criteria, moreover for screening, ranking and classification of the different façades. This research collaboration could be beneficial for the harmonization of different façade tests as well as for the scientific understanding of complicated façade fire behaviour.

Key words: façade test, fire propagation on façade, MSZ 14800-6:2009, JIS A 1310:2019, full-scale fire test, intermediate-scale fire test, screening test, aluminum composite panel.

1 INTRODUCTION

There are many different standard tests for façade fire spreading in the world [1]. It should be the case that most of them have the identical or at least similar purpose of evaluating the fire spread behavior of combustible façades, but strangely enough, basic elements of fire tests such as specimen configuration, existence of window opening, size of fire room or chamber, heating intensity of fire source, and even criteria based on the fire tests, will greatly differ from each other.

2 FAÇADE SPECIMEN

In this research the test specimens were used in both of tests – MSZ 14800-6 [2] and JIS A 1310 [3,4]- almost identical aluminum composite panels (Euroclass B-s2, d0) with core layer made of PE and Al(OH)₃ laminated with aluminum sheets (Mitsubishi product). Between the façade panel and the substrate there is an air-gap and thermal insulation (Euroclass A1) layer (Rockwool product).

3 MSZ 14800-6 FAÇADE TEST (FULL-SCALE) [2]

The Hungarian standardized test procedure aims at determining the vertical and horizontal fire spread properties (fire-propagation limit value T_h) for coatings on building façades with openings, for claddings mounted with or without air-gap, ETICSs etc.

The test rig is a three-storied building, a fire room with standard window in downstairs, on the second level there is an observation room with an opening the same size of the window.

The test procedure simulates a fully-developed indoor fire and inspects the resulting fire-spread from the aspect of the level(s) above. The application of the standard “temperature-time” fire curve in the fire room as per ISO 834-1, MSZ EN 1363-1, ASTM E 119 means a stable starting point against the fire effects with a not realistic test background applied in other test procedures.

The specified fire exposure is ensured by a wood crib of 650 kg. The thermal energy of ~3.25 MW released during the test represents the combustion of a fully furnished room e.g. in flats or in offices, the calculated fire load in the fire room approximately 650 MJ/m² and ensures the fire curve given in Eq. (1) during the test (as per ISO 834-1:1999 standard):

$$T - T_0 = 345 \times \lg(8t + 1) \quad [\text{K}] \quad (1)$$

The wooden frame window of the fire room shall be opened in the 5th minute after ignition. The air supply of the fire room can be regulated by manually adjustable shutters.

Temperature data collection is carried out in the fire room, in the observation room, in front of the façade between the window openings (the standard test lasts 45 minutes).

3.1 Performance criteria of MSZ 14800-6

The façade fire-propagation limit value (T_h) of the façade coating, cladding and ETICS means the length of time measured and specified in minutes when any of the following phenomena occurs:

- *the damage caused by the surface combustion of the model structure spreads up in vertically and in horizontal direction which longer than a limited distance;*
- *the difference between the temperature measured in the flame zone coming out the fire room and the temperature measured behind the window opening on the observation level is not higher than 300 K for longer than 2 minutes;*
- *in case of burning or not burning falling droplets of cladding are heavier than 5 kg.*

3.2 Test, test model (façade cladding system: type ALPOLIC/FR) and testing conditions

- *The entire façade sample was 7.5 m in height and 4.4 m in width as shown in Fig. 1.*
- *Fire room window: an L-shaped steel sheet was installed in order to strengthen the lintel above the window; an insulation strip was prepared around the window.*
- *Observation level opening: no window was installed; instead, the opening was left clear, an insulation stripe was built in the same manner as in the fire room window.*
- *Within the fire room and observation room window opening jambs-wall an ALPOLIC/FR composite plates stiffened with steel sheets on both sides and on top and a stone wool layer was implemented. A perforated steel sheet was used forming a ventilated air gap.*

All standardized test parameters (meteorological conditions, air temperature, wind speed) were existing during the period of time of test procedure from beginning to end.

3.3 Measures, Test Results and Observations

The main phenomena and visible observations happened during the test were monitored, measured and video recorded.

The difference between temperatures measured in front of the wall portion stretching between the window openings and the temperature measured in the window opening at the observation level did not decrease below temperature difference specified as a standard criterion during the test period.

Cladding components above the fire room window opening were completely burned. The Al profiles supporting the cladding components have melted because of high temperature (> 660 °C) and left the

structure splashing through joint gaps of the façade system. No dripping-burning droplets with ignition potential were observed.

Cladding components and underlying support structures, except for those that were directly exposed to output flames from the fire room, remained intact as shown in *Fig. 2*. Due to the design of the cladding support system and the cladding component layout, the aluminum support structure located directly over the fire room was exposed to concentrated fire loads. After destruction of the supports, the structure did not lose much of its original stability as the adjoining supports took over the additional burden. With the exception of the section located directly over the fire room, the stone wool insulation has remained substantially intact. The fire exposure was the most stronger in the field between the two window opening.

During the test according to MSZ 14800-6 method the flame ejected from the opening of fire room attacks the façade-panel but there are barriers against the fast vertical propagation:

- *an additional steel plate and turned in thermal insulation (stone wool) layer on the upper part of the window opening of the fire room and opening of the observation room;*
- *window opening (without any cladding element);*



Fig. 1 Test model before the test



Fig. 2 Test model after the test

3.4 Evaluation based on the criteria from the standard

All of performance criteria were “passed”: there were no occurrence damage larger then limit neither vertical nor horizontal direction, no falling droplets heavier than 5 kg, maximum temperature was 150 °C inside the observation room, this value is significantly lower than the ignition temperature of the most of combustible materials, consequently practically there was no chance for ignition in the observation room.

3.5 Validity of the Test Results

The fire propagation of limit of the ALPOLIC/FR façade system is $T_h \geq 45$ minutes.

According to Hungarian Fire Code this system is applicable ≤ 30 meters of building height.

4 JIS A 1310 FAÇADE TEST (INTERMEDIATE-SCALE) [3]

4.1 Overview of JIS A 1310

JIS A 1310 specifies a screening method for determining the fire propagation of products and constructions of a building façade when exposed to flames ejected from the opening. Details will be described hereinafter.

In JIS A 1310, major measuring items are temperature, incident heat flux, and visual observation. *Fig. 3* shows the installed positions for both heat flux meters and thermocouples. In case of “real” tests on combustible facades except for calibration test, heat flux meters are installed at the top of main façade surface for the purpose of measuring the heat flux into the main façade surface at the top height level, as well as horizontally two meters away from the main façade surface, at the heights of 500, 900, 1500, 2000 and 2500 mm from opening top level for the purpose of measuring the heat flux into the assumed position of an adjacent building in the actual life. Only in case of calibration test, heat flux meters are also installed at the main façade surface at the heights of 500, 900, 1500, 2000 and 2500 mm from opening top level, for the purpose of calibrating the heat output of gas burner inside the combustion chamber. In case of calibration test, averaged incident heat flux on main façade surface should be $(30 \pm 5) \text{ kW/m}^2$ at the height of 900 mm from opening top level, and also $(15 \pm 5) \text{ kW/m}^2$ at the height of 1500 mm from opening top level. Based on the authors’ experience, heat around 900 kW from gas burner inside the chamber would be suitable for satisfying those heat fluxes. Regarding thermocouples, according to JIS A 1310, they should be installed on the façade surface, 50 mm horizontally away from façade surface, at the height of 500, 900, 1500, 2000 and 2500 mm from opening top level.

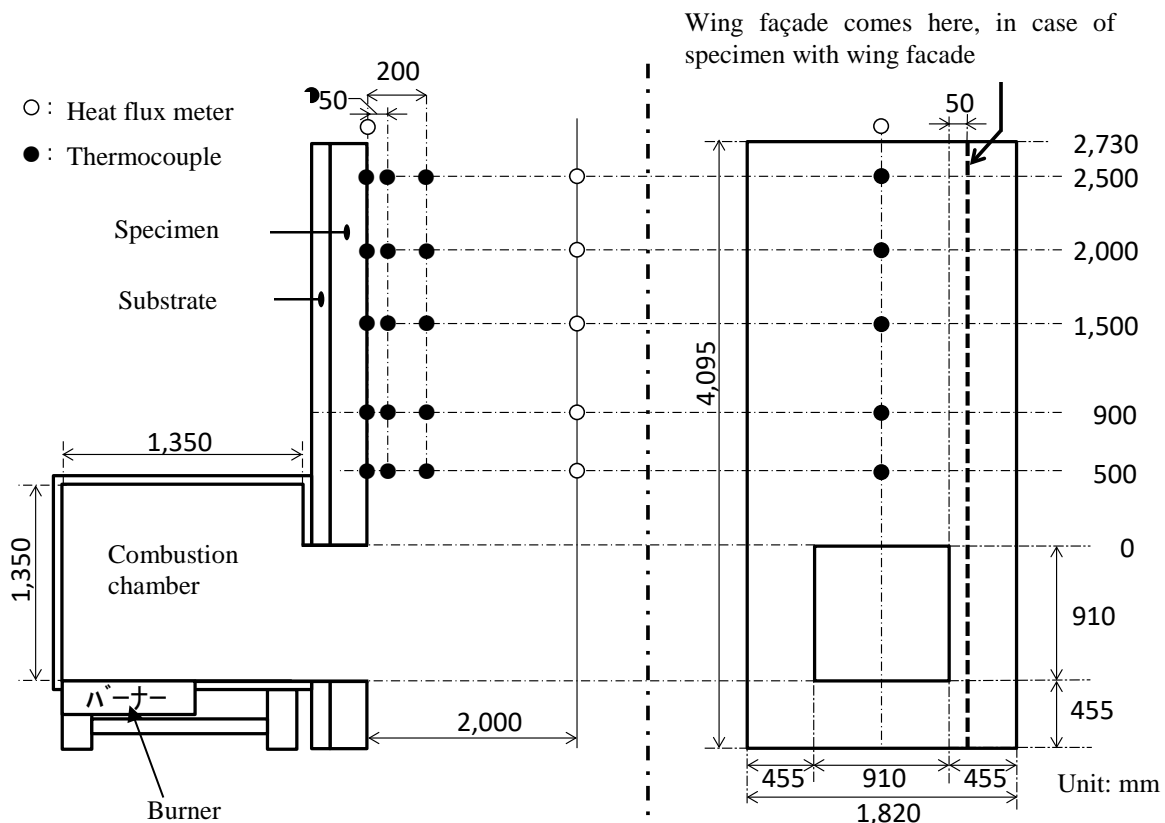


Fig. 3: Position of measuring apparatus (thermocouple and heat flux meter)
 (Left: side view, right: front view of main facade)

4.2 Test specimens for JIS A 1310

In general, test specimens for JIS A 1310 are basically almost similar to that of MSZ 14800-6. The order of layers of main material components is identical to the Hungarian test specimen, but with some minor differences such as substrate board made of calcium silicate boards, and opening edge covered by only aluminum sheets without steel plates.

Furthermore there are two tests conducted, one of them used an ordinary specimen of only main façade, and the other used a specimen combining main façade with wing façade. Both specimens, with and without wing façade, are allowed in the latest version of JIS A 1310: 2019.

4.3 Overview of test results

Specimen of only main façade

Pictures taken during and after the JIS A 1310 test are shown in *Fig. 4* and *Fig.5* respectively. As shown in *Fig. 4*, after 11 min, flame vertically propagated to the higher position of main façade through the central joint, and also started to emerge at the left lateral side. After the test, almost all of the core material located above the opening burned out, and also, central part of aluminum surface sheet above the opening (triangular shape) vanished. Only left side and right side of aluminum sheet was still there hanging from the top of main façade.



Fig. 4 Specimen of only main façade, during JIS A 1310 test



Fig. 5 Specimen of only main façade, after JIS A 1310 test

Specimen combining main façade with wing façade

Pictures taken during and after the JIS A 1310 test are shown in *Fig. 6* and *Fig.7* respectively. Flame ejected from the opening propagated straightforward initially, but at 2 minutes from test start, it began to lean to the corner area between main façade and wing façade, and then fire vertically spread to the upward direction around the corner area. At 4 minutes, fire exceeded the top of specimen at corner area. From 5 to 10 minutes, fire was kept very intensive especially at the corner area. After 10 minutes, fire was kept moderate, but gradually spread horizontally at main façade to the opposite direction of corner area. This could be seen from *Fig. 7* which was taken after the test.



Fig. 6 Specimen with wing façade, during JIS A 1310 test (around 10 min).



Fig. 7 Specimen with wing façade, after JIS A 1310 test

5 EVALUATION BASED ON THE CRITERIA OF JIS A 1310:2019

Summarized tables for comparison are shown in *Table 1*, *Table 2* and *Table 3*.

Table 1. Comparison of temperature at main façade surface

	Height: 2.000 mm		Height: 2.500 mm	
	Peak [°C]	Time exceeding 500 °C [s]	Peak [°C]	Time exceeding 500 °C [s]
Calibration Test	345	-	290	-
Only main façade	655	154* (78, and 76)	794	206
With wing façade	610	404	675	178

* This value is not continuous time but total time

Table 2. Comparison of temperature at horizontally 50 mm away from main façade surface

	Height: 2.000 mm		Height: 2.500 mm	
	Peak [°C]	Time exceeding 500 °C [s]	Peak [°C]	Time exceeding 500 °C [s]
Calibration Test	343	-	293	-
Only main façade	590	70	872	194
With wing façade	764	198	712	208* (158, and 50)

* This value is not continuous time but total time

Table 3. Comparison of incident heat flux at the top of main façade

	Incident heat flux At top of main façade	
	Peak [kW/m ²]	Mean [kW/m ²]
Calibration Test	10	6
Only main façade	19	-
With wing façade	30	-

As shown in *Table 1* and *Table 2*, both specimens of “only main façade” and “with wing façade” demonstrate far higher temperatures than those of “calibration test”, which means that those combustible façade specimens have contributed to enlarging the façade fire propagation compared with non-combustible facade. Indeed, grey-coloured cells in *Table 1 and Table 2* show that the duration time when a measured temperature exceeds 500 °C is two minutes or longer, which is recently included as draft criteria of JIS A 1310: 2019, assuming that massive fire is observed. At the same time, it is hard to see the major difference between the specimens of “only main façade” and “with wing façade”. Especially regarding the peak temperature at 2500 mm height in the centre-line, “only main façade” shows higher values both at surface and horizontally 50 mm from surface than those of “with wing façade”. This is because in case of “only main façade”, fire was intensively damaging the centre-line joint of main façade without deviating to wing façade, and fire propagation inside the vent layer was facilitated even after 10 minutes. On the other hand, in case of “with wing façade”, fire propagation was deviated from centre-line of main façade to the corner part between main façade and wing façade. Therefore, temperature at main façade centre-line did not become so high, even though fire was intensive at the corner part.

On the other hand, as shown in *Table 3*, regarding the peak value of incident heat flux at the top of main façade, there is a clear difference between the specimens of “only main façade” and “with wing façade”. In this regard, for the future criteria of JIS A 1310, it would be better to include the incident heat flux at the top of main façade with further technical discussion on other kinds of combustible façade specimens as well. Otherwise, when there is a wing façade, it will be another option to measure the temperature in the vicinity of corner area in addition to only the centre lines of both main façade and wing façade.

6 DISCUSSION AND SUMMARY

In this collaborative research between Hungary and Japan on façade fire safety, identical Al composite panel façade cladding with ventilated air gap and stone wool insulation was taken as specimen for both the MSZ 14800-6 (full-scale) and the JIS A 1310 (intermediate-scale) test. The specimen passed the criteria of MSZ 14800-6, while it failed the draft criteria of JIS A 1310: 2019, which could assume that draft criteria of JIS A 1310: 2019 are a little bit more severe than the criteria of MSZ 14800-6. In the MSZ 14800-6 test the fire spread was limited and more importantly, fire did not propagate into the inside of upper floor through the window opening.

During the test

- *according to Japanese method the flame ejected from the combustion chamber propagates vertically very close on the surface of façade, very fast, uninterruptedly;*
- *according to Hungarian method the flame ejected from the opening of fire room attacks the façade-panel but there were at least four barriers against the fast vertical propagation:*
 - *an additional steel plate and turned in a thermal insulation (stone wool) layer on the upper part of the window opening of the fire room and in the jambs (lintel) and around the window opening there is a thermal insulation (stone wool) stripe built in;*
 - *an additional steel plate and turned in a thermal insulation (stone wool) layer on the lower part of the window opening of the observation room;*
 - *window opening (without any cladding element) and in the jambs (lintel) and around the window opening there is a thermal insulation (stone wool) stripe built in;*
 - *an additional steel plate and turned in a thermal insulation (stone wool) layer on the upper part of the window opening of the observation room.*

After these barriers the plume loses a lot of its heat energy in consequence of convection and radiation because - theoretical statement - the free space in front of the façade behaves from physical point of view as an endless well; the role of these structural differences are not only very important in the taking

place of the fire propagation but particularly manifest in the final test results and significant for them. This structural arrangement and well-designed “sensitive” details contribute, promote much more moderate fire propagation and serve the decrease of damaged area. It maybe supposed that the behavior of façades with openings better than façades without openings. Fire propagation in the horizontal direction was not extensive neither in the JIS A 1310 test nor in the MSZ 14800-6 test.

Analysis: it is possible to collect more authentic, more reliable and richer in information data in cases of tests on facades with openings opposite to facades without opening in connection with the followings:

- *demodulation of fire propagation up to the upper level(s) with measuring*
 - *of temperature rise and its fluctuation in time,*
 - *of smoke density and its time change,*
 - *of concentration and velocity time change of the different toxic gases developed;*
- *observations of phenomena taking place and data measured carry the implication fundamental importance input for simulations, particularly modelling of the fire propagation process; importance of these is prognosticative, beside the expectable fire propagation, the different strength and direction of wind for the theoretical description of phenomenon which deforms the plume and its approach with mathematical tools, for the following with computer technology and other engineering methods, and for the analysis of probability from point of view of flow technology.*

Laboratory tests carried out on model structures are essentially, practically screening tests, which prepare the decisions of manufacturers for carrying tests in order to qualification, classification, application and extended application according to MSZ 14800-6 method.

It could be described that MSZ 14800-6 is not merely fire test but also faithful representation of actual building façade fire. In this regard, JIS A 1310 (intermediate-scale) represents a more onerous scenario compared to MSZ 14800-6 (full-scale), and it would be possible to consider JIS A 1310 as screening test prior to MSZ 14800-6, at least on this type of aluminum composite panel façades. But naturally, for understanding more general phenomena, it is no doubt that other types of combustible façades should be tested by both tests.

The previous paragraph deals with a fire scenario on a single main façade only. Now authors would like to point out the effect of wing façade in JIS A 1310, which was a massive fire spread along the corner joint between main and wing façades.

7 CONCLUSIONS

- *Regarding the almost identical specimen of aluminum composite panel façade with vent layer and rock wool insulation, it passed the criteria of MSZ 14800-6 (full-scale) but failed the criteria of JIS A 1310: 2019 (intermediate-scale).*
- *As JIS A 1310 represents a more onerous scenario than MSZ 14800-6 for this type of specimen, it could be positioned as screening test prior to performing MSZ 14800-6.*
- *Wing façade contributes to the façade fire propagation along the corner joint between main and wing façades. However, temperatures measured at centre-line of main façade do not reflect this. Therefore, it is necessary to measure the temperatures in the vicinity of corner area. Also, incident heat flux measured at the top of main façade could be compensating data. Research needs how to apply to a movable wing wall in the test apparatus to determine the position (distance) of wing wall from the opening of the main wall. Simultaneously it maybe supposed that the behavior of facades with openings better than facades without openings (or contain a “virtual” or a “fictitious” window).*

For more general information, authors should perform other types of combustible façade tests by both JIS A 1310 and MSZ 14800-6, for more specific correlation clarified.

8 FUTURE WORKS

Test equipment used in MSZ 14800-6 should be supplemented with a movable wing wall [5]. And the range of measured data should be extended to obscuration/extinction of smoke generated and quantitative and qualitative analysis of toxic gases developed (e.g. CO, CO₂, HCN, NO_x, HCl, HBr, SO₂, NH₃ and other components, which after a pre-analysis can be expected to develop during tests) in both test methods. The use of a hood supplied with heat protection above JIS A 1310 test equipment would enable the collection and analysis of these dangerous products during tests.

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SESSION 4: NUMERICAL MODELLING AND CASE STUDIES

- P.105 Experimental study combining accelerated weathering test with fire test regarding fire-retardant-treated wooden facades in Japan
Hideki Yoshioka¹, Miki Nakamura², Manabu Kanematsu³, Yuhei Nishio³, Takafumi Noguchi⁴, and Tatsuo Ando⁴
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- P.114 An engineering method for the contribution of wood: application to facade fires
Bertrand Girardin, Mathieu Duny, Gildas Auguin
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- P.122 Numerical investigation of fire development in a medium scale ISO 9705 compartment-facade configuration
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- P.130 Experimental and numerical investigation of externally venting flame developing in a corridor-facade configuration
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- P.138 Investigation of the fire exposure on a new test method by simulations
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EXPERIMENTAL STUDY COMBINING ACCELERATED WEATHERING TEST WITH FIRE TEST REGARDING FIRE-RETARDANT-TREATED WOODEN FACADES IN JAPAN

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ABSTRACT

Regarding Fire-retardant treated (FRT) wooden specimens, NT FIRE 053 and a couple of JSTM J 7001 tests with modified amount of water were conducted as accelerated weathering tests, while ISO 5660-1 cone-calorimeter tests and JIS A 1310 facade tests were conducted as fire tests. It was found that facade test is more appropriate than cone-calorimeter as fire test for the specimens after the weathering test is conducted, and also that fire performance of FRT wooden facades after accelerated weathering test is still far better than that of untreated wooden facades. Holistic method combining JSTM J 7001 with JIS A 1310 will be newly standardized as JIS A 1326 within 2019.

Key words: fire-retardant treated wood, facade, accelerated weathering, NT FIRE 053, JSTM J 7001, ISO 5660-1, JIS A 1310, and JIS A 1326.

1 INTRODUCTION

It is expected that the revision of the “Building Standards Law” of Japan in 2000 and the enactment of “Act for Promotion of Use of Wood in Public Buildings” in 2010 will result in an increase in the number of cases where wood is used at exterior facades of buildings. Wood is basically a combustible material, so it is often the case that using wood necessitates fire-retardant treatment. However, when Fire-retardant treated (FRT) wood is used outdoors, there is the concern that the chemical will leach away from the surface due to the exposure to rainfall, eventually rendering it unable to maintain the intended fire safety performance. Kawarasaki et al. [1] technically found that FRT wood even with a leaching-resistant chemical would lose its initial fire safety performance after taking an outdoor exposure test.

In Europe, NT FIRE 053 (hereinafter “NT FIRE”) [2] and CEN/TS 15912 [3] have been standardized as accelerated weathering tests, in line with some fruitful technical researches [4, 5]. On the other hand in Japan, there is currently no evaluation that specifically considers the aged deterioration of FRT wood with respect to fire performance. In Japan, ISO 5660-1 cone calorimeter test [6] is normally used for the classification of reaction-to-fire performance of building materials, but it is a small-scale test that cannot appropriately evaluate the fire spread phenomenon at an actual wooden building facade with a ventilation layer, etc.

Considering these backgrounds, authors conducted the experimental study combining accelerated weathering test with fire test. As accelerated weathering test, NT FIRE 053 and several variants based on JSTM J 7001 [7] were conducted. As fire test, ISO 5660-1 and JIS A 1310 facade test [8, 9] were conducted. And, discussion was made to compare those results.

2 OUTLINE OF EXPERIMENT

2.1 Accelerated weathering test

Authors conducted a test based on JSTM J 7001 [7] (hereinafter “JSTM”), which is used in Japan as a real-scale “durability test” for exterior walls in general, but with changed cycles of drying and watering, and the amount of water, in order to promote the leaching of the fire-retardant chemical. Furthermore, NT FIRE (especially Method A) was also conducted for comparison.

The experiment equipment for JSTM is outlined in Fig. 1(a), and the test cycle used is shown in Fig. 1(b). Each cycle consists of 1.5 hours for drying and 2 hours for watering. Cycle counts are 60 cycles (hereinafter “JSTM-60”), and 180 cycles (hereinafter “JSTM-180”). The specimen was placed vertically, and 1.0 l/min·m² of water was sprinkled over the surface. An infrared lamp was used to dry the specimen. The heating was adjusted so that the surface temperature on the specimen was 80°C.

Outline of the sprinkling equipment in NT FIRE is shown in Fig. 2(a), and the test cycle used in Fig. 2(b). Each cycle is to consist of 96 h of water exposure and 72 h of drying. The tests were conducted under the condition of 4-cycle, which is for screening purpose (hereinafter “NT FIRE-4”), and also 12-cycle (“NT FIRE-12”), which is supposed to be a real test. Specimen surfaces had a slope of 18° when they were exposed to water, and 0.3 l/min·m² of water was sprinkled over the specimen surface. The temperature inside the chamber was set to 60°C when drying.

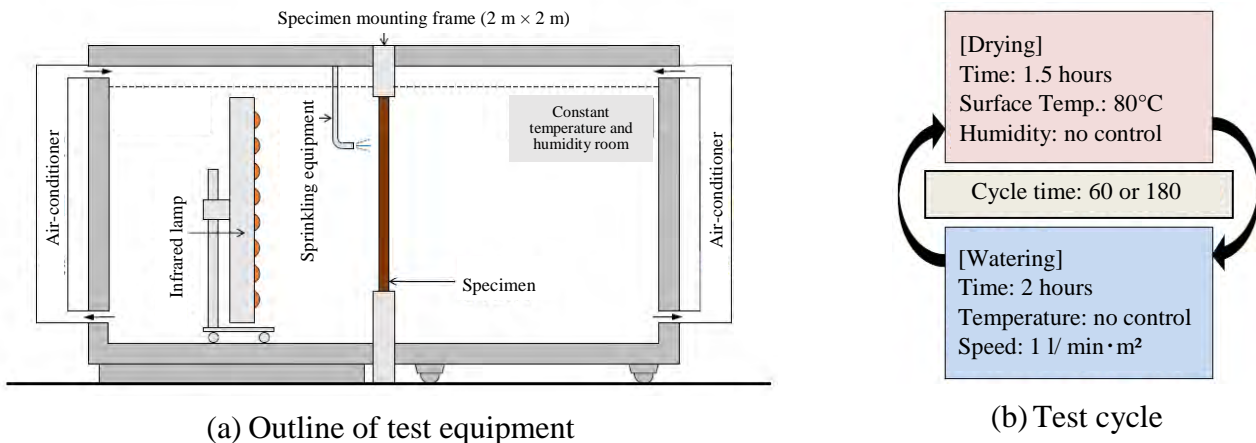


Figure 1: Outline of JSTM J 7001.

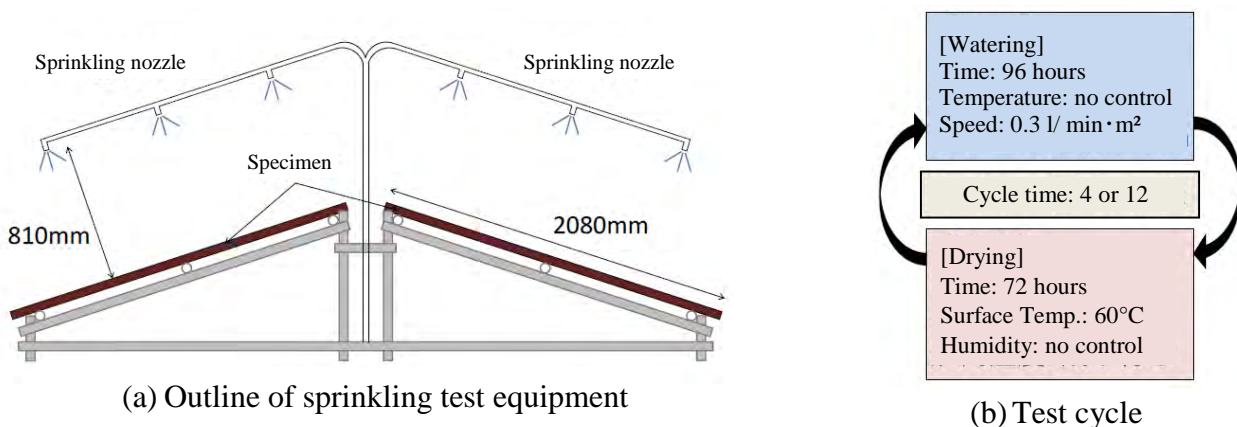


Figure 2: Outline of NT FIRE 053 (Method A).

2.2 Outline of specimens

Table 1 shows outline of specimens prepared for this test, including those that underwent accelerated weathering test (JSTM-60, JSTM-180, NT FIRE-4, and NT FIRE-12), and those that did not undergo accelerated weathering test (No FRT (untreated), FRT, and FRT with low chemical injection). To prepare the FRT wood specimens, a phosphate amino resin fire-retardant chemical was pressure-injected into the wood specimens, and the surface of the specimens was finished with water-repellent paint. To prevent the chemical from leaching from the side of the specimen during the accelerated weathering test, aluminium tape was pasted on the side for JSTM test, while the side was coated with alkyd resin for sealing for NT FIRE test. The specimens were dried at 60°C for 7 days before and after the test for JSTM-180 and NT FIRE-12, and the residual chemical and the chemical remaining ratio were calculated using the simple equations. The mass of the specimens was measured before and after the test of JSTM-60 and NT FIRE-4.

Table 1: Outline of specimens.

With or without Accelerated weathering test	Test condition	Fire test	Surface dimensions during accelerated weathering [mm]	Average amount of injected chemical (minimum to maximum) [kg/m ³]	
Without Accelerated weathering test	No FRT (untreated wood)	Facade	—	—	
		Cone		—	
	FRT (ordinary)	Facade	—	164 (119 to 196)	
		Cone		No data	
	FRT with low chemical injection	Facade	—	51 (40 to 63)	
		Cone		45 (40 to 50)	
With Accelerated weathering test	JSTM-60	Facade	1980 × 1980 (× 2 specimens)	118 (101 to 164)	
		Cone		142 (128 to 164)	
	JSTM-180	Facade		128 (100 to 167)	
		Cone		135 (134 to 135)	
	NT FIRE-4	Facade		2080 × 1000 (× 4 specimens)	126 (106 to 188)
		Cone			136 (134 to 139)
	NT FIRE-12	Facade			139 (108 to 174)
		Cone			132 (130 to 133)

2.3 ISO 5660-1: Cone calorimeter test

After the accelerated weathering test, a piece of 100 mm × 100 mm was taken out from the inside of the specimen, 100 mm or more from its end. The cone calorimeter test was then conducted according to ISO5660-1. Before the test, the specimens were dried under conditions of 23°C and 50% RH until the mass difference became less than 0.5% in 24 hours. The test was conducted under the heat flux of 50 kW/m² for a duration of 20 minutes. The heat release rate was calculated using the oxygen consumption method. For comparison, specimens without accelerated weathering test (no FRT, FRT, and FRT with low chemical injection) were also tested under the same test conditions.

2.4 JIS A 1310: facade test in Japan

Specimens were constructed as shown in Figure 3. Each specimen measures 4095 mm in height and 1820 mm in width, and has a square opening of 910 x 910 mm. Specimens were arranged from above the opening in ascending order of injected chemical quantity.

Facade specimen and combustion chamber are aligned with each other at their openings. The burner inside the chamber was ignited, and flame was ejected out from the opening for 20 minutes. Each specimen is composed of wooden facade on the surface and wooden vertical furring channels (W (45 or 90) x D15 x H4095 mm) on the back of wooden facade, which are screwed to the substrates made of calcium ciliate boards. Totally five vertical furring channels were installed at a horizontal interval of 455 mm, on the back of wooden facade. The rear side of wooden facade surfaces are horizontally 15mm distant from the substrate because of those vertical furring channels, and this 15mm area could be considered to be vent layer. The area around the opening was covered with a ceramic fibre blanket to prevent the flame from directly entering the vent layer.

A calibration test was conducted in advance with no flammables attached to the exterior, and the ejected flame and plume from opening was adjusted by the gas burner inside the combustion chamber so that the incident heat flux to the wall surface was $(30 \pm 5) \text{ kW/m}^2$ at a height of 900 mm from the top end of the opening, and $(15 \pm 5) \text{ kW/m}^2$ at a height of 1500 mm. Around 900 kW heat output to the gas burner was found to be suitable. Then, during the real tests with combustible facades, thermocouples were installed at the locations shown in Figure 4 to measure the exterior surface temperature and the internal temperature of the vent layer. A heat flux meter was placed at the top end of the specimen to measure the incident heat flux.



Figure 3: Outline of equipment, (JIS A 1310 facade test).

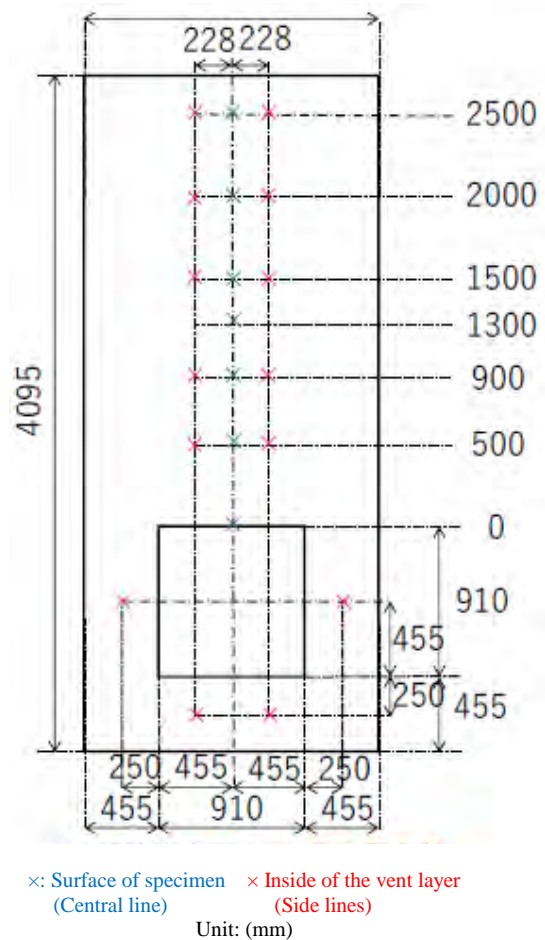


Figure 4: Locations of thermocouples.

3 TEST RESULTS

3.1 ISO 5660-1: Cone calorimeter test

Figure 5 is a time-series graph of the Heat Release Rate (HRR), and Figure 6 compares the Total Heat Released (THR) of each case. Criteria according to Building Standard Law (BSL) of Japan is 200 kW/m² for peak HRR and 8 MJ/m² for THR. And when this criteria is met for 20 minutes then it is classified as “noncombustible”, 10 minutes as “quasi-noncombustible”, and 5 minutes as “fire retardant”. For the specimens without accelerated weathering test, those with a larger chemical injection had a lower initial peak of HRR and THR. The specimen (FRT, without accelerated weathering test) was found to have the performance of a “quasi-noncombustible” level according to BSL criteria.

For the specimens after an accelerated weathering test, the heat release result increased, even with a low cycle number, such as JSTM-60 and NT FIRE-4. With an increase in the cycle number, both initial peak of HRR and THR increased, and those specimens (JSTM-180, NT FIRE-12) came to be unable to maintain the performance of even “fire retardant”, as their THR exceeded 8 MJ/m² at 5 minutes.

Comparing the specimens among “FRT with low chemical injection”, “JSTM-180” and “NT FIRE-12”, “FRT with low chemical injection” had a small amount of injected chemical and resulted in high THR in cone test. On the other hand, that initial peak of HRR was lower than those of JSTM-180 and NT FIRE-12. It was presumed chemical on specimen surface was leached by the accelerated weathering test.

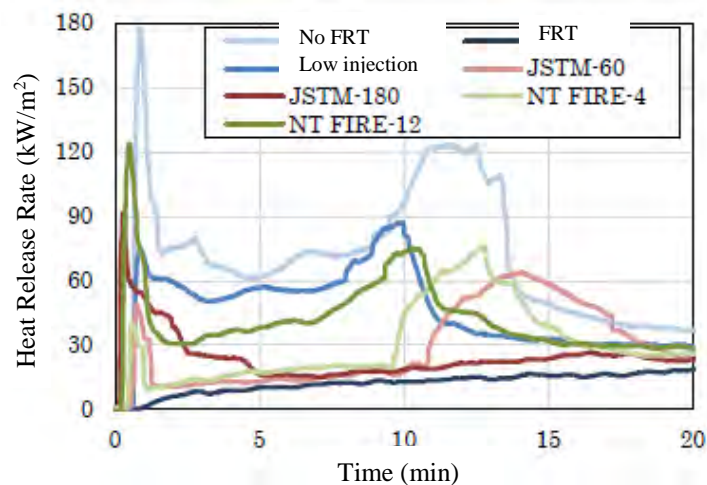


Figure 5: Graph of Heat Release Rate (HRR).

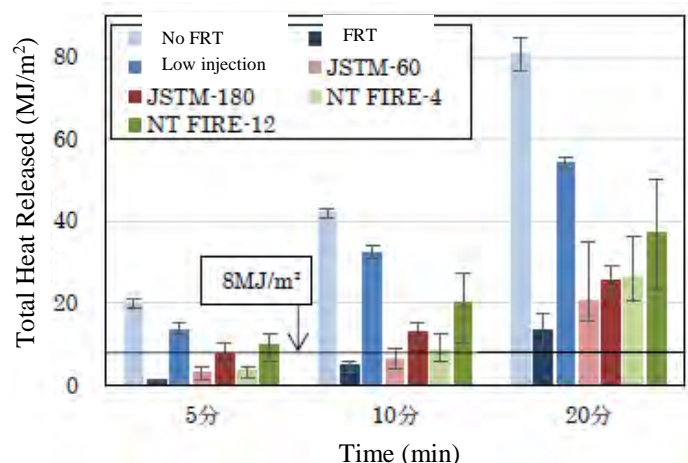


Figure 6: Comparison of Total Heat Released (THR).

3.2 JIS A 1310: facade test in Japan

3.2.1 Specimen damage after facade test

Specimen damage after facade test and the burn-through parts are shown in Figure 7. After each facade test, a grid wire net of 100 mm × 100 mm per mesh was applied to the facade specimen surface, and if over half of a certain grid was burned through, and then that grid was judged to be “burned through”. There are many places around the centre line of the facade specimen remaining without burned through, because the vertical furring channel was existing at the centre line and the specimen was fixed with screws.

Specimen “No FRT” was burned through up to the top end, while specimen “FRT” was only burned to 1300 mm height from the opening top end. This demonstrates that chemical treatment is effective in reducing the facade fire spread. When comparing the specimens between “FRT” and “JSTM-180”, no major difference was observed regarding the damage. It is presumed that even when the chemical on the surface layer is leached after accelerated weathering test, the specimen is not burned through if there is some chemical remaining inside the specimen.

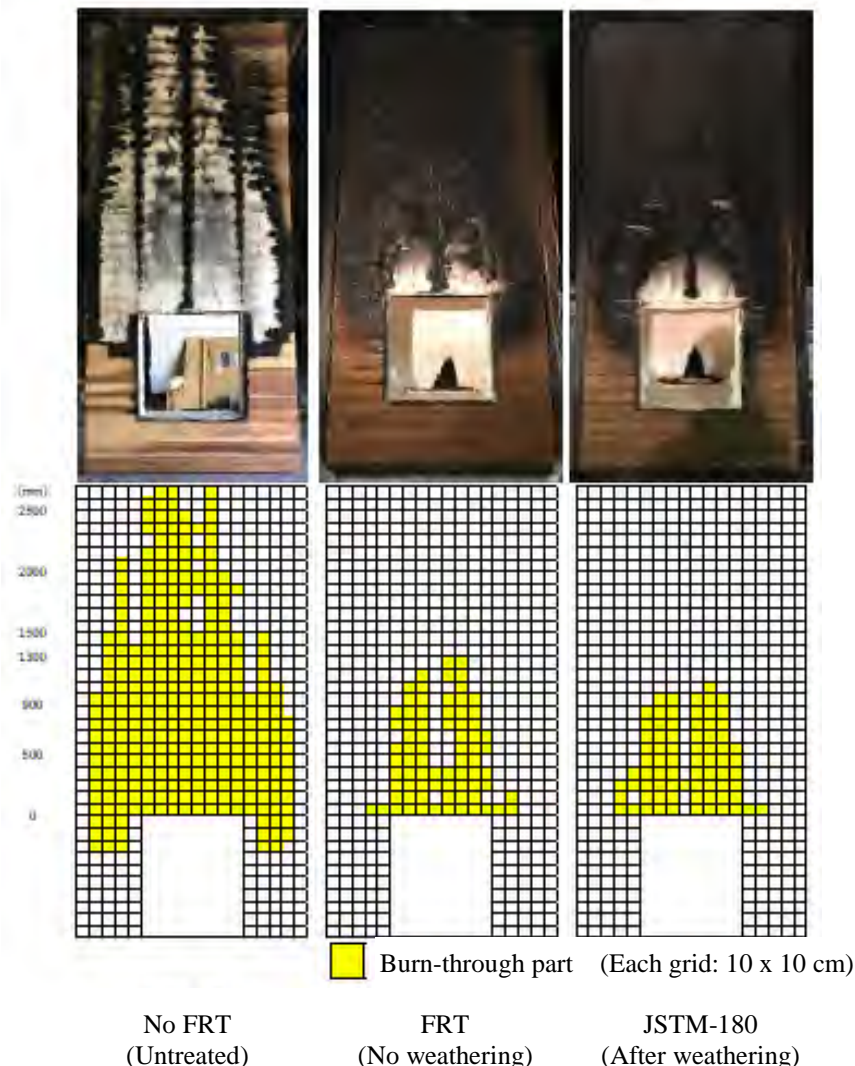


Figure 7: Specimens after facade tests.

(Top row: still pictures, bottom row: burn-through parts indicated by yellow-coloured grids).

3.2.2 Temperature and incident heat flux

“Duration time when the temperature is higher than 500°C”, “Time when the temperature reached 500°C at a height of 1500 mm, 2000 mm, and 2500 mm from the opening top”, and “Maximum incident heat flux at the specimen top” are shown in Table 2. The maximum facade surface temperature at each height level is shown in Figure 8. The vent layer temperatures at each height described in Table 2 are the higher values among those at two measurement points at the same height. 500°C is referenced as the indicator for the occurrence of fire spreading, according to authors’ experience of JIS facade tests.

As shown in Table 2, regarding the vent layer temperature at 2000 mm and 2500 mm, only the specimens “No FRT” and “FRT with low chemical injection” exceeded 500°C. And duration time was 0.3 minutes for “FRT with low chemical injection”, it was assumed that almost no impact on fire spread. Regarding all the specimens with the weathering tests (JSTM-60, JSTM-180, NT FIRE-4, and NT FIRE-12) which were initially fire-retardant treated, and also the specimen “FRT” without weathering test, temperatures did not exceed 500°C at 2000 mm and 2500 mm. This suggests that fire spread is controlled thanks to the chemical injection.

Table 2: Compiled results of temperature and incident heat flux.

With or without Accelerated weathering test	Specimen		Duration of time where temperatures of 500°C and higher continued (min)			Maximum incident heat flux at specimen top (kw/m ²)
			[Time when the temperature reached 500°C (min)]			
			1500 mm	2000 mm	2500 mm	
-	Calibration test		—	—	—	8.9
Without Accelerated weathering test	No FRT (untreated wood)	Surface	17.3 [0.9]	1.9 [1.0]	1.3 [14.3]	28.6
		Vent layer	6.9 [13.1]	4.8 [15.2]	2.0 [18.1]	
	FRT (ordinary)	Surface	—	—	—	10.1
		Vent layer	—	—	—	
	FRT with low chemical injection	Surface	8.8 [8.0]	—	—	12.9
		Vent layer	7.7 [12.3]	0.3 [19.7]	—	
With Accelerated weathering test	JSTM-60	Surface	—	—	—	9.8
		Vent layer	—	—	—	
	JSTM-180	Surface	—	—	—	10.6
		Vent layer	—	—	—	
	NT FIRE-4	Surface	8.6 [11.1]	—	—	10.2
		Vent layer	1.8 [18.2]	—	—	
	NT FIRE-12	Surface	2.3 [17.7]	—	—	10.6
		Vent layer	—	—	—	

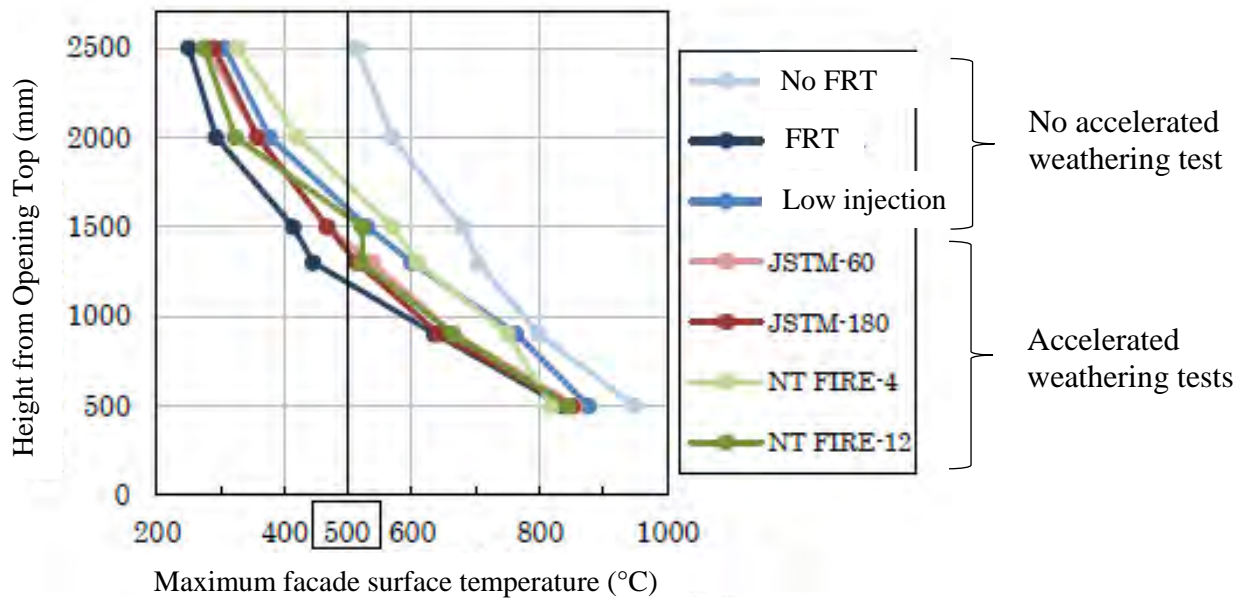


Figure 8: Maximum facade surface temperature at each height.

3.3 Comparison between the cone calorimeter test and the facade test

Regarding cone calorimeter results, especially among those specimens that underwent the accelerated weathering tests, the more the cycle number was, the larger peak HRR and THR were, as shown in Figures 5 and 6. On the other hand, regarding the facade tests on the specimens with accelerated weathering, the cycle number did not make major impact on their results. Then, regarding the facade test results of the specimens without accelerated weathering, the greater the injected chemical, the lower the temperature, which was the same tendency as heat release result in cone calorimeter tests.

4 SUMMARY

In this research, authors conducted the experimental study combining accelerated weathering test (NT FIRE 053 and JSTM J 7001) with fire test (ISO 5660-1 and JIS A1310), for some types of FRT wood and untreated wood. Then the followings were found.

(1) Regarding the results of ISO 5660-1 cone calorimeter tests conducted after the accelerated weathering tests based on JSTM J 7001 and NT FIRE 053 (Method A) with variance in the number of cycle for drying and watering, the more the cycle number was, the larger peak HRR and THR were. Especially after conducting the weathering test with large number of cycle, then the result failed to meet the criteria of even “fire retardant material” (the third class in Japan), though before the weathering test it was originally classified as “quasi-noncombustible material” (the second class in Japan).

(2) Regarding the JIS A1310 facade tests, those specimens with accelerated weathering tests even in the large number of cycle showed not so much different results on fire propagation from the original FRT wooden facade without accelerated weathering. In short, both of them did not have massive fire propagation over the facade, while untreated wooden facade showed massive facade fire during the test.

This is the different result from ISO 5660-1 cone calorimeter. It could be said that after the injected chemical leaching out of the surface, HRR in the cone calorimeter increased, but fire spreading in the facade test was not greatly increased, as there was still enough chemical remaining inside the specimen. Based on these findings, the combination of JSTM J 7001 (especially, JSTM-180) and JIS A1310 was considered to be reasonable by the discussion and agreement made among the drafting committee members, and it will be standardized as JIS A 1326 in 2019 [10]. Also, it should be noted that findings above are still limited to the accelerated weathering tests conducted in this research, and further research should be continued, being compared with natural exposure tests of certain period of times as well.

ACKNOWLEDGEMENT

The authors are grateful to the committee members of drafting JIS A 1326, for their technical discussion.

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AN ENGINEERING METHOD FOR THE CONTRIBUTION OF WOOD: APPLICATION TO FAÇADE FIRE

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ABSTRACT

The modelling of the fire development in buildings can be achieved using simple up to complex models including engineering tools based on computational fluid dynamics (CFD) simulations. These simulations must consider several phenomenon, such as heat transfer, material degradation and pyrolysis, combustion and fluid dynamics. However, for modelling costs and in order to apply these models in commercial application, the approach has to be kept as simple as possible.

A numerical methodology for engineering studies is proposed in this paper. It combines the ability for wood surfaces to extinguish, based on fuel burnout or surface temperature, and the dynamic variation of the heat release rate depending on the thermal aggression. This behaviour is modelled using a simple relation extracted from cone calorimeter experiments. This avoids the additional characterization cost necessary for pyrolysis studies and limits the uncertainties because a single experimental relation is used compared to several numerical parameters.

The simulation of a façade test shows that this methodology allows a better modelling of the development and extinguishment of the wood fire contribution, and better reproduction the charring pattern compared to a classic ignition temperature with fixed heat release rate approach. In both case, the results are slightly conservative. This is a first step towards a more realistic modelling methodology of the reaction to fire of materials.

1 INTRODUCTION

In order to enhance the energy efficiency of buildings, façades are becoming more sophisticated in both configurations and compositions. However, the amount of combustible materials is much higher than for traditional façades. Therefore, the risk of external fire spread is more important. Among these combustible materials, wood is becoming more and more significant.

The behaviour of woods under fire was extensively studied for decades¹⁻⁶ and several physical parameters were examined, notably ignition temperature or critical heat flux, extinction limits and heat release rate vs heat flux^{2,7-10}. Pyrolysis models with different levels of complexity have been developed to model the fire behaviour of materials such as woods. It is possible to consider simple pyrolysis model, with the decomposition of wood as a single material, releasing fuels (combustible gases) and water vapour, and leading to the formation of a char which can itself decompose; or more complex approaches involve the decomposition of each component of the wood such as lignin and cellulose or even the different type of cellulose^{1,6,11,12}. However, the more complex the approach, the more data is required and the higher the possible source of uncertainties. Nevertheless, fire safety engineering studies are generally performed with simpler models. These models involve the characterisation of a simple criteria such as ignition temperature¹³⁻¹⁵. With regard to the numerical model and software, these simpler models cannot necessarily consider all the physical phenomenon

occurring in fires such as extinction due to the decrease of the surface temperature or the fuel burnout. Similarly, while it is known that materials behave differently depending on the impinging heat flux¹⁶, this behaviour cannot be reproduced at the time, other than using complex models such as pyrolysis models.

This work proposes a numerical methodology and its application to the modelling of tailored-made wooden façade experiments¹⁷. The contribution of the wood is modelled through an engineering model considering both ignition temperature and HRR vs. heat flux data criteria. The approach is reversible to consider self-extinguishment phenomena and allows the fire to dynamically response to the thermal aggression.

The final goal is to be able to accurately model the contribution of combustible materials such as wood with numerical models and the different phenomenon occurring during fires. The validation of the methodology and the sensitivity of the input data have thus to be tested on different configurations including compartment fires and façades fires.

2 NUMERICAL MODEL AND EXPERIMENTAL DATA

2.1 Methodology for the contribution of wood

The numerical simulations are performed with Fire Dynamics Simulator¹⁸ (FDS) version 6.7.0. This methodology is implemented using the basic tools from FDS such as devices, ramps, and controls and can be used from FDS version 5. The code (FDS) developed by the NIST is widely used in the fire safety community.

The methodology to consider the contribution of wood is as follows (see also Table 1):

- Ignition and heat release happen when the local surface temperature gets higher than a critical ignition temperature criteria (T_{ig})^{13,14,19}
- Heat release rate varies with the thermal aggression. The rate of heat release is dependent on the gauge heat flux (gHF) parameter in FDS. The relationships between HRR and gHF are extracted from cone calorimeter experiments
- Extinction occurs if either one of the flowing condition is met:
 - o Surface temperature becomes lower than T_{ig}
 - o Exhaustion of the combustible fuel of the wood. This criterion is dependent on the density of wood, the thickness of the linings, and the rate of heat release that can change over time and thermal aggression.

The results are compared with a more generic approach using the ignition temperature and the heat release rate per unit rea parameters from FDS. The same ignition temperature is used in both approaches. An HRRPUA value of 100 kW/m² is considered for this methodology.

	Ignition	HRRPUA	Extinction
Developed methodology	$T_{wall} > T_{ig}$	=f(gHF)	$T_{wall} < T_{ig}$ or fuel burnout
Generic methodology	$T_{wall} > T_{ig}$	= fixed value	None / imposed by RAMP

Table 1: Schematization of the criteria or the contribution of wood

2.2 Cone calorimeter scale

A numerical model of a cone calorimeter apparatus (see Figure 1) is addressed. The experimental setup is modelled with 5 x 5 x 5 mm³ mesh. A total of 128 000 cells is used in the model. The cone

heater is placed at 25 mm above the surface of the sample. The top of the numerical model is assumed to be the extraction of the hood taken at 24 L/min as in the ISO 5660-1²⁰ standard. The surface temperature of the cone heater is fixed depending on the desired impinging heat flux (see Figure 1) and its emissivity is taken at 1.

Even if simpler models exist, it is assumed that the resolution of the fluid environment around the sample helps to gain confidence and reliability about the thermal response of the sample. The wood surface consisted in 18 mm thick wood (density around 530 kg/m³) with a perfectly insulated backing.

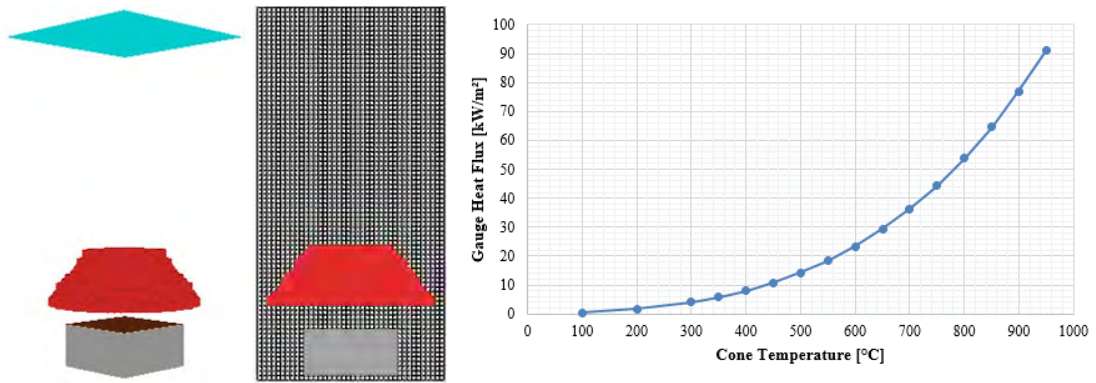


Figure 1: Presentation of the numerical model for cone calorimeter (left) and calibration curve of the heater (right)

The cone test data are extracted from Fateh *et al.*^{21–23}. The ignition and heat release rate behaviour of 18 mm thick M3 Okoumé wood with a similar density as the one used during Dunny’s test¹⁷ were studied. Assuming a heat of combustion of 18.5 MJ/kg¹⁷, the HRRPUA is ranging between 120 kW/m² under 20 kW/m² exposure up to 180 kW/m² at 90 kW/m². The time to ignition (tig) of the wood ranges between 124 s under 20 kW/m² exposure and decreases at 10 s under 50 kW/m² irradiance and between 5 and 2 s under 70 and 90 kW/m² exposure.

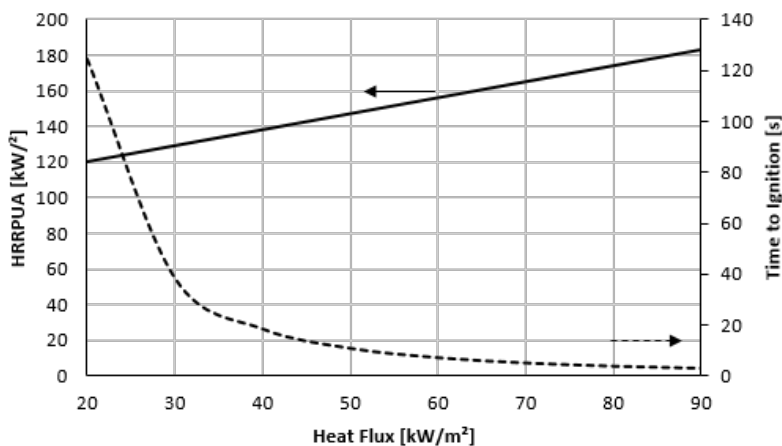


Figure 2: HRRPUA and time to ignition for a 18 mm thick M3 Okoumé plywood^{21–23}

2.3 Façade model

The experimental set-up from Dunny¹⁷ is considered. It consists on a tailored-made façade test where a façade is exposed to the fire from a wood crib. The façade consists in 2.5 x 3.75 m² (width x height) wood linings above the wood crib.

The experimental heat release rate (HRR) is presented in Figure 3. For the calibration (“wood crib only”) performed using insulant as façade and the wood experiment (“wood crib + wooden façade”) both, peaks of HRR values (pHRR) between 240 and 300 s are observed at around 1200 kW and 2000 kW for inert and wooden façades respectively.

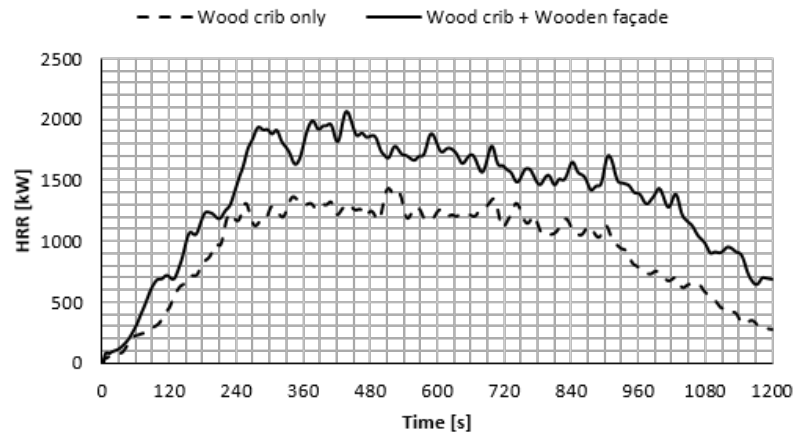


Figure 3: Experimental results with wood crib and M3 Okoumé linings (straight lines) and wood crib contribution (dotted lines)

A numerical model of this façade test is addressed. A $3.8 \times 3.6 \times 7.0 \text{ m}^3$ domain (width x length x height) is meshed using $0.1 \times 0.1 \times 0.05 \text{ m}^3$ grid (width x length x height). A total of 191 520 cells is used. The initial wood crib is modelled using a $0.8 \times 0.8 \times 0.8 \text{ m}^3$ solid obstruction. Based on preliminary sensitivity studies, it was found that the calibration experiments with inert façade were properly modelled when only the upper part (top face and halves of the lateral faces) of the wood crib releases fuels.

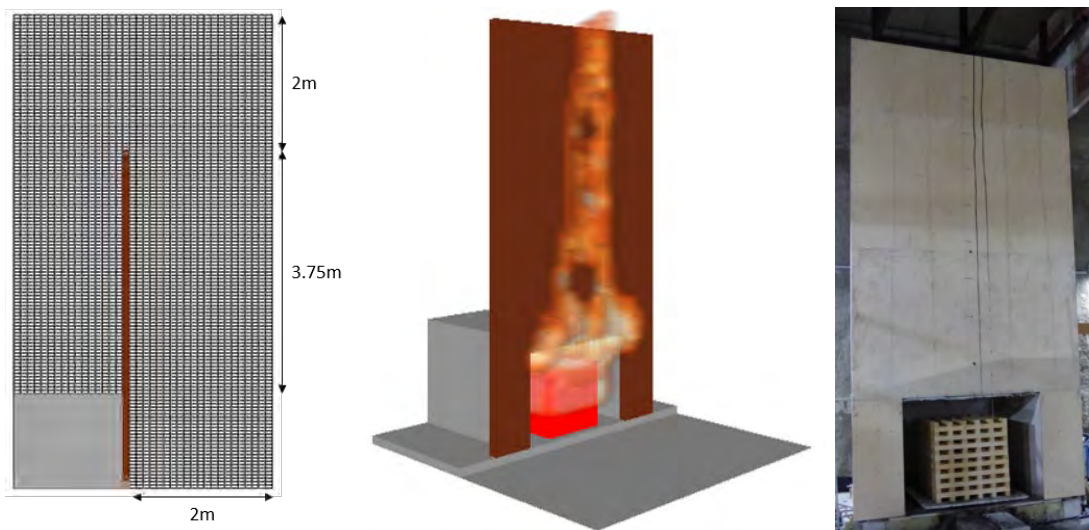


Figure 4: Presentation of the computational domain and the experimental set-up¹⁷: side view with mesh (left), front view (center) and test facility (right)

3 RESULTS AND DISCUSSION

3.1 Validation of the methodology at cone scale

The first parameter needed in the numerical approach to consider the contribution of wood is its ignition temperature. This criteria can be obtained following Janssens' method^{14,15} by plotting the impinging heat flux \dot{q}_e'' as a function of $t_{ig}^{-0.55}$ (see equation 1, with t_{ig} being the time to ignition under \dot{q}_e'' exposure) or can be obtained experimentally as the heat flux at which ignition does not occurs. Once this critical heat flux is known, the ignition temperature (T_{ig}) can be calculated from a heat balance at the surface (see equation 2)

$$\dot{q}_e'' = \dot{q}_{cr}'' \left[1 + 0.73 \left(\frac{k\rho C_p}{h_{ig}^2 t_{ig}} \right)^{0.55} \right] \quad 1$$

$$\varepsilon \dot{q}_{cr}'' = h_c (T_{ig} - T_\infty) + \varepsilon \sigma (T_{ig}^4 - T_\infty^4) \quad 2$$

Based on these equations and the cone calorimeter data extracted from Fateh²¹⁻²³, the ignition temperature of the wood can be estimated. Using a heat transfer coefficient ranging between 8 and 15 W/m/K, an ambient temperature of 20 °C and an emissivity ranging between 0.8 and 1, the ignition temperature T_{ig} can be estimated at 352 ± 32 °C.

Using the thermal properties of wood given in the Eurocode 5, the cone calorimeter experiments are simulated and the numerical times to ignition are compared to the experimental ones. Indeed, as the thermal properties of the studied wood are not known precisely and are difficult to obtain, it is important to validate the approach and the value of the ignition temperature used in the methodology and to gain confidence that the ignitability of the wood is correctly modelled using the thermal properties from the Eurocode 5⁷.

The comparison of the experimental data with the numerical ones is presented in Figure 5. It can be observed that using an ignition temperature of 360 or 380 °C leads to a good prediction of the times to ignition. An ignition temperature of 360 °C is used hereafter as it leads to comparable but conservative times to ignition compared to the experimental results.

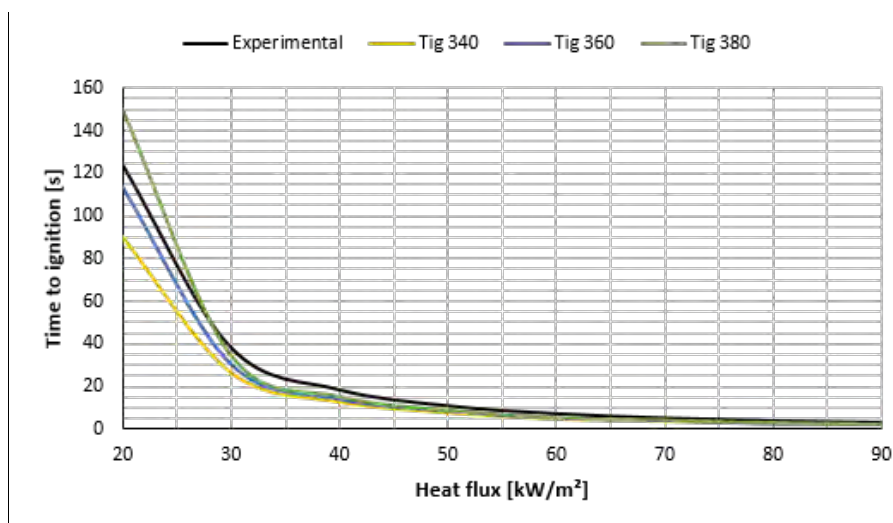


Figure 5: Experimental and numerical times to ignition with ignition temperature of 340/360/380 °C

3.2 Façade modelling

The experimental and predicted heat release rates are presented in Figure 6. Both the classical (“fixed HRRPUA”) and the developed methodology (“variable HRRPUA”) allow modelling correctly the heat release rate. However, after 840 s when the wood crib contribution starts to decrease, it can be observed that only the variable HRRPUA method permits to follow the experimental results. The extinction phase is thus modelled with a better accuracy compared to the classical method. Moreover, using the classical approach, there would be no extinction as the numerical implementation of the ignition temperature is not reversible in FDS at the time.

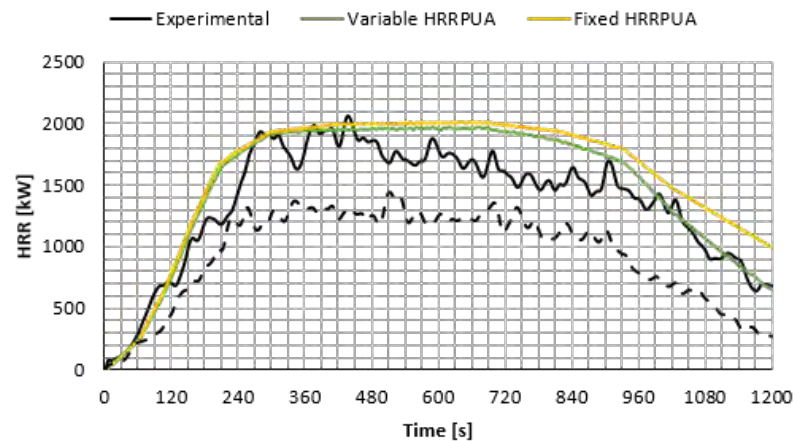


Figure 6: Experimental and numerical results using a generic Tig+fixed HRRPUA or using the Tig+variable HRRPUA (wood crib is the dotted curve)

The experimental results in terms of charring pattern are compared with the numerical observations in Figure 7 using both methodologies. It can be seen that both the variable HRRPUA and the standard methodology over-predict the charring profile. Indeed, the experimental observations show a narrower profile at the top of the façade. Nevertheless, the generic model does not permit to model the increased charring on top of the wood crib compartment. On the opposite, this behaviour is perfectly reproduced by the model using variable HRRPUA.

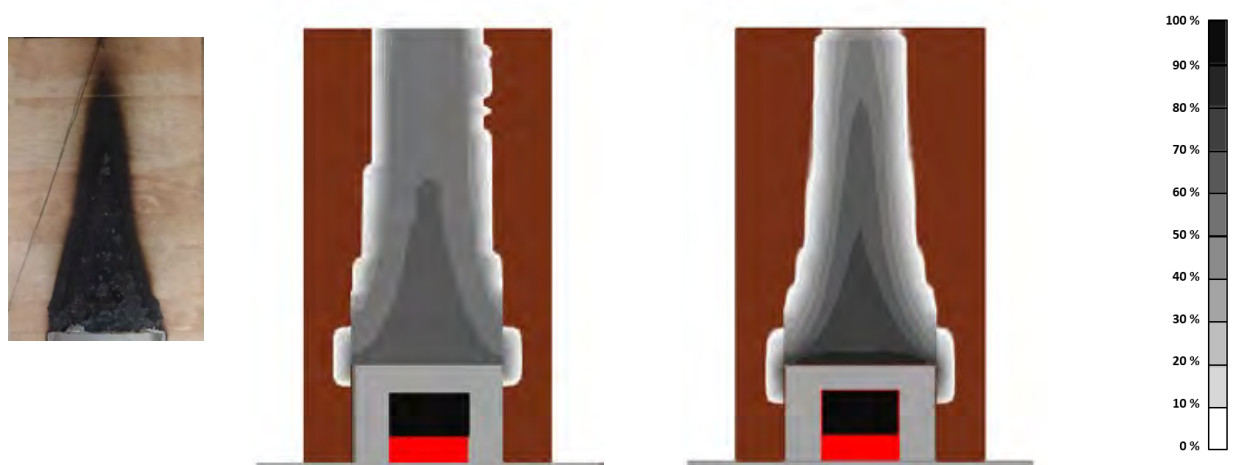


Figure 7: Experimental observations (left) and numerical simulation charring (in %) of the façade using standard Tig+HRRPUA (middle) and Tig+variable HRRPUA (right)

4 CONCLUSIONS

This study presents a methodology for fire safety engineering. The ignition and extinction of wood can be considered due to insufficient thermal aggression, leading to lower surface temperature, or fuel burnout. The heat release rate dynamically responds depending on the thermal aggression. This behaviour is modelled using a simple relation extracted from the analysis of cone calorimeter experiments. It is assumed that this avoids the additional characterization cost necessary for pyrolysis models and limits the uncertainties as a single experimental relation is used compared to several numerical parameters. Indeed, there is no need to characterize Arrhenius parameters or to make assumption about mass transport or decomposition function as the experimental behaviour is directly used as input data. Moreover, cone calorimeter experiments would still have been requested to validate the determined parameters.

Using the generic thermal properties from the Eurocode 5⁷, it is possible to model with confidence the cone results and especially the times to ignition. As the heat release rate and ignitability are validated at this scale, it is thus possible to model more complex tests. The simulation of a tailored-made façade test shows that the methodology seems to allow a better consideration of the wood fire contribution with ignition and self-extinguishment phase, a better reproduction of the charring pattern compared to a classic ignition temperature with fixed heat release rate approach. In both cases, the results are slightly conservative. This is a first step towards a more realistic methodology for the modelling of reaction to fire. Other configurations such as LEPiR 2 for façade fires could be studied as well as compartment fires.

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NUMERICAL INVESTIGATION OF FIRE DEVELOPMENT IN A MEDIUM SCALE ISO9705 COMPARTMENT-FAÇADE CONFIGURATION

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ABSTRACT

This study aims to numerically investigate the fundamental physical phenomena governing fire development and transition to Externally Venting Flames (EVF) of liquid pool fires in compartment façade configurations. Experiments previously performed using a ¼ scale ISO9705 room with an extended façade is simulated using Fire Dynamics Simulator (FDS). The burning rate of the liquid n-hexane pool fire is modelled, and predictions of the compartment's interior thermal fields are compared with the experimental data showing good agreement in all considered test cases. A parametric study is also performed to examine the important physical parameters including the fire load and opening geometry, which govern the transition to EVF and their subsequent development in different phases. This work provides insights into best practice in numerical simulations that can be applied to model façade fires in the frame of performance-based design.

1 INTRODUCTION

Worldwide, development and implementation of performance-based codes are becoming a growing fire safety engineering trend. The utilization of performance-based codes requires the use of advanced fire simulation tools, such as zone or Computational Fluid Dynamics (CFD) models. These tools can provide a wealth of information regarding the detailed characteristics of the flow- and thermal-field developing at the interior and exterior of the fire compartment, characteristics of externally venting flames (EVF) and their thermal impact on the façade. Though numerous investigations have been conducted using CFD-based techniques to simulate fire development in compartment-façade configurations [1-4] there are scarce studies specifically focusing on the development and characterization of the resulting EVF in medium scale configurations and relevant façade fire safety issues [5-7]. Aiming at filling this gap, a numerical methodology has been developed to further investigate EVF development and its effect on the façade.

The effect of ventilation on the EVF development and the façade heat exposure has been assessed using numerical tools and the Eurocode methodology [8]. Both Forced and Natural Draught conditions have been investigated when studying the EVF characteristics in a corridor-compartment-façade configuration exposed to natural fire conditions, based on the large-scale experimental data provided by Klopovic and Turan [9]. Recently, a numerical study has been published [3] focusing on the appropriate use of fire barriers to prevent façade fires. Several different façade construction techniques have been studied with a special emphasis on the use of combustible insulation materials as part of the façade configuration. Numerical simulation results indicated that the use of combustible insulation materials significantly increased fire spreading. Aiming at filling this gap, a numerical methodology has been developed to assess the ability of currently available CFD tools to accurately describe fire development at the interior of an underventilated compartment and its effect on the characteristics of the EVF.

2 EXPERIMENTAL SETUP

2.1 Medium scale compartment-façade configuration

In that frame the Fire Dynamics Simulator (FDS) open source code (Version 6.5.3), has been used to simulate the turbulent, multi-component and reactive flow-field developing at the interior and exterior of a series of compartment-façade configurations. Numerical predictions are compared to the obtained experimental measurements from medium-scale fire tests as presented in detail previous research work of the authors [10]. The compartment was a ¼ scale model of an ISO 9705 compartment, *Fig. 1*. The internal compartment dimensions were 0.60 m x 0.90 m x 0.60 m; the external façade wall measured 0.658 m x 1.8 m. A double layer of 0.0125 m thick fireproof gypsum plasterboards was used as an internal and external lining material. A summary of the main operational parameters of the examined i.e. opening height (H), opening width (W), ventilation parameter ($AH^{1/2}$, with A being the area of the opening), ambient temperature (T_{∞}) and relative humidity (RH_{∞}), total fire duration (t_{dur}), fuel mass (m_f), total heat release (Q_{tot}), average heat release rate (HRR) at the interior of the fire compartment (Q_{ins}) and excess HRR (Q_{ex}) [10], for the examined test cases, is given in *Table 1*.

Table 1. Summary of main operational parameters for the examined test cases

	D-1.00L	D-2.35L	D-4.70L	W-2.35L	D-demo
H (m)	0.5	0.5	0.5	0.3	0.5
W (m)	0.2	0.2	0.2	0.2	0.2
$AH^{1/2}$ ($m^{5/2}$)	0.044721	0.044721	0.044721	0.026833	0.044721
T_{∞} ($^{\circ}C$)	25.8	26.7	26.5	26.4	20
RH_{∞} (%)	42.0	42.0	47.0	36.0	40
t_{dur} (s)	372	525	595	659	120
m_f (kg)	0.655	1.539	6.078	1.539	-
Q_{tot} (kW)	79.0	132.0	233.0	105.0	200.0
Q_{ins} (kW)	-	106.5	106.5	49.35	62.3 for 15mm grid
Q_{ex} (kW)	-	25.5	126.5	55.65	137.7 for 15mm grid

2.2 Measurement equipment

The overall thermal behaviour of the compartment-façade configuration was investigated by measuring temperatures and heat fluxes at various locations. More specifically, 10 K-type 1.5 mm diameter thermocouples, located at the front (CF) and rear (CB) corner of the compartment and 4 thermocouples vertically distributed at the centerline of the opening were used to determine the thermal field developing at the interior of the compartment.

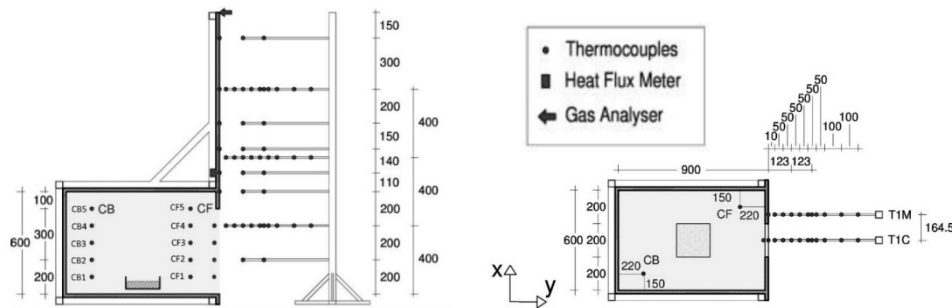


Fig. 1. Schematic drawing of the medium scale compartment façade ISO 9705 apparatus and sensor locations.

Emphasis was given to the characterization of the thermal environment adjacent to the façade wall along the height of the fire plume both in the centreline and off-axis positions 164.5 mm away from the centreline. Towards this end, 14 thermocouples were placed in various locations across the façade

wall, whereas 27 additional thermocouples were distributed among two thermocouple trees as depicted in *Fig. 1*. All thermocouples measurements were recorded using a Universal Data Logging Interface designed in LabView software; the sampling frequency was 1 s [10]. The recorded thermocouple data, obtained at the interior of the compartment, were corrected for radiation using a “post-processing” methodology [10].

3 NUMERICAL SETUP

3.1 Simulation details: effect of grid size

A detailed review on grid resolution quality criteria enabled to perform a grid sensitivity study to compromise between model accuracy and computer capacity. Input data, assumed or based on experimental data, may introduce additional uncertainty into the model. Appropriate choice of the model geometry, resolution of the computational grid and boundary condition is essential and may define the analysis outcome. In order to treat these uncertainties, a grid sensitivity analysis was conducted for a demo case of the ¼ scale ISO 9705 geometry with a 0.2 m by 0.5 m opening with a prescribed constant HRR_{pre} of 200 kW. Eight different orthogonal meshes were used (7.5 mm, 10 mm, 15 mm, 20 mm, 25 mm, 30 mm, 35 mm and 40 mm cell sizes) and predictions of the temperature at positions CB and CF at the interior of the compartment are presented in *Fig. 2*. Predictions of the velocity profile in the opening are also presented.

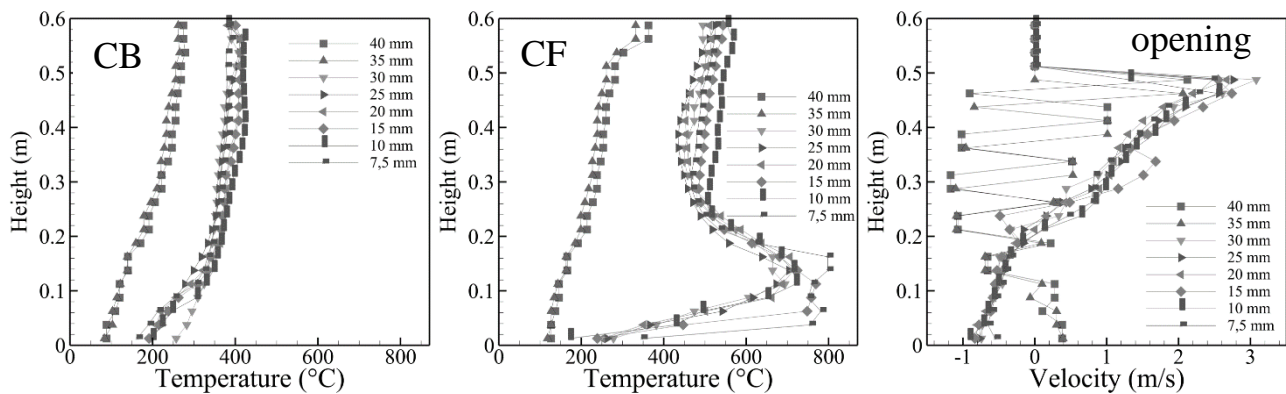


Fig. 2. Grid sensitivity results throughout comparison of gas temperature at the interior of the fire compartment at position CB (left), CF (middle) and velocity distribution at the opening (right) for test case D-demo.

The selected 15 mm cell size numerical grid is used in the control volume containing the fire room and the attached façade and the total number of computational cells is 388,800. In the general context of compartment fire simulations, the quality of the utilized grid resolution is commonly assessed using the non-dimensional $D^*/\delta x$ ratio, where D^* is a characteristic fire diameter and δx corresponds to the nominal size of the grid cell. The $D^*/\delta x$ ratio corresponds to the number of computational cells spanning D^* and is representative of the adequacy of the grid resolution. If the value of the $D^*/\delta x$ ratio is sufficiently large, the fire can be considered well resolved. Several studies have shown that values of 10 or more are required to adequately resolve most fires and obtain reliable flame temperatures [11]. The 15 mm cell size mesh fulfils the $D^*/\delta x \geq 10$ criterion. At the beginning of the numerical simulation, the entire computational domain is assumed to be still (zero velocity), exhibiting a temperature of 20°C and the relative humidity is set at 40%. The “Very Large Eddy Simulation” mode of FDS has been used for the simulation cases. The time step is dynamically adjusted in order to satisfy the Courant-Friedrich-Levy (CFL) criterion [12]. The CFL condition asserts that the solution of the equations cannot be updated with a time step larger than that allowing a parcel of fluids to cross a grid cell according to *Eq. 1*. The exact CFL value needed to maintain stability depends on the order of the time integration scheme and the choice of the velocity norm [13].

The velocity norm value is set to unity, corresponding to the more restrictive L_1 norm for the velocity vector as depicted in Eq. 2, where δt is the time step and $\frac{\|\mathbf{u}\|}{\Delta}$ the velocity norm.

$$\text{CFL} = \delta t \frac{\|\mathbf{u}\|}{\Delta} < 1 \quad (1)$$

$$\frac{\|\mathbf{u}\|}{\Delta} = \frac{|u|}{\delta x} + \frac{|v|}{\delta y} + \frac{|w|}{\delta z} + |\nabla \cdot \mathbf{u}| \quad (2)$$

The total simulation time is selected to be equal to the respective duration of each test case. Open boundaries are imposed at all boundaries external to the enclosure, with background species of ambient air and wall boundary conditions are used at walls, ceiling and floor. For the RTE, 104 control angles are used whereas time and angle increment are valued 3 and 5 respectively. Concerning the radiation solver for RADCAL calculations, it is assumed that the n-Heptane gas is used as surrogate to n-Hexane gas behaving as a grey medium with 0.125 m pathlength. In order to simulate the “realistic” fire condition of each test case, a variable mass loss rate according to available experimental data of fuel consumption rate has been used as the fire source by using mass-flux boundary condition. The soot yield, which represents the fraction of n-hexane fuel mass converted to smoke particulates, is set equal to 3.5% and the corresponding CO yield was set equal to 0.1 % [14]. Simulations are conducted using up to 500 CPU hours with a 3GHz processor.

3.2 Simulation details: effect of volume extension

The numerical grid extends to the outside of the enclosure, in order to effectively simulate air entrainment phenomena through the openings and burning outside the compartment. The size of the physical domain extending at the exterior of the fire compartment, is an important parameter that may influence the EVF development [15] and the temporal evolution at the interior of the compartment [16]. Six different cases have been investigated, by varying the external volume extension (ΔL); cases of ΔL values of 25 mm, 300 mm 500 mm and 700 mm are depicted in Fig. 3 respectively.

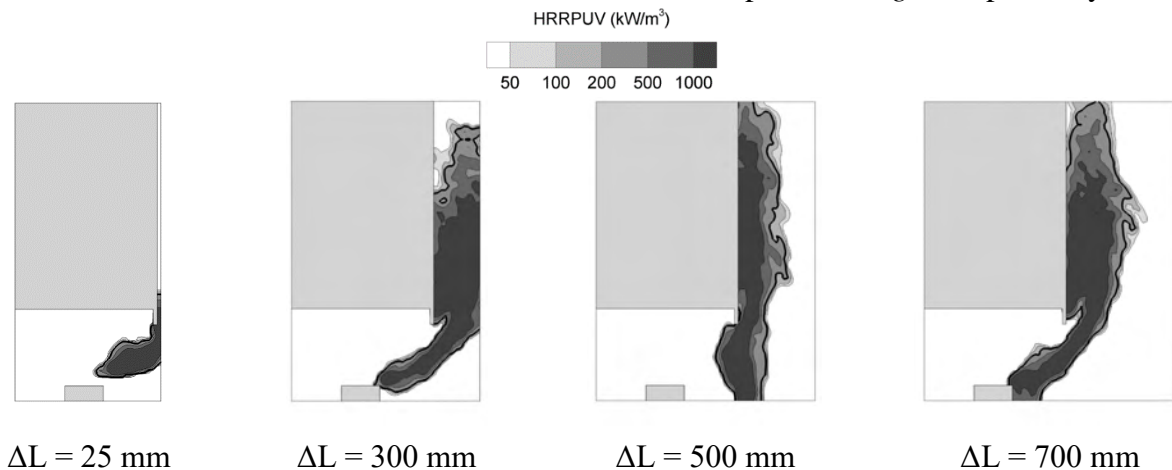


Fig. 3. Predictions of the EVF envelope 94.8 s after fire initiation for test case D-demo with ΔL valued 25 mm, 300 mm, 500 mm and 700 mm.

The flames presence represented using the heat release rate per unit volume (HRRPUV) are displayed in Figure 3. A HRRPUV cutoff value of 200 kW/ m³ (default value used by FDS to show flames) is also represented as a bold contour in the same figure. Relevant predictions of the gas temperature at different heights at the interior of the fire compartment in positions CB and CF are depicted in Fig. 4. Numerical results indicate that an external volume extension (ΔL) of 100 mm can be used to achieve “convergence”. Based on those numerical results, a 100 mm grid extension has been applied

in the x- and 30 mm in the z-direction respectively for test cases D-1.00L, D-2.35L, D-4.70L and W-2.35L respectively.

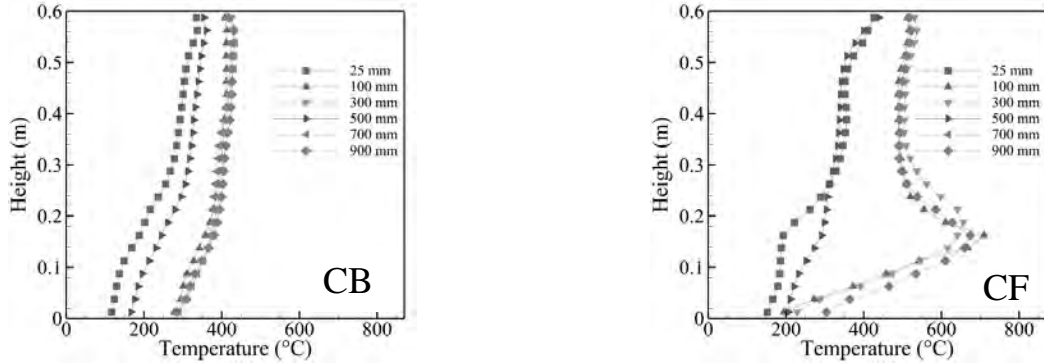


Fig. 4. Effect of the extension volume on the gas temperature at the interior of the fire compartment at position CB (left) and CF (right) for test case D-demo.

4 RESULTS AND DISCUSSION

4.1 Thermal field at the interior of the fire compartment

The temporal evolution of the gas temperatures at the interior of the compartment for every test case are presented in Figs. 5 and 6 respectively at heights from the ground: 0.1 m (CB1 and CF1), 0.3 m (CB3 and CF3) and 0.5 m (CB5 and CF5). Experimental measurements (Exp.) are compared to CFD predictions (FDS).

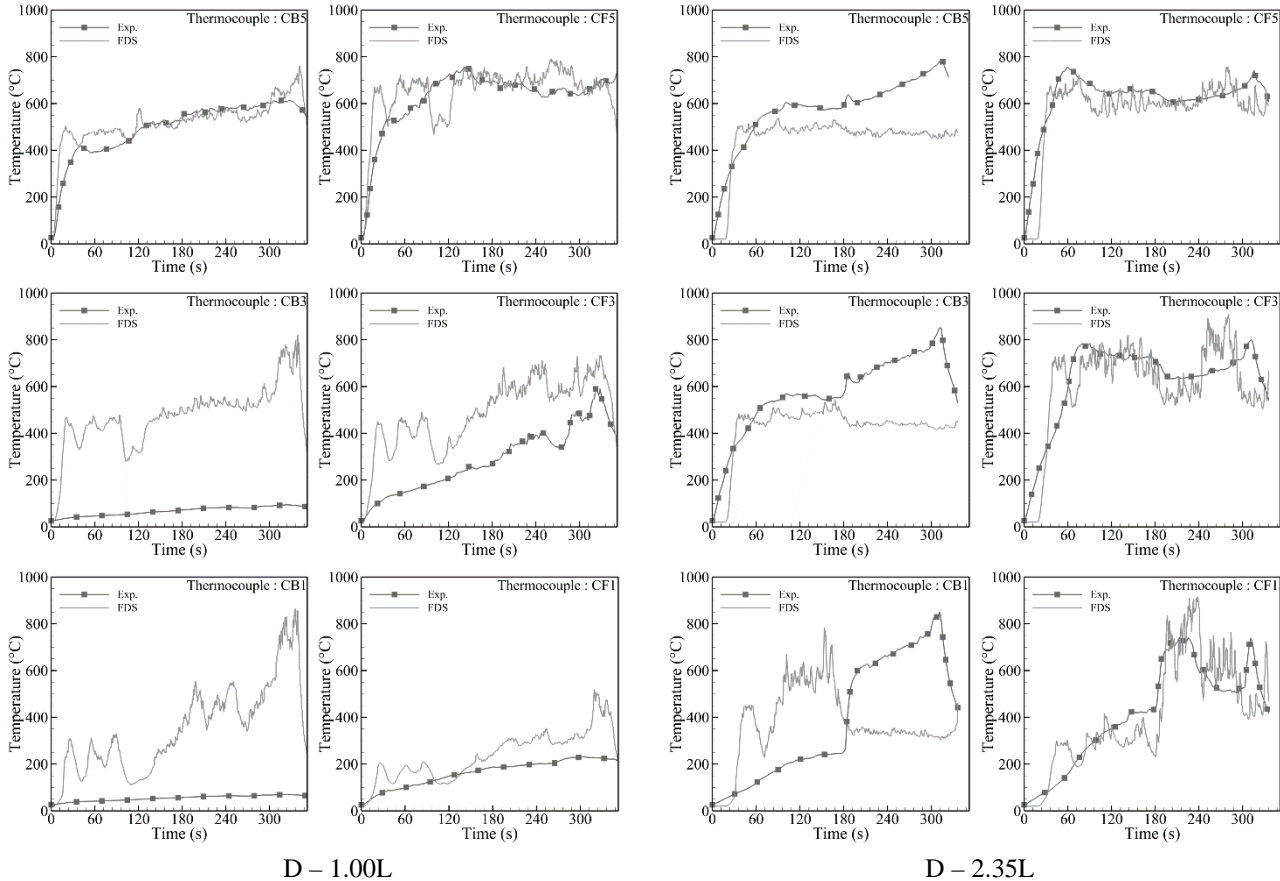


Fig. 5. Temporal evolution of gas temperature at heights 0.1 m, 0.3 m and 0.5m from the ground for D-1.00L (left) and D-2.35L (right).

Generally, predictions of the gas temperature at the interior of the fire compartment show good levels of qualitative agreement with measured values. In test case D-1.00L, numerical results over-predict the gas temperature, particularly in the lower part and in the rear corner of the compartment. whereas in test cases D-2.35L, D-4.70L and W-2.35L, FDS tends to slightly under-predict the measured values. In *Fig. 6*, it can be seen for the case D – 4.70L that the two peaks observed experimentally at approximately 3 min and 8 min seems to be reproduced numerically with a time lag. This behaviour may be attributed to the difficulty of the FDS code to accurately predict the presence of combustion regions in the interior of the fire compartment in under-ventilated conditions [9] due to oxygen depletion, pertaining to the examined test cases. Combustion model in FDS assumes that fuel and oxygen burn instantaneously when mixed. This assumption may not be appropriate for incomplete combustion that commonly characterizes under-ventilated compartment fires.

4.2 EVF ejection and fire phases

As observed in all test cases, initially combustion is constrained in the interior of the fire compartment “internal flaming”, IF phase, and in the vicinity of the fuel pan an advection stream is created. Gradually, the flame front moves away from the fuel pan, expanding radially and horizontally towards the opening. In that phase, external flame jets and quick flashes appear at the exterior of the fire compartment, signifying the beginning of the “intermittent flame ejection”, IFE stage.

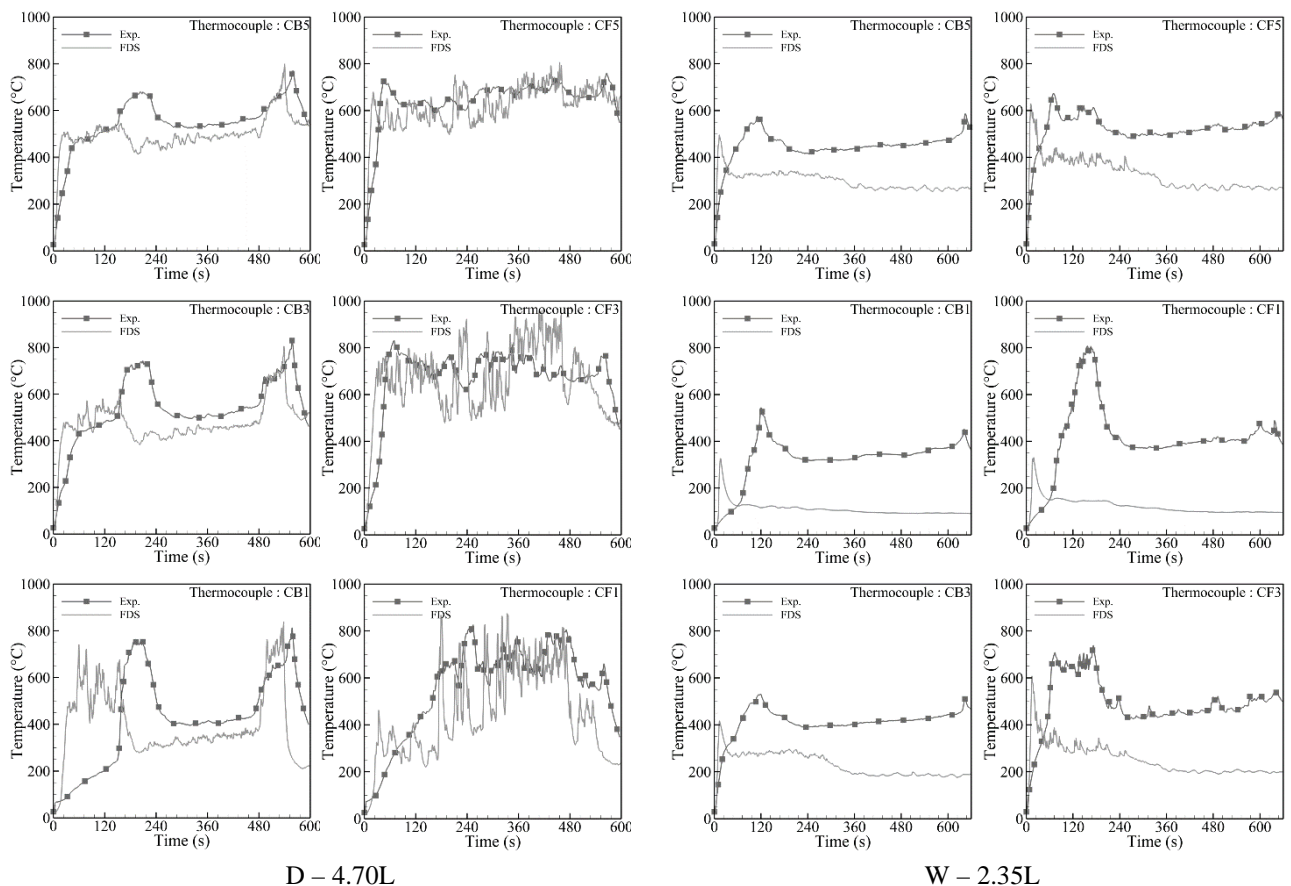


Fig. 6. Temporal evolution of gas temperature at heights 0.1 m, 0.3 m and 0.5m from the ground for D-4.70L (left) and

As time passes, “consistent external flaming”, CEF phase, is observed due to the sustained external combustion of unburnt volatiles, during the quasi-steady phase of fully developed fire [9, 10]. Various parameters affect the development and duration of these phases in rectangular fire compartments, e.g. the effect of size of the opening [17] and the fuel type [18]. In order to further investigate the

occurrence of each phase in relation to Q_{ins} , D-demo geometry has been used to simulate various test cases by applying a prescribed constant HRR_{pre} at the burner ranging from 30 kW to 330 kW. Relevant Q_{ins} values in relation to HRR_{pre} and the maximum HRR inside the enclosure according to Kawagoe correlation [17] is also plotted for comparison. IF phase is observed for up to 50kW, as Q_{ins} equals HRR_{pre} ; an illustration is depicted in Fig. 8. From 60 kW to 140 kW a nearly constant value of Q_{ins} is observed and both IF and IFE phases are observed. During the IFE phase, between 170 and 190 kW, flames are located in the area between the burner and the opening. A new level of Q_{ins} is reached when HRR_{pre} values are greater than 200 kW and CEF phase is observed with oscillating EVF behaviour. When HRR_{pre} values are greater than 250 kW EVF behaviour is highly unpredictable and depends on numerical parameters. A correlation has been derived for Q_{ins} in relation to HRR_{pre} and ventilation parameter $AH^{1/2}$, as depicted in Eq. 3.

$$Q_{ins} = 925 A\sqrt{H} \quad (3)$$

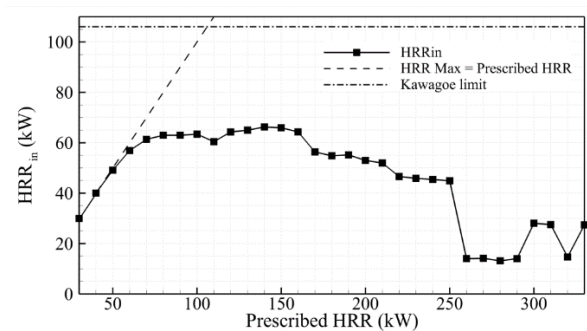


Fig. 7. Q_{ins} in relation to HRR_{pre} .

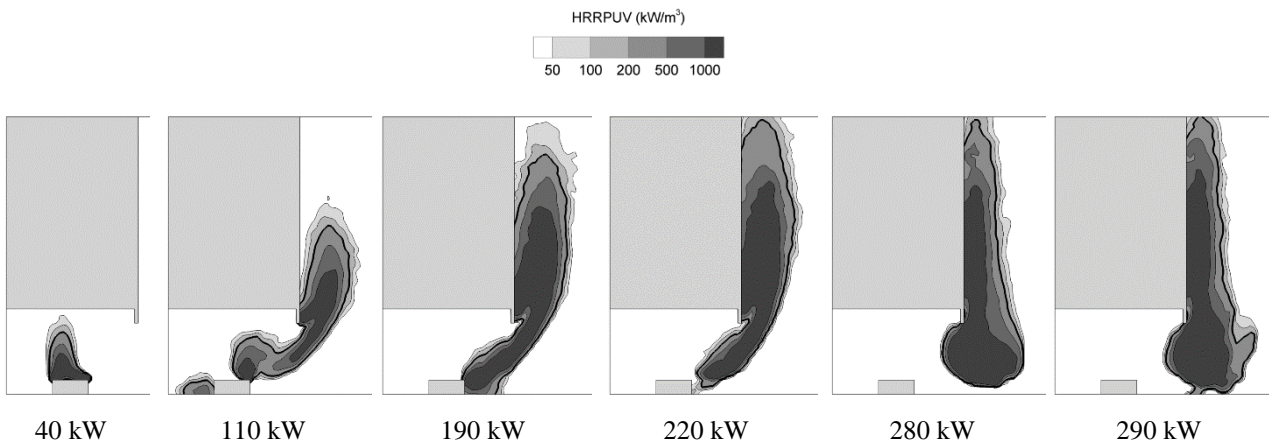


Fig. 8. Illustration of fire phases for different prescribed HRR_{pre} .

5 CONCLUSIONS

The dynamic nature of EVF requires the use of advanced modelling methodologies, capable of describing the relevant physical phenomena. The commonly used prescriptive methodologies are based on a phenomenological approach that exhibits certain limitations, especially when unusual structures are considered. CFD tools may provide significant assistance to the fire safety engineering analysis of EVF, by offering the opportunity to obtain an in-depth view of the spatial and temporal distribution of important physical parameters such as velocity, gas temperatures, wall temperatures, heat fluxes etc. In the current work, a series of medium scale compartment-façade fire tests were analysed numerically, aiming to investigate the effect of ventilation conditions in EVF development

and fire phases. The obtained predictions are compared to available experimental data; good qualitative and, in certain cases, quantitative agreement is observed.

ACKNOWLEDGMENT

This study has been financially supported by the “Fire-Facts” project in the frame of the ARISTEIA action (operational program "Education and Lifelong Learning") that is co-financed by Greece and the E.U. and by the E.C. in the frame of two FP7 projects and "ELISSA: Energy Efficient Lightweight-Sustainable-Safe-Steel Construction" (EeB.NMP.2013-1, Grant No. 609086).

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EXPERIMENTAL AND NUMERICAL INVESTIGATION OF EXTERNALLY VENTING FLAME DEVELOPING IN A CORRIDOR-FAÇADE CONFIGURATION

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ABSTRACT

This work aims to investigate the fire development of a liquid pool in a corridor and externally venting flames (EVF) aiming to contribute to fundamental fire research towards ensuring fire safety of high-rise buildings. This study aims at experimentally and numerically investigate, with the use of FDS, EVF development in corridor-like geometries to identify the key factors influencing their characteristics and impact on the façade. A parametric study has also been performed to investigate the effects of ventilation and fuel distribution. Numerical results of gas temperatures, flame heights and heat fluxes for the interior and exterior of the configuration were compared to experimental data. In the corridor interior, good qualitative and occasionally quantitative agreement is observed for the gas temperatures. The performance of FDS in predicting EVF gas temperatures and heat flux to the adjacent façade is improved for larger opening sizes. Regarding heat flux at the façade, good quantitative agreement is observed, especially at lower heights.

1 INTRODUCTION

The study and understanding of the physics in enclosure fires is of considerable importance to the fire safety engineering community, however most of the available data concern cubic-like enclosures [1, 2, 3]. Even though it has been demonstrated that the geometry of an enclosure affects fire development [4, 5, 6], experimental and theoretical aspects of corridor-like enclosures has not been systematically studied. Most of the studies in enclosure fires are related to under-ventilated conditions, as this region is the worst scenario for enclosure fires usually corresponding to cases where the mass of the pyrolyzed fuel is not completely burned inside the enclosure due to restrictions on the oxygen availability.

Currently, there are no specific methodologies to evaluate risks associated with EVF in “performance-based” fire safety codes and only few numerical simulation studies have been carried out on the burning characteristics of EVF in corridors and relevant façade fire safety issues. To close this knowledge gap, this study is aimed at investigating numerically the burning behaviour of liquid fuel pool fires in corridor-like geometries in order to identify the key factors influencing EVF characteristics and their impact on the façade. The large-eddy-simulation (LES) based CFD code, Fire Dynamics Simulator (FDS) version 6.7.0 was used and the simulation results are compared and validated against experimental data obtained by the authors’ group [4]. The FDS predictive accuracy of the upper layer gas temperatures in enclosures [9-11] is found to be limited, the main drawback

being the insufficient representation of the combustion inefficiencies during under-ventilated fires [9, 11]. Despite the above-mentioned limitations, FDS may adequately be used for a qualitative assessment of the parameters that may influence the medium-scale enclosure fire development [12, 13, 14]. A wealth of information regarding the detailed characteristics of the flow- and thermal-field developing inside or outside the compartment can be provided and as a result, the thermal impact of EVF on the façade elements can be thoroughly assessed. A parametric study has also been performed to further investigate the effects of ventilation and location of the burner.

2 EXPERIMENTAL AND NUMERICAL SETUP

2.1 Experimental facility

Figure 1 shows a schematic view of the experimental set-up along with the experimental measurement locations, consisting of temperatures inside the corridor, heat fluxes on the floor of the corridor enclosure and on the façade, heat release rate, mass loss rate and flame height of the EVF [7], which was closely reproduced in the numerical setup. The effect of ventilation was investigated by altering the dimensions of the opening. Four different door-like openings were used, with their dimensions shown in Table 1, and two different load cell positions were investigated. A summary of the main operational parameters i.e. burner position, opening height (H_o), opening width (W_o), total fire duration (t_{dur}), total heat release rate (HRR) experimentally measured in the hood (\dot{Q}_{exp}), theoretical HRR (\dot{Q}_{th}) and ventilation regime (Under or Over ventilated, indicated as U or O respectively). \dot{Q}_{th} , is calculated by multiplying the measured fuel mass loss rate by the heat of combustion of ethanol, 26.78 MJ/kg [15]. The maximum HRR in stoichiometric conditions inside an enclosure, $1500A_oH_o^{1/2}$, is calculated [15].

Table 1. Summary of main operational parameters for the examined test cases.

Test cases	Burner position	$W_o \times H_o$ [m ²]	$1500A_oH_o^{1/2}$ [kW]	Q_{exp} [kW]	Q_{th} [kW]
FR30W25H25	BOX A	0.25 x 0.25	46.5	31.0	42.7
FR30W30H30		0.30 x 0.30	73.5	56.1	75.3
FR30W50H25		0.50 x 0.25	93.8	75.1	102.0
FR30W50H50		0.50 x 0.50	265.1	69.5	91.1
BC30W25H25	BOX F	0.25 x 0.25	46.9	39.5	64.5
BC30W30H30		0.30 x 0.30	73.9	70.0	110.6
BC30W50H25		0.50 x 0.25	93.8	77.0	120.5
BC30W50H50		0.50 x 0.50	265.1	105	150.0

2.2 Numerical Setup

In the general context of compartment fire simulations, the quality of the utilized grid resolution is commonly assessed using the non-dimensional $D^*/\delta x$ ratio, where D^* is a characteristic fire diameter and δx corresponds to the nominal size of the grid cell. The $D^*/\delta x$ ratio corresponds to the number of computational cells spanning D^* and is representative of the adequacy of the grid resolution. If the value of the $D^*/\delta x$ ratio is sufficiently large, the fire can be considered well resolved. Several studies have shown that values of 10 or more are required to adequately resolve most fires and obtain reliable flame temperatures [8,16]. In the current study, aiming to fulfil the $D^*/\delta x \geq 10$ criterion and, at the same time, reduce the required computational cost, a 0.02 m cell size was selected ($D^*/\delta x=10$). The numerical grid extends to the outside of the enclosure, in order to effectively simulate air entrainment phenomena through the opening and burning outside the compartment. The size of the physical domain “extensions”, 1.0 m in the x- and 1.5 m in the z-direction, have been selected following findings in a relevant study on the effect of computational domain size on numerical simulation of

compartment fire [17]. The outer dimensions of the simulation domain are depicted in Fig. 1 and the computational grid consists of 375,000 cubic cells.

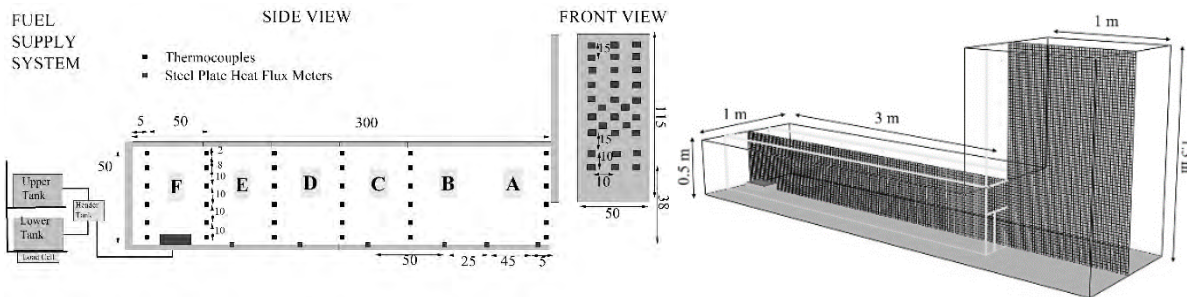


Fig. 1. Schematic of the experimental facility (left) and numerical setup (right).

The measured heat release rate was used as an input to the FDS simulations. All walls, including the facade wall, consist of fibreboard with the following properties: 0.02 m thickness, 300 kg/m³ density, 0.9 emissivity. The soot yield, which represents the fraction of ethanol fuel mass converted to smoke particulates, is set equal to 0.8 % and the corresponding CO yield was set equal to 0.1 %, according to available measurements for ethanol [15]. The entire computational domain (both indoors and outdoors) is assumed to be initially still (zero velocity), exhibiting a temperature of 20°C. Concerning turbulence modelling, both turbulent Sc and Pr values were chosen to be equal to 0.5. There is no rigorous justification for these choices other than through direct comparison with experimental data for strong buoyant flows originating from enclosure fires occurring inside compartments [9]. For the radiative transport equation, 104 control angles are used, whereas time and angle increments are valued 3 and 5 respectively. Concerning the radiation solver, it is assumed that the gas behaves as a grey medium with a 0.125 m path-length L for RADCAL calculations. The total simulation time is selected to be equal to the respective duration of each test case, c.f. Table 1. Open boundaries are imposed at all boundaries external to the enclosure and wall boundary conditions are used at walls, ceiling and floor. Numerical results of the temporal evolution of gas temperatures, flame heights and heat fluxes for the interior and the exterior of the configuration were compared to available experimental data [4].

2.3 Effect of pan position

To that respect, Figs. 2 presents the spatial distribution of the instantaneous gas temperature inside the corridor for one characteristic test case where the burner is located at the back of the corridor respectively. Experimental work by the author's group in fire and burning behaviour in corridor-like enclosures using liquid pool fires, revealed that for most cases three distinct burning regions (*Region I*, *Region II* and *Region III*) have been observed. *Region I* corresponds to the fuel-controlled period (growth period), where the combustion efficiency (the ratio between \dot{Q}_{act} and \dot{Q}_{th}) is close to unity and thus \dot{Q}_{act} and \dot{Q}_{th} are almost equal. After this phase, during *Region II*, the fire gradually becomes ventilation-controlled and \dot{Q}_{exp} reaches a plateau until the flames eject through the opening. This *Region II*, for which the proposed relations apply, corresponds to underventilated conditions with the unburned fuel not yet to burn at the exterior of the corridor. Note that \dot{Q}_{exp} inside the enclosure does not reach the maximum value, estimated as $1500A_oH_o^{1/2}$, that has been found for rectangular compartments [7]. This value is decreased, calculated to be approximately $1100A_oH_o^{1/2}$, indicating that the amount of air inflow in long corridors is less than in rectangular enclosures with the same opening geometry [8]. Flames ejection, as observed visually and through the image processing algorithm, is associated with a sudden increase in the \dot{Q}_{exp} , indicating the beginning of *Region III*, where sustained external burning is observed until a plateau is formed near the end of the test indicating that steady state conditions are established. For the cases when ventilation-controlled conditions are achieved, the normalized steady

state mass burning rate is found to increase linearly with the normalized ventilation factor which is consistent with previous findings with cubic-like enclosures. The effect of opening size on the air flow rate into the corridor was also examined, and the ventilation coefficient, C , for corridor-like enclosures during post-flashover conditions was found to decrease with an increase of the ventilation factor. The location and size of the fuel pan was also found to have a strong impact on HRR and subsequent EVF characteristics [6].

During *Region I*, corresponding to 120 s from fire initiation, low gas temperatures are observed in the lower layer as fresh air enters the enclosure through the opening, located at the far-right side of the corridor. In both cases FDS accurately predicts the spatial distribution and the entrainment of fresh air to the corridor. In test case BC30W30H30, during *Region II*, where 400 s was chosen as an indicative time instance, the highest temperatures are observed at the vicinity of Boxes E and D indicating that combustion mainly takes place at these locations and flames gradually propagate towards the opening seeking available oxygen [18, 19]. FDS results, though able to depict the gas temperature vertical stratification, do not accurately reproduce the combustion zone; for instance, as in the numerical simulation of the BC30H30W30 test case the fire plume is mainly located at the back of the corridor, at Box F, near the vicinity of the burner. This results in higher temperatures developed and stronger recirculation zone formed.

During *Region III*, the difference of gas temperatures between the upper and lower layers decreases towards the closed end (far left) of the corridor, but still, they cannot be assumed uniform inside the corridor. In *Region III*, at 900 s, flames fill the upper layer of the corridor extending towards the opening and eventually emerge from the opening when the HRR becomes sufficiently large. FDS captures well the phenomenon that the flame detaches from the burner after external burning was observed as depicted in the FDS spatial temperature distribution, though higher temperature levels can be observed. Overall, predictions of gas temperature at the interior of the corridor show good levels of qualitative agreement with the measured values; FDS accurately predicts the presence of the fire plume at the vicinity of Box A, resulting in the emergence of EVF at the exterior of the corridor.

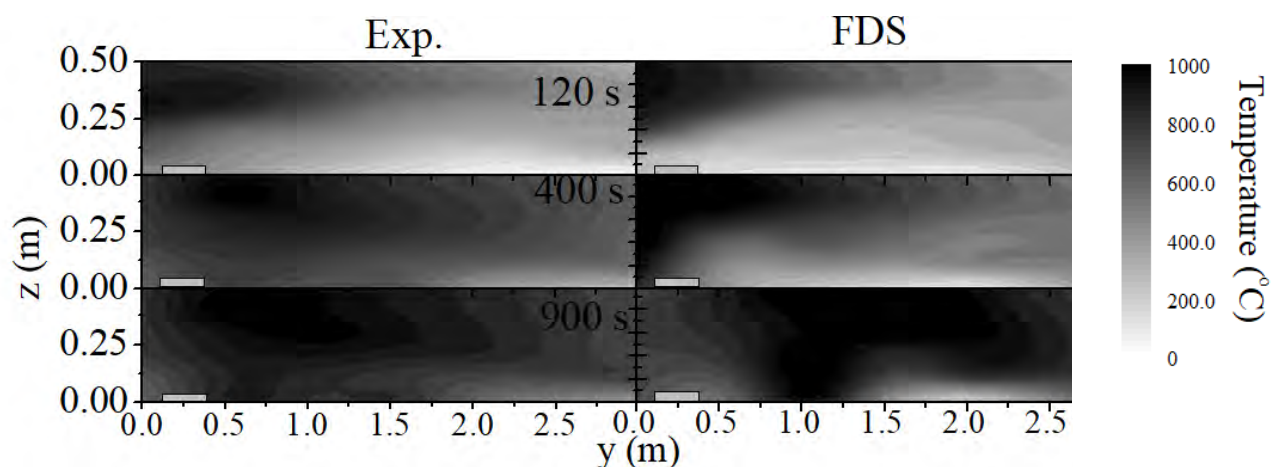


Fig. 2. Spatial distribution of the gaseous temperature at the corridor interior (BC30W30H30).

The temporal evolution of the heat fluxes at the floor level of Box D and on the façade centreline at 38 cm above the ground, are illustrated in Fig. 3. In the BC30W30H30 test case, most of the combustion occurs inside the corridor, resulting in much higher heat fluxes on the corridor floor. Though FDS accurately predicts the heat flux evolution at the ground floor of the corridor, especially during *Region III*, it considerably under-predicts the heat flux on the façade centreline due to the under-prediction of the external burning. In the FR30W30H30 test case, where the fuel pan is located

close to the opening and EVF almost instantly eject through the opening, exposing the façade to significantly increased heat flux values, FDS qualitatively indicate the EVF emergence and subsequent façade heat exposure.

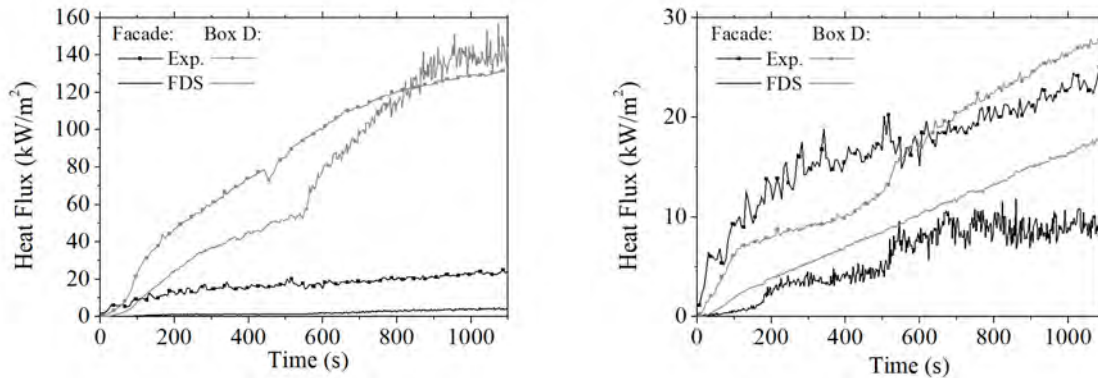


Fig. 3. Predictions and measurements of the temporal evolution heat fluxes for test cases BC30W30H30 (left) and FR30W30H30 (right).

2.4 Effect of ventilation factor

Fig. 5 illustrates the temporal evolution of the measured and predicted upper layer gas temperatures at a height of 48 cm in Boxes A, C and E for all test cases. In order to quantify the predictive capability of the numerical model and to facilitate comparison between those time dependent quantities, the metrics ε_1 and ε_2 , as defined and used for fire simulations by Audouin et al. [20] and the ASTM E1355-97 [21] standard guide, are calculated according to Eq. (1), where x and y represent experimental and numerical values. Results of the respective functional analysis used to compare the time-dependent values for the upper layer temperatures for Boxes A and E are presented in Table 2. The lowest values for the projection coefficient ε_1 and respectively the highest for the inner product cosine ε_2 are highlighted respectively to assist the interpretation of the results.

$$\varepsilon_1 = \frac{\|\bar{y} - \bar{x}\|}{\|\bar{x}\|} = \sqrt{\frac{\sum_{i=1}^n (y_i - x_i)^2}{\sum_{i=1}^n (x_i)^2}}, \quad \varepsilon_2 = \cos(\bar{x}, \bar{y}) = \frac{\langle \bar{x}, \bar{y} \rangle}{\|\bar{x}\| \|\bar{y}\|} = \frac{\sum_{i=1}^n x_i y_i}{\sqrt{\sum_{i=1}^n (x_i)^2 \sum_{i=1}^n (y_i)^2}} \quad (1)$$

Generally, predictions of the gas temperature at the interior of the corridor show good levels of qualitative agreement with measured values. In more details, it was found that gas temperatures at the interior of the corridor when the burner was located at the back of the corridor exhibited significantly higher temperatures, as is also depicted in the spatial temperature distribution presented in Fig. 5. In under-ventilated cases with low ventilation factors (e.g. BC30W25H25), FDS under-predicts the experimental values at the vicinity of the burner and the fire plume location is not accurately predicted. Higher ventilation factors result in more accurate predictions both in the front and the rear of the corridor and trends are accurately captured. EVF are predicted to eject through the opening consistently but temperature profiles at *Region III* do not remain constant for test cases BC30W30H30, BC30W50H25 and FR30W50H25. In FDS simulations, the flame plume moves towards the opening more intensively compared to the experiments, thus resulting in under-prediction of temperatures at the back of the corridor and over-prediction at the vicinity of the opening at Box A. When the burner was positioned near the opening in over-ventilated cases (e.g. FR30W25H25 and FR30W50H50), gas temperatures at the interior are substantially under predicted, c.f. Table 2. Numerical simulation results are further used to provide additional information regarding the flow

field developed at the interior of the corridor and the exterior in the vicinity of the facade. Predictions of the gas phase velocity along with the resulting fire plume and resulting EVF envelope at 900 s after fire initiation in Region III, are depicted in Fig.4.

Table 2. Errors ε_1 and ε_2 for Boxes A and E for all simulated test cases.

Test cases	Box A		Box E	
	ε_1	ε_2	ε_1	ε_2
FR30W25H25	0.47	0.988	0.35	0.995
FR30W30H30	0.12	0.992	0.44	0.998
FR30W50H25	0.33	0.971	0.20	0.992
FR30W50H50	0.24	0.957	0.08	0.965
BC30W25H25	0.33	0.998	0.32	0.992
BC30W30H30	0.42	0.936	0.78	0.937

In FDS there is a limit on the amount of volumetric HRR released in each grid cell. By default, an empirical value of 200 kW/m^3 is used as a limit based on the grid size which is also used in the current analysis of the numerical simulations. The effect of burner position on the predicted fire plume shape and velocity field is evident. In under-ventilated test cases, FR30W30H30, FR30W50H25 and BC30W25H25, BC30W50H25, BC30W50H50, significant portion of combustion takes place at the exterior of the corridor. This is due to the inadequate mass air flow rate that cannot sustain complete combustion, thus resulting in unburnt gaseous fuel and smoke exiting the corridor which leads to a more intensified EVF.

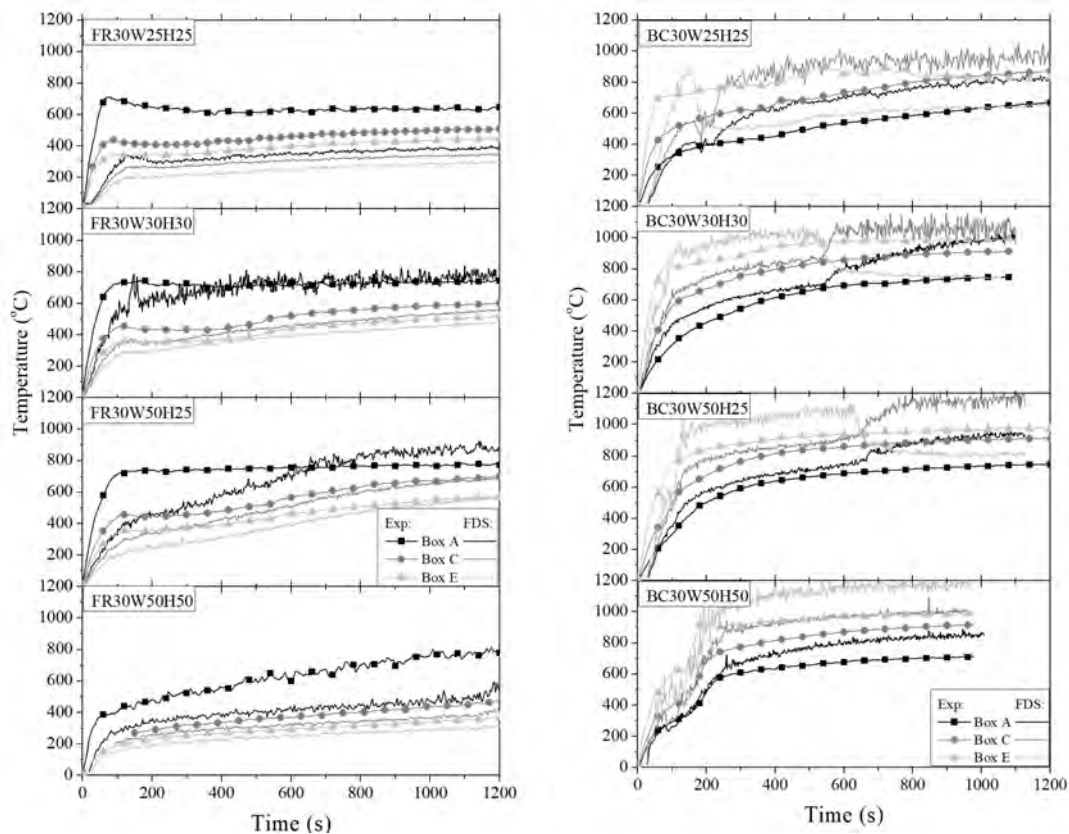


Fig. 5. Experimental and numerical temporal evolution of the gas temperature at a height of 45 cm at the interior of the corridor in Boxes A, C and E for FR (left) and BC (right) test cases.

Figure 6 depicts the vertical distribution of the time-averaged (over *Region III*) radiative heat flux measured using thin steel plate probes [16, 19] at the centreline of the façade for all test cases. Measured heat fluxes decrease with increasing height, as expected. The highest heat flux is located always along the centreline, except for test cases when the front of the enclosure is completely open, i.e., BC30W50H50 and FR30W50H50. Measured heat flux values are generally higher than predictions in all test cases and predictions in decreased ventilation areas indicate better agreement with experimental data. Nevertheless, the discrepancies are larger for cases where the burner is positioned at the rear of the corridor and cases where the width of the opening equals that of the corridor. Those cases include the fuel-controlled cases, where the predictive ability of FDS is known to be lacking.

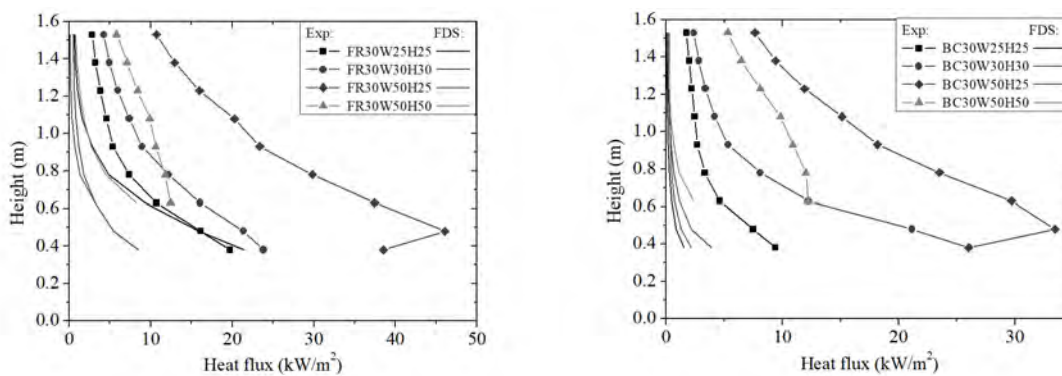


Fig. 6. Experimental and numerical temporal evolution of the gas temperature at a height of 45 cm at the interior of the corridor in Boxes A, C and E for FR (left) and BC (right) test cases.

3 CONCLUSIONS

The dynamic nature of EVF requires the use of advanced modelling methodologies, capable of describing the relevant physical phenomena in sufficient detail. The commonly used prescriptive methodologies are based on a phenomenological approach that exhibits certain limitations, especially when unusual structures are considered. CFD tools may provide significant assistance to the fire safety engineering analysis of EVF, by offering the opportunity to obtain an in-depth view of the spatial and temporal distribution of important physical parameters such as velocity, gas temperatures, wall temperatures, heat fluxes etc. In the current work, an extended series of medium scale fire tests using liquid pool fires were analysed numerically, aiming to investigate the effect of pan location and ventilation parameters. The obtained predictions are compared to available experimental data. In the interior of the corridor, good qualitative and occasionally quantitative agreement is observed for the gas temperatures. FDS captures well the detachment and propagation of the flame when the burner is positioned at the back of the corridor. However, FDS generally under-predicts the combustion zone and the fire plume seems tilting at the rear of the corridor. The performance of the CFD tool in predicting EVF gas temperatures and heat flux to the adjacent façade is improved for larger opening sizes. Regarding the heat flux at the exposed surface of the façade, good quantitative agreement is observed, especially at lower heights near the opening. FDS generally under-predicts experimental values under over-ventilated conditions. The present work provides a framework towards understanding the physics of the fire growth in corridor-shaped structures, but future experiments should aim at further investigating the effect of corridor geometry (e.g. investigation of different aspect ratios and geometrical configurations). The predictive ability of the numerical model will be further assessed by using a larger dataset of medium- and full-scale corridor-façade fire configurations in a range of realistic fire scenarios.

ACKNOWLEDGMENT

Present work has been financially supported by “ELISSA: Energy Efficient Lightweight-Sustainable-Safe-Steel Construction” project (FP7-2013-NMP-ENV-EeB). Technical assistance of Mr. M. McKee, Mr. B. Veighy and Mr. K. Kowalski is gratefully acknowledged.

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INVESTIGATING THE FIRE EXPOSURE IN A NEW TEST METHOD THROUGH NUMERICAL SIMULATIONS

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ABSTRACT

Numerical simulations using the Fire Dynamics Simulator (FDS) is used to assess the impact of different heat release rates (HRR) on a novel façade fire assessment method similar in size to the BS 8414-1 method. The novel method is developed as an alternative method to all current methods used within the European Union. In addition to the new set of measuring devices a combined set of measuring points representative of those in common assessment methods are added in the model. In this work the impact on these additional measuring stations is investigated by measuring heat flux, wall temperatures and corresponding thermocouple temperatures. The HRRs used in this study are adopted from measurements of HRR from the BS 8414-1, SP Fire 105 and the ISO 13785-2 methods. It is found that qualitatively similar results are found for the BS 8414-1 and the ISO 13785-2, while lower temperatures and heat fluxes are found using the SP Fire 105 HRR.

1 INTRODUCTION

A number of different test standards are employed in Europe to assess the fire performance of external walls and façade claddings [1 - 2]. The development of the façade fire assessment methods started a long time ago, e.g. the SP Fire 105 method [1] was developed during the 1970-80s by designing suitable assessment criteria and fire load [3 - 4] and there is a whole body of corresponding research work, both experimental and numerical [5 - 11] supporting the development of other test methods. However, having a variety of methods is impeding industry and trade between the European countries, thus a harmonization is preferable. Over the years, there have been several attempts to produce a single European approach to assess the fire performance of façade systems and the outputs from these projects have been used to develop an alternative methodology. In the recent push for a European harmonization, it has been suggested that one medium scale and one large scale test method will replace all previous national methods [1]. In this complex process it is crucial to take into account national regulations and measurements that go beyond the EN 13501 (reaction to fire and fire resistance, see the discussions in [1]) classification system. An alternative assessment method has been proposed based on the DIN 4102-20 and BS 8414-1 methods [1], in order to match these prerequisites. An alternative test method for the development of a single European approach to the assessment and classification of the fire performance of façade systems has been provided in Ref. [1], suggesting two alternative ways forward:

- Proposed test method – to retain the current BS 8414-1 and DIN 4102-20 test methodologies and develop supplementary protocols and revised classifications to enable the local regulatory requirements to be met and to retain access to historic data wherever possible.
- Alternative test method – a combined test and classification system covering the major performance characteristics identified by regulators, based on the modification of the existing BS 8414-1 and DIN 4102-20 test and associated classification methods to meet local regulatory requirements but without historical data.

To realize this proposal more work is needed in terms of research and a round robin across the member states.

However, the alternative test method is largely untested and it is not clear how this new system performs in terms of fire exposure in comparison to the old national methods, thus a series of simulations have been performed to assess the possible variations and similarities between the existing methods in comparison to the new alternative method. All three methods define an amount of fuel to be used, eg, in BS 8414-1 and ISO 13785-2, a volume of wood, and in SP Fire 105, a volume of heptane. The HRR during a test differs between the three methods, both quantitatively but also in duration. All three methods also define the geometry of the combustion chamber, see e.g. [10 - 11] for more details. In total, results from three simulations using the fire load from three different test methods, namely SP Fire 105, BS 8414 and the ISO 13785-2 against the alternative test method setup are presented in this paper. The HRR is assumed to be released from an object with the same physical dimensions, to avoid different dynamics and the fire source is modelled by an “HRR per unit area” releasing a certain amount of fuel per area unit. The fuel is specified as in the methods, wood in the case of BS 8414-1 and heptane for SP Fire 105.

2 MODELLING

The numerical work was performed using Fire Dynamics Simulation (FDS) version 6.3.0 [12]. The Navier-Stokes equations in the limit of low-speed, thermally-driven flow with an emphasis on smoke and heat transport from fires are solved by the FDS software. The algorithm used is an explicit predictor-corrector scheme that is second order accurate in space and time where turbulence is treated by means of Large Eddy Simulation (LES) in the Deardorff form. This contrasts with other CFD codes for fire safety engineering where Reynolds averaged Navier-Stokes models are used. The heat transfer by radiation is included in the model via the solution of the radiation transport equation for a gray gas. The equation is solved using a finite volume technique for convective transport, thus the name given to it is the Finite Volume Method (FVM). When using 100 discrete angles, the finite volume solver requires about 20 % of the total CPU time of a calculation, a modest cost given the complexity of radiation heat transfer.

The geometry of the façade is presented in Figure 1, and is similar to the BS 8414-1 which consists of a main test wall at least 2.6 m wide and 6.0 m high above the fire compartment and a return wall of minimum width of 1.5 m and the same height as the main wall as shown in Figure 1. In Figure 1, the assessment points are shown, the lintel of the fire room is 2.0 m from the ground, thus the points 1-3 are located 2.6 m from the ground, the subsequent rows are at 3.0 m, 3.6 m and 4.0 m above ground. Furthermore, the assessment points are placed symmetrically in relation to the 2.0 m wide fire room.

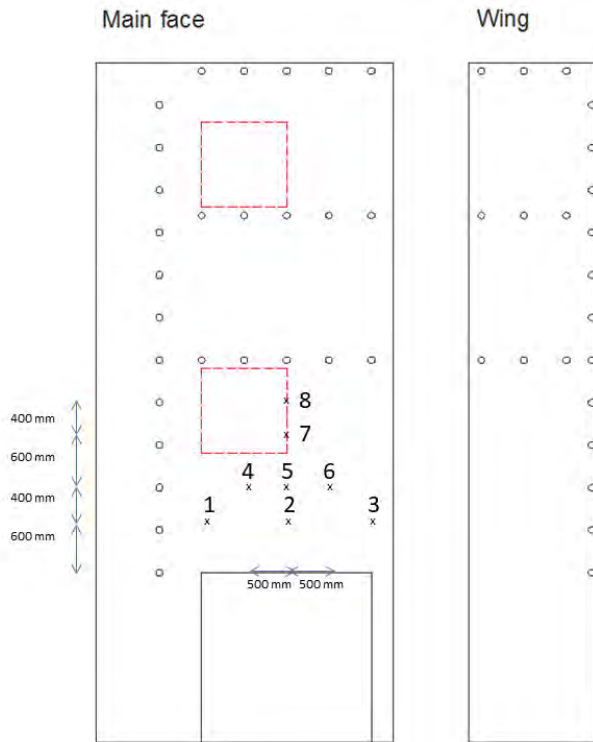


Figure 1. Experimental set-up in the alternative method. The rings represent measuring stations included in the alternative method while the impact in this work is assessed at the measuring points 1-8, however measuring points 1 and 3 will not be shown.

The HRRs are adopted from experimental means and by information provided in the standards, see Refs [10 - 11]. The curves are presented in Figure 2, as seen the HRR differs both quantitatively and in duration. The HRR is assumed to be released from an object with the same physical dimensions, to avoid different dynamics in the simulations and the fire source is modelled as an HRR per unit area releasing a certain amount of fuel per area unit where the fire source is 1.5 m x 1.0 m x 1.0 m (width x length x height) placed 0.5 m from the ground. The fuel is specified as in the methods, wood in the case of BS 8414-1 and heptane for SP Fire 105, see [10 - 11] for more details.

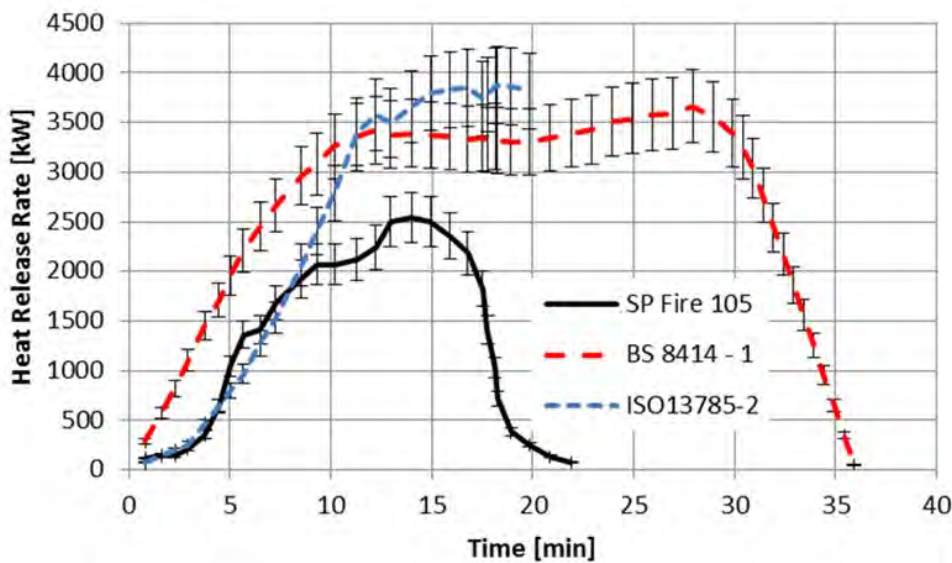


Figure 2. Heat release rates from the three different test methods SP Fire 105, BS 8414-1 and ISO 13785-2. The heat release rates are adopted from Ref. [12].

The material properties are presented in Table 1. One important aspect in defining simulations is resolving the conflict between their overall accuracy and the computational time required. The simulation must have a sufficiently resolved mesh to provide accuracy while the finer the mesh size the more processing time is required. To help resolve this a mesh resolution study was performed using 20 cm, 10 cm and 5 cm cubic grids for the three different HRRs. A general recommendation for the mesh size relevant for buoyant plumes is to compute the ratio characteristic fire diameter (D^*) and the nominal grid size (dx), where the recommended range is $10 < D^*/dx < 20$. For SP Fire 105 HRR at maximum intensity, the ratio characteristic is found to be 6.6, 13.3 and 26.6 for the 20 cm, 10 cm and 5 cm grid, respectively this means that the 10 cm grid gives a sufficiently good resolution considering $10 < D^*/dx < 20$, however previous comparisons with experimental data indicates that simulations using the 5 cm grid performs better. Note that the ratio will be increased for the BS 8414-2 and the ISO 13785-2 simulations due to the increased peak intensity of the HRR, see Figure 2. More information on the grid sensitivity studies are presented in Ref. [10-11]. In order to have distinct comparisons the same grid is chosen in all three cases.

Table 1. Material properties used in the simulations.

Material\Properties	Conductivity [W/mK]	Density [kg/m ³]	Specific heat [J/gK]
Wall material	0.242	975	1.0
LW Concrete	0.15	840	1.0

3 RESULTS

The simulations were run for all three fire loads and the wall temperatures as indicated in figure 1 were studied in order to compare the different fire loads impact on the experimental set-up. Mean values of the temperatures at point 2, 5 and 7 as indicated in Figure 1 are presented in Table 2, where the mean value is taken between 750s – 850s in order to assess the elevated wall temperatures on the façade along the centre position of the fire room. Note that the material in the façade has a rather low thermal conductivity yielding high surface temperatures above 650 °C.

Figure 3 shows the three simulations beside each other in a comparison of the wall temperature after 800 s. The impact of the flames coming out of the fire room impinging on the façade is clearly visible and results in significantly elevated temperatures, more than 650°C, up to or above 4 m (the second mesh from the ground ends at 4 m above the ground) from the ground.

Table 2. Mean value of wall temperatures (°C) at three positions between 750 – 850s.

Position	2	5	7
BS 8414 - 2	762	756	727
ISO 13785 - 2	757	753	731
SP Fire 105	722	730	676

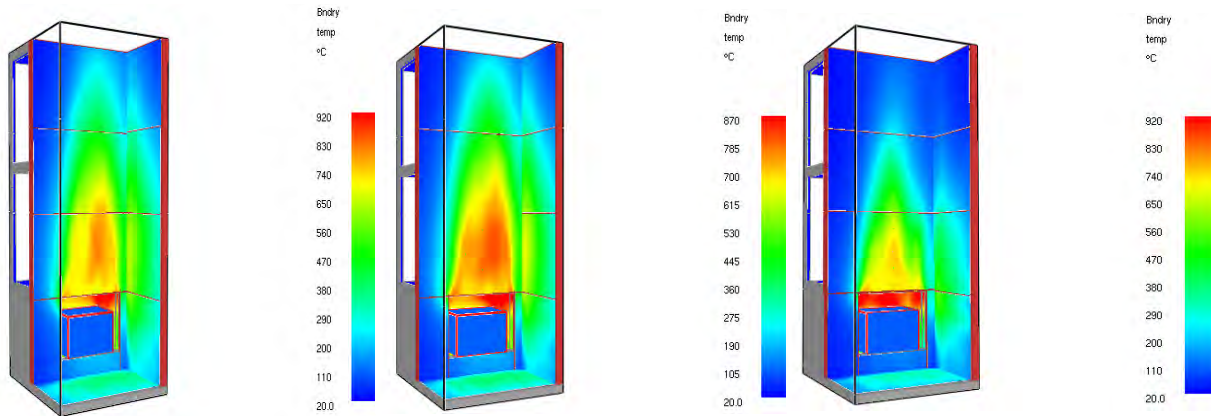


Figure 3. The instantaneous wall temperature after 800 s on the façade for the three different HRRs, BS 8414-2 (Left), ISO 13785-2 (Centre) and SP Fire 105 (Right).

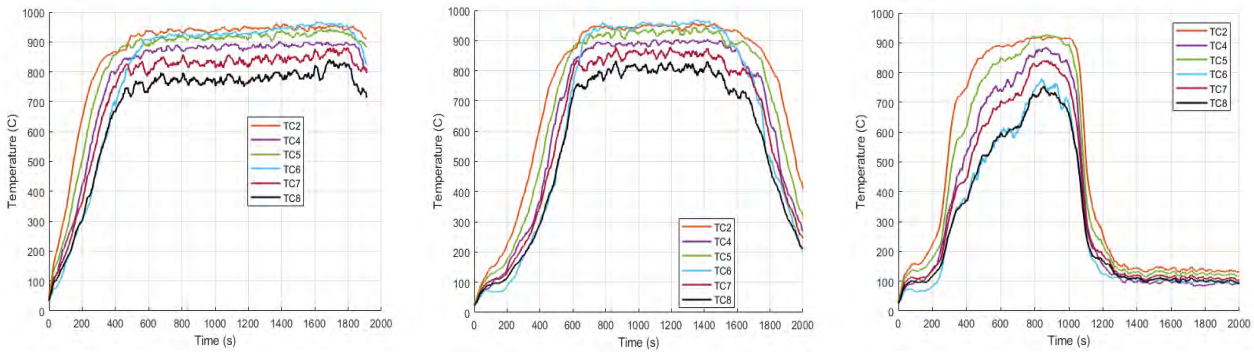


Figure 4. The TC temperatures (0.5 mm thermocouple) computed in the cell closest to the façade for the eight positions for the three different fire sources, BS 8414-1 (Left), ISO 13785-2 (Centre) and SP Fire 105 (Right).

The TC temperatures computed in the cell closest to the façade are shown in Figure 4. Maximum temperatures of around 900°C for an extended period of time are found for all three cases. In Figure 5, a comparison at two different points are displayed indicating that the fire source of the BS 8414-1 and the ISO 13785-2 is quite similar whereas the SP Fire 105 is slightly lower.

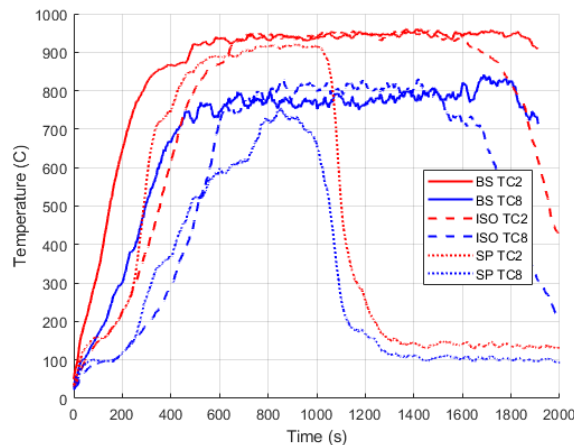


Figure 5. A comparison of TC temperatures at two positions for the three different fire sources, BS 8414-1, ISO 13785-2 and SP Fire 105.

In Figure 6 and 7 the heat fluxes (kW/m^2) are displayed. The heat flux is the incident radiative flux plus the convective flux. Note that incident heat flux does not account for radiation leaving the surface and that the temperature used for the convective portion is the actual surface temperature as opposed to a user defined temperature of a gauge or similar device. Moreover, a positive output quantity for heat flux means heat is being transferred into the surface.

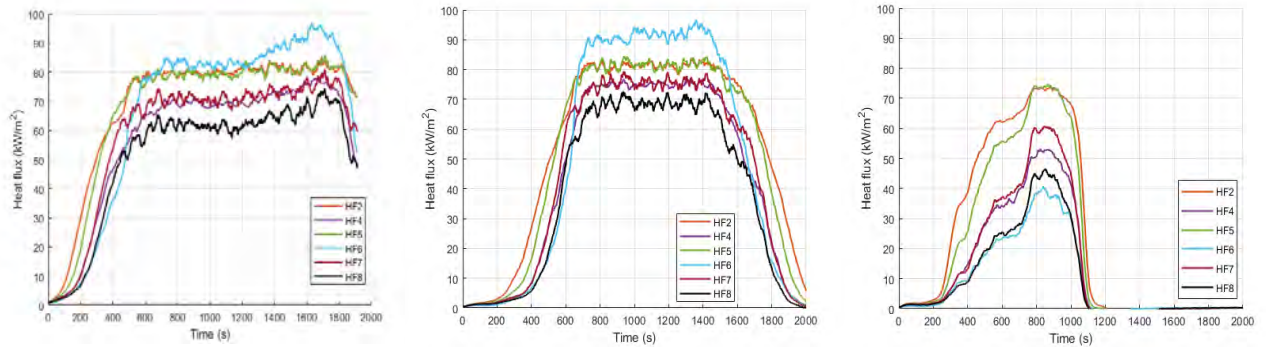


Figure 6. Heat fluxes at eight positions for the three different fire sources, BS 8414-1 (Left), ISO 13785-2 (Centre) and SP Fire 105 (Right).

Similarly, to the temperatures the quantitative level of the heat fluxes for the BS 8414-1 and the ISO 13785-2 is similar whereas the level for the SP Fire 105 is lower, see Figure 7.

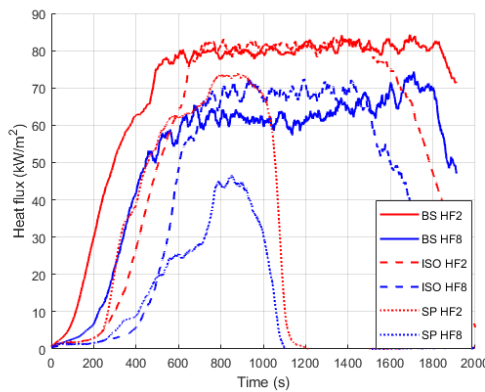


Figure 7. A comparison of incident heat fluxes at two positions for the three fire loads.

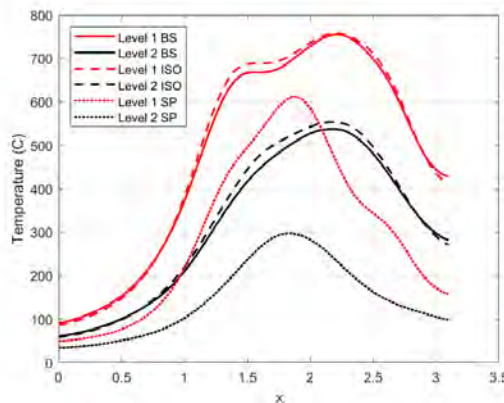


Figure 8. A comparison of computed wall temperatures on the main face of the façade at the first two lower horizontal levels marked by rings in Figure 1 for the three different HRRs.

Lastly indications of temperatures to be used for classification purposes are indicated in Figure 8, where wall temperatures are computed at the two lower horizontal levels marked by rings in Figure 1 are displayed. The levels are 4.0 m and 5.0 m from the ground, respectively. The wall temperatures are computed on the main face of the façade (not including the wing) beginning at the outer boundary ($x=0$) and ending at the corner ($x=3.1$). The wall temperatures are mean valued over 750 s to 850 s. Again we find similar temperatures for the BS 8414-1 and the ISO 13785-2 methods whereas lower temperatures for the SP Fire 105 method are found. Note that there is a drop of around 200°C between lower (level 1) and the higher level (level 2).

4 DISCUSSION

In the present paper a numerical study is performed on a novel alternative assessment method for fire safety of façades. The method is similar in size and fire source to the British method BS 8414-1 however a new classification system is proposed with as few classes as possible resulting in 4 new classes. The new classes are defined from the heat exposure and performance is determined for flame spread and falling parts. The assessment performance of this new method is largely unknown thus a numerical study of fire exposure on this façade is of interest and validates this study. Furthermore, a comparison of the effect of different HRRs on the same façade rig is rarely investigated. Although, completely new set of measuring devices at different places of the façade is used in the assessment method (marked by rings in Figure 1), measuring points used in the previous standards are adopted for a comparison. A selection of 8 measuring points is added to the façade, at these points the heat flux and temperatures are computed in addition the overall wall temperature over the whole façade is shown. To this end, a series of simulations using the same geometric set-up while varying the HRR are performed. The HRRs are to represent those of the competing methods BS 8414-1, ISO 13785-2 and the SP Fire 105 methods and the HRR is assumed to be released from an object with the same physical dimensions, to avoid potential differences in the dynamics. The HRRs are adopted from experimental means and by information provided in the standards, see Refs [10 - 11]. Previously a grid sensitivity study was performed suggesting that a 5 cm cubic mesh is suitable for the SP Fire 105, here the same grid is used in all three cases to simplify the comparisons. It is worth to note that the ratio of the characteristic fire diameter and the nominal grid size is larger at maximum intensity for the BS 8414-1 and the ISO 13785-2 methods suggesting that this grid is suitable for these methods as well.

In the numerical model, the impact of the flames coming out of the fire room impinging on the façade is clearly visible moreover significant differences stemming from the three different HRRs and fuels are found. The fire source is modelled as close to the original source as possible, see Refs [10 - 11] for details. The fire results in significantly elevated temperatures, more than 650°C, up to or above 4 m from the ground. Moreover, the heat flux is computed as radiative flux plus the convective flux however the radiation leaving the surface is neglected. The temperature used for the convective portion is the actual surface temperature as opposed to a user defined temperature of a gauge or similar device as is common. In summary, the quantitative levels of the temperatures and the fluxes for the BS 8414-1 and the ISO 13785-2 is similar whereas the level for the SP Fire 105 is lower, see Figures 5 and 7.

In summary, the calculated temperatures for the large-scale method are qualitatively similar in all three cases using the HRRs found in SP Fire 105, ISO 13785 and the BS 8414. Quantitatively, the temperatures found using the HRR from the SP Fire 105 are slightly lower in some locations and

show a slightly larger spread which seems to be due to the lower HRR used in this method while the other two methods are similar. The current simulation efforts indicate that the fire exposure of the test methods BS 8414-1 and the ISO 13785-2 are similar and more severe than that of the SP Fire 105. Furthermore, it can be concluded that also the DIN 4102-20 is much less severe than the BS 8414-1 and the ISO 13785-2 methods, however, the case of the external fire (the wood crib placed outside the fire room) may have larger impact than the original method due to the difference in dynamics, see [1]. It seems that the proposed alternative method would be an as severe or more severe test method in most cases indicating that it is a good candidate for a harmonized assessment method. To realise the alternative method more research is needed as well as a round robin program between the member states to investigate the robustness, reproducibility and repeatability of the method.

ACKNOWLEDGMENT

The work was partly financed by the EU project, European assessment procedure for the fire performance of façades in response to the EU Tender ref - 531/PP/GRO/IMA/16/1133/9108.

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SESSION 5: RISK MANAGEMENT AND REGULATION

- P.147 **Development of the exterior facade fire evaluation and comparison tool, effect™**
Susan Lamont, Arup, Dubai, UAE, and
Birgitte Messerschmidt, National Fire Protection Association (NFPA), Quincy, USA
- P.155 **A fire risk assessment method for reduced height buildings with etic facade systems**
Piergiacomo Cancelliere¹, Paolo Setti², Samuele Sassi², Angelo Lucchini³, Alberto Stefanazzi³,
Silvio Messa⁴, Eleonora Anselmi⁴, Arianna Villotti⁵, Mauro Madeddu², Paolo Canzani²
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⁵ Italian South Tyrol Fire Service, Bolzano, Italy
- P.163 **A European framework to ensure fire safety in taller buildings**
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Yves Martin¹, Margo Colson², Kurt De Proft³
¹ Civ. Eng, Deputy Head of Department, Belgian Building Research Institute - Centre Scientifique et
Technique de la Construction (CSTC), Brussels, Belgium
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DEVELOPMENT OF THE EXTERIOR FAÇADE FIRE EVALUATION AND COMPARISON TOOL, EFFECT™

Susan Lamont, Arup, Dubai, UAE
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ABSTRACT

As a consequence of several recent fires in high-rise buildings involving combustible exterior wall assemblies (façades), global enforcement authorities are revisiting their existing building inventories to assess the hazard posed by the exterior walls, the likelihood and consequence of a fire spreading over multiple stories of the building via the exterior walls and, therefore, the risk to life safety. In early 2018, Arup completed a research project for NFPA [1] to develop and validate a risk assessment methodology and a freely available electronic tool to assist Authorities Having Jurisdiction (AHJs) in assessing the risks of their high-rise and intermediate-height building inventory. The methodology involves: identification of key variables associated with the exterior walls and the building (e.g. façade materials and geometries, evacuation strategy, building fire protection systems, etc.); characterization of those variables in terms of risk or mitigation potential; and incorporation of them into an engineering-based risk model whose output will be a means for AHJs to prioritize mitigation. A qualitative assessment approach to risk ranking is utilized, consisting of two steps: an initial screen and a further evaluation based on more detailed building information. This two-step approach recognizes the challenges facing AHJs including the variability in these systems as field installed, the lack of data/information on specific installations, and the orientation of the tool to users who may not have the full engineering capability to make these initial assessments.

1 INTRODUCTION

In the last decade we have seen an increasing number of fires involving combustible exterior walls (façades) on high-rise buildings. The fires have happened globally in cities such as Dubai, Shanghai, Atlanta, London and Melbourne. What all these fires had in common was rapid fire spread over the exterior of the building. In most cases, fire spread was too fast for the fire department to control before it had spread to large parts of the interior and exterior of the building. This rapid fire spread is linked to the increased use of combustible façade materials in recent decades, particularly Metal Composite Materials (MCMs) or Aluminium Composite Panels (ACPs) with highly combustible cores.

Consequently, global AHJs have been looking to assess the hazard posed by exterior walls, the likelihood and consequence of a fire spreading over multiple stories of the building via the exterior walls and therefore the risk to life safety. While these fires are becoming more common there is insufficient data to quantify the likelihood and consequence of a fire based on the current data. There are several factors which may impact the level of risk and the consequent priority for detailed inspection and/or remediation of a building. AHJs are seeking a means to make assessments and decisions based on risk but have been lacking methodology or a tool to do so until now.

The online Exterior Façade Fire Evaluation and Comparison Tool (EFFECT™ www.nfpaeffect.com) was made available in February 2018. Based on the risk methodology outlined in this paper, it is

intended to assist the AHJs globally in assessing the risks of their high-rise and intermediate-height residential and commercial building inventory with combustible façade assemblies.

The basis of high-rise fire safety design internationally is to provide layers of fire protection to contain a fire to a single story or the room of fire origin. These layers of safety include active fire protection systems such as automatic detection and fire alarm, smoke control systems, automatic sprinklers, wet standpipes and hardened elevators to assist fire fighters. Passive systems are equally important and provide protected escape routes, protected fire fighter access and barriers to fire and smoke spread from floor to floor or apartment to apartment. If there are deficiencies or holes in these layers, then the fire safety afforded to occupants and fire fighters is reduced.

The choice of materials for construction is another layer of safety. International codes and standards restrict use of combustible materials in the building fabric and structure to prevent them contributing fuel to a fire. The issue at hand is that combustible materials used in some exterior wall systems have or could contribute significant fuel to a fire. The orientation and in many cases the connectivity of the exterior wall system laterally and vertically up the building is likely to promote rapid fire spread over multiple stories on the exterior, and then breaking through the exterior wall system into the interior of the building. A risk assessment is needed to consider the robustness of all these layers.

2 RISK ASSESSMENT METHODOLOGY

The EFFECT™ risk-informed methodology involves:

- Identification of key variables (component materials, connection systems, cavities, installation techniques and geometries, wear and tear of systems, proximity to other structures, occupancy type, egress routes, evacuation strategy, building fire protection systems, etc.);
- Characterization of those variables in terms of risk or mitigation potential; and
- Incorporation of the variables into an engineering-based risk model whose output will be a means for AHJs to prioritize mitigation.

2.1 Scope and assumptions

EFFECT™ is based on the following assumptions:

- The tool is intended for high-rise buildings comprising residential or business occupancies or a mix of both. Where the building is a mix of residential and business, it should be treated as a residential building due to the greater life safety risk associated with sleeping occupants.
- High-rise is defined as a building over 18 m in height, measured from fire department access level to the topmost occupied floor.
- The likelihood of a fire is reviewed in the context of ignition sources within the vicinity of the combustible exterior wall system (e.g. parked vehicles, cabling, electrics, lights, PV panels, balconies, BBQs, adjacent buildings etc.), within the cavities of the exterior walls and from a fire breaking out from the interior of the building.
- The tool is intended to have global applicability with minor geographical variations. The tool is not a code-compliance check, although it is based on the first principles of fire safety to, as far as practicable, meet the intent of life safety codes.
- The tool is only for buildings with a combustible exterior wall problem. It is not suitable for assessing internal fire safety provisions only.
- The tool is for assessment of existing buildings only. It is not a design tool.
- The tool is only suitable for buildings with a steel or concrete frame (i.e. not timber).
- It does not recommend mitigation strategies as these need to be project specific. It can however be used to assess the impact of potential mitigation strategies and their impact on the risk score.

2.2 Tiered approach

In general, the fire risk assessment (FRA) tool is intended to be used by AHJ's to assess a portfolio of buildings across a town or city where there is a concern that the exterior walls are built-up from combustible materials. The FRA tool is intended to provide a framework to aid the AHJ to prioritize buildings in their jurisdiction and to conduct an initial FRA of each building, assessing the highest priority buildings first. A tiered approach to risk assessment as adopted by ASCE 41 [2] allows the tool to prioritize buildings for detailed assessment when there is a city or large portfolio of buildings:

- Tier 1 – Desktop study of a portfolio of buildings to establish a priority ranking for further assessment. This could be by a building owner, facilities manager or the AHJ. A small number of questions with clearly pre-defined answers are posed of the users for the Tier 1 assessment to inform the ranking of buildings that then require further detailed assessments.
- Tier 2 – A FRA evaluation by the AHJ, prioritized by the ranking in Tier 1, involving on-site inspections, review of as built information and maintenance records, sampling and laboratory testing of unknown exterior wall materials.

In some instances, the Tier 2 assessment will highlight the need for a more detailed risk assessment by a qualified engineering team of façade and fire engineers. This could be because of the complexity of the building, complexity of the exterior wall patterns, difficulties in identifying the exterior wall systems/materials or because the owners' objectives go beyond life safety only (e.g. business continuity or upgrading the exterior wall system to achieve better aesthetics, acoustics, thermal performance, etc.) This more detailed FRA is Tier 3, which is outside the scope of EFFECT™.

Tier 1 and 2 are further sub-divided into two parallel processes, "A" and "B", which focus on: A) exterior wall fire hazards and ignition sources, and B) internal fire safety provisions, respectively. The two parallel processes have been introduced for the following reasons:

- If there are no combustible exterior walls, then no further assessment is required. This may be established at Tier 1A or, if it is unknown or in doubt at this early stage, at Tier 2A.
- It allows the AHJ to identify deficiencies interior to the building which should be rectified regardless of the situation with the exterior walls (e.g. the fire pumps are off or the fire alarm panel has multiple faults). These changes can be identified through the "B" processes at each Tier.
- Separating the two subjects provides more visibility of the results to the AHJ and simplifies the tool as the "B" process should be familiar to most AHJs.

2.3 Type of risk assessment

There are three main types of risk assessment: quantitative, semi-quantitative and qualitative. All of these approaches are used in the fire safety industry, as described by Meacham et. al. [3]. Quantitative analysis is only possible if there is statistical data. There is no statistical data linking all the variables of combustible exterior walls on a high-rise building with the likelihood or consequence of a fire spreading externally over multiple stories of a building. There are several reported fire incidents in the last 20 years which provide evidence of how fires have spread and how fire safety provisions have reacted. However, the actual impact of the exterior walls, of each fire safety provision or of the combination of fire safety provisions cannot be quantified in this context without further research. A qualitative approach has instead been adopted for EFFECT™, based on a risk matrix as shown in Figure 1. This type of risk matrix is commonly used across a range of industries, not just fire safety. The publicly available specification 79 [4] (PAS 79) published by the British Standards Institute is a qualitative fire risk assessment (FRA) method that uses this type of matrix. The risk matrix approach within PAS 79 was adopted to define the likelihood of fire spread over multiple stories of a building via the exterior wall system, the consequence of this fire scenario for each occupancy type and increasing building height and, therefore, the final project risk matrices.

Potential consequences of fire hazard	Likelihood of fire hazard		
	Low	Medium	High
Slight harm	Trivial risk	Tolerable risk	Moderate risk
Moderate harm	Tolerable risk	Moderate risk	Substantial risk
Extreme harm	Moderate risk	Substantial risk	Intolerable risk

Figure 1. Risk ranking method

As presented in Figure 1, risk is a function of the likelihood of the fire event and the consequence of the fire event. To arrive at likelihood and consequence, the hazards must first be established. As all of the FRA tools currently available consider a fire interior to the building, a rigorous method to capture knowledge from experts in the field and to define the variables most likely to contribute to the hazards and likelihood of an exterior wall fire acting over several stories of a building was needed. Therefore, the analytical hierarchy process [5] (AHP), which is used in several industries to obtain a collective view from professionals where no quantified data exists, was used. It ranks the relative importance or hierarchy of variables to each other. The outputs of the AHP informed which variables have been included in EFFECTTM.

To identify the hazards most likely to contribute to a fire over multiple stories of a building via the exterior walls and the fire safety provisions required for life safety during this fire scenario, teams of engineers in Arup, Jensen Hughes and NFPA were asked to rank the relative importance of fire hazards and fire safety measures in this context. As an example, detection, fire alarm, exits, management and smoke control were compared in terms of their importance to facilitate means of escape and warning during an exterior wall fire. The results showed a greater weighting for fire alarm and exits than detection, management or smoke control. This makes sense as an exterior wall fire may not be detected by normal means if it remains on the exterior of the building. Because an exterior wall fire can spread rapidly, alerting people to leave the building and providing robust protected escape routes is important.

Similarly, the same individuals were asked to rank exterior wall ignition sources, combustible exterior wall materials, vertical connection of combustible exterior wall materials over the building height, perimeter fire-stopping and cavity barriers in terms of their contribution to the likelihood of a fire spreading over multiple stories of a building via the exterior walls. The combustible content of the exterior walls was considered to be the greatest influence, followed by ignition sources and vertical connectivity of the exterior walls over the height of the building. Perimeter fire-stopping and cavity barriers were deemed to be lower in the hierarchy. This is also reasonable as cavity barriers may delay fire spread via the cavity but they cannot delay fire spreading via combustible cladding. Perimeter fire-stopping is intended to prevent an interior fire breaking into the floor above but if the fire enters the exterior wall cavity or starts on the cladding these are also likely to become ineffective. Further research is required but this is the current professional opinion of the pool of experts answering the AHP. Containment and extinguishment measures were also looked at as part of the AHP.

2.4 Variables assessed

As mentioned previously, Process A requires information on exterior wall fire hazards and ignition sources. This includes the insulation material within the thickness of the exterior wall system, the outer cladding materials, cavity size, connectivity of the exterior wall system over the building and ignition sources inside the building, exterior to the building and inside the cavity of the exterior walls. Process B looks at the likelihood and consequence of means of egress and warning being compromised. It considers the detection and fire alarm system, exits and fire compartmentation.

Sprinklers are considered in respect of their ability to reduce ignition risks interior to the building in Process A and are not relied upon in Process B as the fire is assumed to be exterior to the building and across several floors of the interior of the building simultaneously. The water supply/pressure serving the sprinkler system is unlikely to have been designed to contain such a large fire.

Membranes such as vapor barriers within the exterior walls are not assessed at either Tier 1 or Tier 2. This is because the type of properties that a vapor barrier requires to perform its role as a seal to the building normally means that they are also combustible. Typically, this is addressed in codes by excluding the vapor barrier from the requirement to be non-combustible or limited combustibility. Disregarding their presence is also considered reasonable for the EFFECT™ risk-based method. Cavity barriers and perimeter fire stopping are not relied upon when determining the fire performance of the exterior wall system, based on their hierarchy in the AHP assessment.

2.5 How EFFECT™ works

Questions with clearly pre-defined answers are posed in both the Tier 1 and Tier 2 assessments. Tier 1 includes a small number of questions that could be answered through a questionnaire by a Facilities Management team to initially screen many buildings. Tier 1 prioritizes the buildings by Process A, which is the likelihood and consequence of a fire because of the exterior wall assembly hazards and ignition sources. If the results from Process A do not produce a risk greater than “tolerable” but the building scores “moderate”, “substantial” or “intolerable” in Process B, then the AHJ should conduct an inspection against the applicable fire safety code at the premises or use an alternate FRA tool intended to address a fire which remains in the room or compartment of fire origin.

Upon completion of Tier 1, the AHJ should inspect each premises in order of the priority determined from Tier 1. The purpose of Tier 2 is to confirm or amend the priority risk ranking assigned to the building in Tier 1 due to a greater understanding of exterior walls, combustible materials, ignition sources and the fire safety provisions. It is envisaged that Tier 2 is completed by a more experienced user (code official, AHJ, certifier, building control, fire safety professional) but specialist expertise in exterior wall design or construction is not required. Tier 2 questions can be applied to each elevation of a building separately if the elevations have different façades or different ignition sources. This helps the user clearly identify the areas requiring remediation and why. The elevation with highest risk ranking is the overall building fire risk. The User’s Guide [6] which accompanies EFFECT™ provides useful information to help answer the questions within the tool.

To help the user identify the exterior wall systems present, and specifically what type of insulation materials and cladding materials are present, a 5-step process is suggested:

1. Review as-built drawings where they are available. The user must check they reflect the current installation and there have been no upgrades or changes to the exterior walls.
2. Look at any material submittals that are available for the insulation and/or cladding to help identify the materials used and any fire testing and certification that might have been done.
3. Visually inspect the building including touching/tapping the materials that are visible or can be seen by opening exterior shaft doors/hatches etc.
4. Remove (with help from a contractor) material samples of the cladding and insulation (typically 100 mm square) for laboratory identification. Several samples may be required if different materials or different colours of the same material are present across the exterior walls. Samples should be taken from discrete areas and away from ignition sources. Materials should be replaced or repaired to avoid increasing susceptibility to ignition.
5. Laboratory testing. The User’s Guide provides information on the types of tests to ask for depending upon the suspected material, accreditation of laboratories, sample sizes needed, etc. Once the materials are known, the questions within Tier 2 can be answered by the user.

2.6 Occupancy types and evacuation strategies covered

The tool is limited to three combinations of occupancy type and evacuation strategy:

- Sleeping risk and “all-out” evacuation strategy (which may occur in phases);
- Sleeping risk and “stay-put” evacuation strategy; and
- No sleeping risk (i.e. office) and “all-out” evacuation strategy (which may occur in phases).

An “all-out” evacuation can only be assumed if there is the ability to sound the alarm throughout all areas of the building using an “all-out” or “all-call” button at the main fire alarm panel. As most high-rise buildings adopt a phased evacuation strategy, an all-out alarm would usually be activated manually by the fire department or building management. A “stay-put” (also referred to as “defend-in-place”) evacuation strategy for apartment buildings assumes that building occupants not affected by a fire directly remain in their apartment. Only the apartment affected by a fire/smoke would be in alarm and only these occupants would be expected to evacuate. If fire/smoke spreads then other alarm bases would be expected to automatically activate but there is no ability to simultaneously raise the alarm in all areas of the building.

2.7 The EFFECT™ risk matrices

For both Process A and Process B, EFFECT™ provides a risk matrix for each occupancy type and evacuation strategy. These are presented in Figure 2.

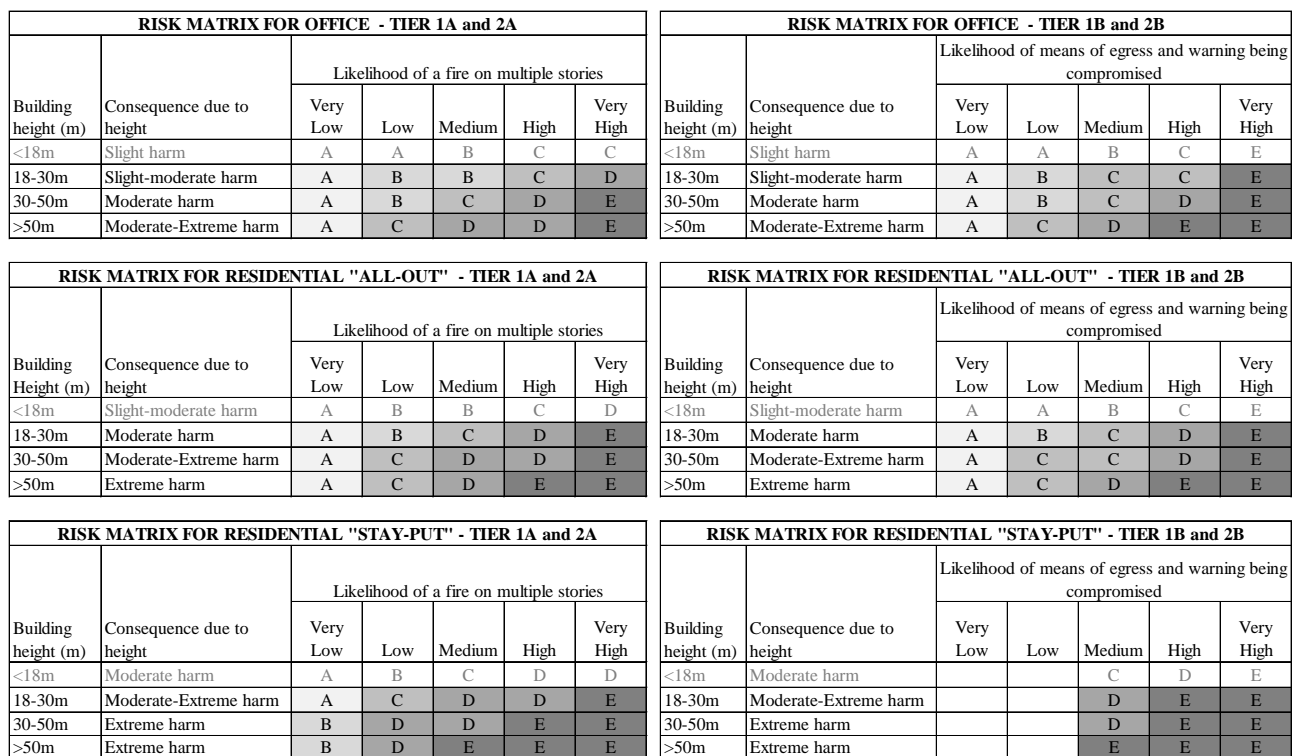


Figure 2. Risk matrices for Process A (left) and Process B (right)

The matrices provide a risk score from A-E (Trivial (A), Tolerable (B), Moderate (C), Substantial (D) or Intolerable (E)). For Process A, the risk depends upon the likelihood of fire over multiple stories vs the consequence of same. For Process B, the risk depends on the likelihood and consequence of means of egress and warning being compromised. The matrix is based on the PAS 79 [4] matrix but expanded to include “very low” and “very high” on the likelihood scale and “slight-moderate harm” and “moderate-extreme harm” on the consequence scale.

It can be seen in Figure 2 that the Process A risk matrix for an office occupancy has less red and orange than that for a residential building with a “stay-put” evacuation strategy. For residential occupancies the lowest consequence is “slight-moderate” versus “slight” for offices. The highest consequence is “moderate-extreme” for offices and “extreme” for residential. As also evident from Figure 2, the Process B risk matrix for an office occupancy has less red and orange than for a residential building with a “stay-put” strategy. For the fire scenario considered by this tool, that is a fire involving the exterior walls and spreading over multiple stories, it is not possible to score better than “substantial” if the fire alarm cannot be raised throughout the building.

2.8 Generating the EFFECT™ risk matrices

To arrive at the risk matrices, each variable assessed by the tool is given a relative score from “low” to “high” based upon the pre-defined answers given by the users to the questions in Tier 1 and Tier 2. The consequence of a fire involving the exterior walls is quantified based on building height, occupancy type, evacuation strategy and extent of fire alarm coverage. An increase in building height increases evacuation times and makes external firefighting more difficult. There is a greater consequence for occupants who are asleep, particularly where a “stay-put” egress strategy is adopted.

For Process A, the likelihood of fire over multiples stories is assessed based on the hazards and specifically the presence of ignition sources and fuel in the form of combustible cladding or insulation within the exterior walls. The following are examples of the scoring system for ignition hazards:

- Unsprinklered buildings and balconies pose a relatively “high” ignition hazard.
- External lights, parked vehicles and kitchen exhaust points pose a “medium” ignition hazard.
- Fully sprinklered buildings with no external ignition sources and no ignition sources in the cavity of the exterior walls would score a “low” ignition hazard.

Regarding the hazard related to the fuel available in the exterior walls, mineral wool insulation would score as “low” whereas a polyurethane (PUR) foam insulation will score “high”. Stone cladding would score a “low” while ACPs with a core of 100% polyethylene would score “high”. Vertical connectivity of combustible materials would score a “high”. These scores are combined by the tool to arrive at a score for the exterior wall assemblies based on typical results of large-scale fire testing.

The hazards are combined to arrive at a likelihood of fire over multiple stories of a building. If there is no ignition source or no fuel, then the likelihood is “low”. There must be both of these together. There is a step-change in likelihood if the combustible materials in the exterior wall are vertically connected. For example, a likelihood score of “high” will change to “very high” if the combustible materials are vertically connected/continuous over more than one story of the exterior wall.

For Process B, the likelihood of means of egress and warning being compromised is assessed based on the evacuation strategy for the building, availability of protected exits, reliable detection and fire alarm systems and robust compartmentation. The following provides a few examples:

- If stairs are locked or not adequately protected by fire-rated construction, this would score “high”.
- If only a single stair is adequately protected (i.e. whether the building has one stair only or other stairs are somehow unprotected) this would receive a score of “medium”.
- A “defend-in-place” or “stay-put” strategy would score “high”.
- A fire detection alarm system that has not been tested and maintained would score as “high”.
- Complete compartmentation would score “low”.

The hazards are combined to establish a likelihood of means of egress and warning being compromised. There is a step-change in likelihood if compartmentation is poor because fire and

smoke can be expected to more rapidly spread throughout the building interior. For example, a likelihood score of “high” would change to “very high” if the compartmentation is also poor.

2.9 Result of risk assessment

The Tier 1 assessment results in an outcome for a building in terms of Process A and Process B, as shown in 3. Prioritization is based on the combination of these two outcomes. The outcome of Tier 1A has a higher weighting. For example, a building with a combined outcome of E-E would be the top priority, followed by E-D, D-D and D-C, etc. A building with A-F or B-F would have lower priority. Buildings identified at Tier 1 as having a risk score “C” (i.e. “moderate”) and above, will need to be further evaluated and refined through a Tier 2 assessment, in order of priority. A risk score of more than “trivial” as established in Tier 2 will indicate that mitigation measures are recommended.

Building	Tier 1 Prioritization		Action
	Process A	Process B	
1	E	C	Tier 2 assessment required as process A prioritization > Tolerable
2	E	B	
3	D	C	
4	D	B	
5	C	D	
7	C	A	
8	C	A	
9	B	B	
10	B	D	Fire safety provisions to be assessed using alternate tool
11	A	D	
12	A	C	No action
13	A	B	
etc.			

Figure 3. Example of score and prioritisation in Tier 1

3 CONCLUSION

EFFEFFECT™ has been developed as a freely available online resource to assist AHJs and others who need to assess the fire risk posed by combustible exterior walls across a portfolio of buildings. A two-tier FRA process allows a quick assessment to be made in Tier 1 which then could be used to prioritize the buildings where further information is needed to perform a more detailed Tier 2 assessment. Since its introduction in February 2018, EFFEFFECT™ has approximately 450 users, including AHJs, consultants and building owners. The EFFEFFECT™ User’s Guide [6] provides important information about exterior wall systems and their role in external fire spread, and can be used as a reference document for anyone interested in fire safety of existing buildings with combustible exterior walls.

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A FIRE RISK ASSESSMENT METHOD FOR REDUCED HEIGHT BUILDINGS WITH ETIC FAÇADE SYSTEMS

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ABSTRACT

Currently, a specific method for assessing the risk of fire spread for building façades has not been defined. The NFPA has implemented a Fire Risk Assessment tool based on a qualitative method, although it's referred to buildings with incombustible structures and heights greater than 18 metres. This paper proposes a semi-quantitative method that begins with the estimation of a "starting building risk baseline" (baseline level of risk) by associating the typical parameters of Fire Safety Engineering (FSE) with risk indexes. The process then moves to analyse the likelihood of occurrence of the identified fire scenarios followed by an estimation of their magnitude. Basing on a matrix, therefore, a level of risk is obtained, and it is compared with the "starting building risk" which allows highlighting any possible risk variation: usually, risk level increases compared to the baseline level. The second part of the process is based on the analysis of the façade system and how it can reduce the level of risk for the overall building considered. The proposed method has been specifically developed for External Thermal Insulation Composite Systems (ETICS) and it has been validated by experiments conducted on different ETICS façade samples.

1 INTRODUCTION

Commonly, risk assessment is a complex and challenging process, full of uncertainties, so it is generally difficult to come to identical results from different evaluators. The convergence, the consensus on a certain risk assessment, rather than the accuracy of the calculations, depends on the transparency of the process and the methods that have generated it, considering also the limitations of assumptions and physical models taken into account throughout the evaluation process.

For buildings with combustible façade systems, there is no active fire protection system that could limit the fire that spreads on the façade itself. If the fire breaks out inside the building, sprinkler systems could control it within the fire compartment, but if the fire occurs or spreads over several floors the intervention of fire brigade could represent the only way to put off the fire and restore safety conditions. Consequently, passive fire protection measures are very important for the façade system design.

For a fire risk assessment, a quantitative analysis is very difficult to make due to the lack of availability of statistical and reliable data. Furthermore, there are no data that could connect all the variables influencing the risk of fire in a combustible façade system.

In the last years, there have been numerous cases of fire that have shown evidence of how fires have spread and how the fire safety provisions have reacted, but the actual influence of each fire safety provision cannot be accurately quantified. Consequently, the need to find a risk assessment method, able to connect all the variables that affect the risk level and based on experimental evidence deduced from experimental tests thought for the purpose. This paper proposes a semi-quantitative method that begins with the estimation of a "starting building risk baseline" (baseline level of risk) by associating the typical parameters of Fire Safety Engineering (FSE) with risk indexes.

2 THE SEMI-QUANTITATIVE METHOD

The proposed semi-quantitative method is based on “checklists” and it easily allows the outcome of rapid results, using data already known. A certain number of potential risk factors are identified, and each one is assessed using a specific checklist, which allows, through a series of questions, to examine the various variables that are considered relevant, in terms of likelihood and magnitude. The questions provided, at the same time, both directly and indirectly give indications on how to reduce the causes of risk. Figure 1 gives the flow-chart of the assessment process. The assessment process has been organized in three main steps. The purpose of the first step (Step 1), is intended to define a “starting risk level” analyzing the common characteristic of the building and the basic safety measures provided within the building. Thereafter, the checklist focuses on the estimation of the likelihood of an outbreak of a fire on the façade (Step 2-a) and on the damage caused (magnitude) of the considered credible event scenario (Step 2-b). The result can be an increase in the previous risk level compared to the basic line achieved in Step 1. If there are important differences among the façades systems, the assessment process suggests analyzing each configuration on their own. The checklist of this step (Step 3), goes hands by hands with some graphics schemes and constructive details aiming to reduce or even eliminate the previous increase of the assessed risk level. In the end, the reached level of risk could be acceptable or not, depending on the prefixed threshold.

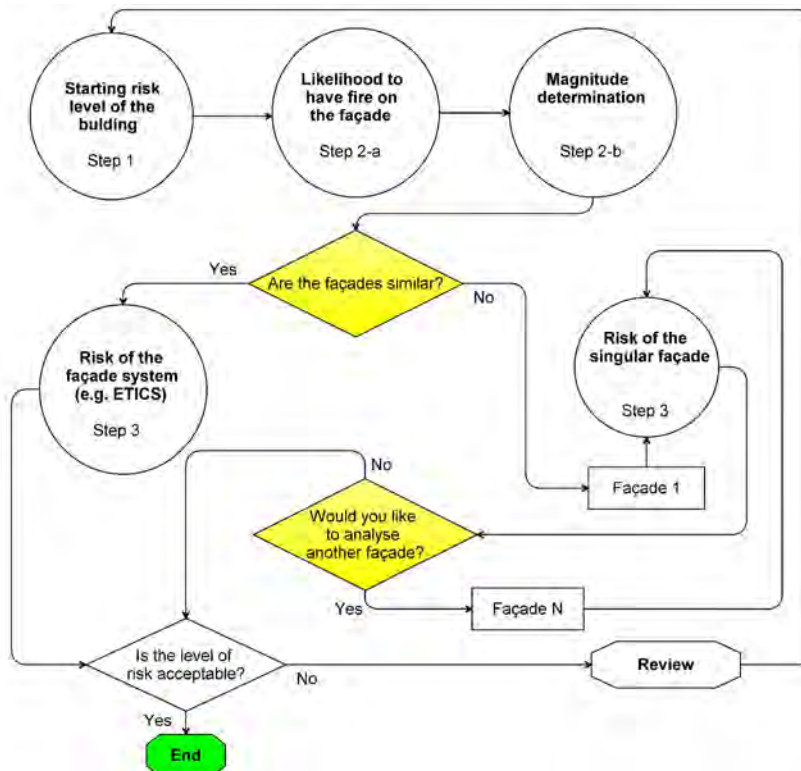


Fig. 1. Risk assessment flow-chart with the main steps of the process.

2.1 Estimation of a "starting risk level" of the building (Step 1)

To estimate the baseline “starting building risk” level, the typical parameters of fire safety engineering have been considered. In particular, the assessment process considers building size, since a bigger “area” increases the likelihood to have an ignition source and difference in elevation can change the magnitude due to the fire brigade effort during the fire shut down rescue operations.

Also, the average value of the generic fire load density, connected to the type of building occupancy, has been taken into account.

Then, in the process are evaluated the differences between buildings with incombustible structure (as masonry, reinforced concrete buildings, etc.) and buildings with combustible structure (as Cross Laminated Timber building).

Other typical parameters that have been considered are:

- escape route system;
- fire brigades' accessibility;
- compartmentation;
- fire detection and alarm system;
- presence or absence of active protection systems.

Figure 7 a) list an example of the questions of this first part of the checklist.

2.2 Analysis of façade fire scenarios (Step 2-a)

The likelihood that the fire can reach the façade can be estimated through an analysis of the proper scenarios. In particular, the three macro-scenarios normally adopted by various international guidelines are:

- a. internal fire that reach the facade coming out through openings;
- b. external fire directly affecting the façade. In this case the source of ignition could be due to the carelessness of the occupants, or at the ground level it may occur due to a burning vehicle, garbage bins on fire or vandalism;
- c. fire on an adjacent or nearby building that affects the facade of the considered building. In this case, the façade could go on fire for radiation or by direct combustion if the facades are contiguous.

The external fire scenario has been divided among fire at the ground floor and fire on balconies or other external spaces above the ground level, due to the differences of possible ignition sources (for example, the fire on the façade at the ground floor could be caused by a burning vehicle or by a vandalism, which cannot occur on balconies).

The check-list analyses the possibility to have one of the mentioned scenarios. Figure 7 b) reports as example a proposed check-list question.

a. Internal fire scenario

The facade may be involved by a fire originating inside a compartment, which comes out through opened windows, or comes out breaking the glasses after the flashover. The causes of an internal fire can be various. Measures to reduce the risk of fire inside the building can be identified by referring to the general principles of fire safety. The measures to reduce the likelihood that the combustible façade could be reached by fire may consist in prescriptions about the class of fire reaction of the portions of the facade surrounding the openings, in having provisions of firebreaks between the floors and the continuation of the system of internal compartments also on the façade. It is important to highlight that façade is both the facade system and the complex of window elements (frames, curtains, shutters, roller shutters, sunshades, etc.). Other important parameters are the vertical distance between the openings and the presence or absence of balconies able to contain the height of the flame coming from the opening placed below them.

b. External fire scenario

The façade can be involved by a fire that develops outside, at a certain floor level or at the base of the considered building.

The sources of ignition could be due to the carelessness of the occupants (cigarette butts, candles, etc.), or, in a roof, they could be due for example to the negligence of an operator who lay a waterproofing membrane by flaming, or a photovoltaic system or even a chimney.

As regards to the fire at the ground level, it is possible that it may occur due to a burning vehicle, garbage bins on fire or vandalism.

In addition to technical measures also management measures as the prohibition of accumulating waste or other combustible materials on balconies, the prohibition of smoking on balconies of public buildings, preventing the parking of vehicles near the building, etc., could be adopted.

c. Fire caused by an adjacent building on fire

In this case, the façade could go on fire for radiation or by direct combustion if the façades are contiguous.

2.3 Magnitude analysis (Step 2-b)

The common parameters of fire safety engineering have been considered to estimate the magnitude by the considered fire scenario. In particular, if occupants are awake or could be asleep, if occupants are familiar with the building or not, and it depends on the occupancy type.

In addition, in some buildings, there could be occupants that need additional help in case of fire (like children, old people, people that receive medical cures, people with disabilities, etc.) so these parameters are also considered.

Other considered variables are the crowding index, the presence or absence of safety teams or emergency plans, the distance to the fire brigade station and the presence of goods with relevant value for the collectivity (heritage buildings, museums, etc.).

Figure 7 c) reports as example a question asked at this step of the process.

At the end of this part, using a matrix to combine the level of likelihood and the level of magnitude for assessing the risk of fire, it is possible to observe the aggravation of the previous “starting risk level”, as it’s shown in Figure 2.

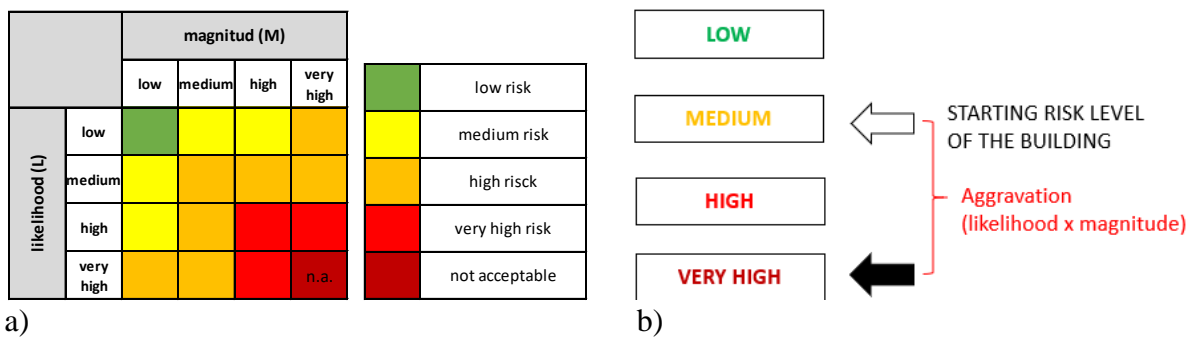


Fig. 2. a) likelihood – magnitude matrix; b) variation of the risk level in output from Step 1.

2.4 Fire behaviour of ETIC system with different insulation materials

The choice of the façade insulation material, as well as the choice of the material of the other components of the façade system, can only be made considering a series of aspects including but not limited to economic aspects, thermal conductivity of materials and not only referring to their reaction to fire. Some combustible material could reach a sufficient fire performance if considered as part of the finished system. Therefore, the determination of the fire behaviour of the façade can be done in a proper manner by means of a test method taking into account the most significant façade fire hazardous parameters. The proposed test method has been developed in order to reproduce the scenario of internal fire that reaches the façade through openings. To recreate this scenario, a 500 kW premixed gas burner has been used, positioned 5 cm below the edge of the façade, able to reach a constant flame height of about 120 cm.

The test was designed to have the following fundamental features:

- repeatability;
- the ability to be representative of the real façade fire scenario situation;
- the ability to return useful information for the definition of the main significant hazardous parameters.

In order to record the temperature variation, fifty-seven thermocouples have been positioned in different layers (Fig. 3-b). In addition, five radiometers have been positioned, two at the side, to measure the external thermal-electromagnetic radiation, including the angle effect, and two more to measure the radiation through the window (fig. 3-a).

Table 1 shows the executed test of ETICS with different insulation material and support.

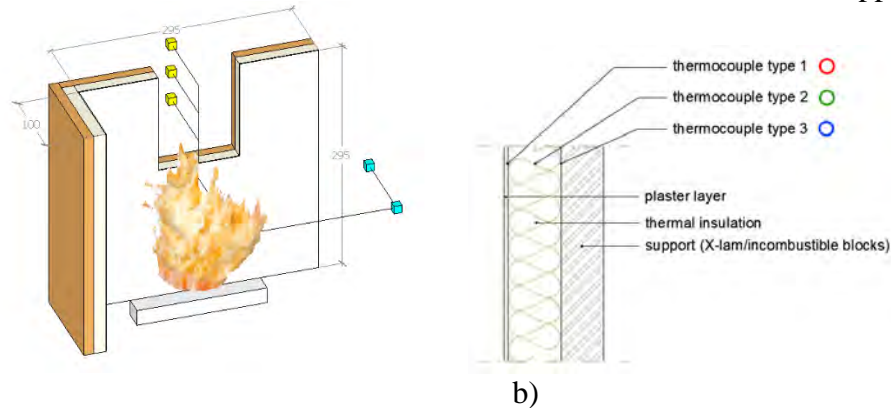


Fig. 3. a) view of the specimen position of the radiometers; b) position of thermocouples on the specimen layers.

Table 1. Executed tests.

test number	Support frame	Insulating material	plaster layer thickness	Reaction to fire insulation material
1	Autoclaved aerated concrete blocks	Mineral insulation boards	7 mm	A1
2	Cross Laminated Timber	Rock wool	7 mm	A1
3	Autoclaved aerated concrete blocks	Wood fibres	7 mm	E
4	Cross Laminated Timber	Wood fibres	7 mm	E
5	Autoclaved aerated concrete blocks	EPS	7 mm	E
6	Cross Laminated Timber	EPS	7 mm	E
7	Concrete blocks	EPS with graphite	20 mm	E
8	Autoclaved aerated concrete blocks	PIR (low performance)	7 mm	BS2d0
9	Cross Laminated Timber	PIR (high performance)	7 mm	BS2d0
10	Cross Laminated Timber	PUR (generic)	7 mm	F
11	Autoclaved aerated concrete blocks	PUR (for ETICS)	7 mm	E
12	Cross Laminated Timber	PUR (for ETICS)	7 mm	E

2.5 Integration of the risk assessment process with schemes and constructive details (Step 3)

The entire assessment process is integrated with technical solutions provided in the form of graphic schemes and constructive details. If the design solutions compliance with these schemes a determined level of building fire safety can be guaranteed. These schematic solutions give advice and support the designer in identifying the most vulnerable parts of the building façade. These parts of the building façade should have positive behaviour, in terms of fire reaction to prevent the occurrence of the fire scenarios. As an example, Figure 4 highlights the façade of the first floor (whose vulnerability couldn't protect from a fire that breaks out at the base of the building), the façade above the windows and the bands under the windows (that have to prevent the fire spread of an internal fire, along the upper floors or towards the roof) and the façade near balconies (that have to prevent the spread of a fire that breaks out on a balcony).

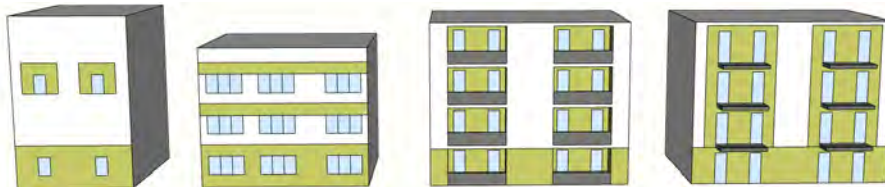


Fig. 4. Most vulnerable parts of the building that should have an incombustible façade system to prevent the occurrence of the typical fire scenarios and the consequent fire spread on the façade.

Alternatively, to provide an incombustible insulation material inside the ETICS façade, the executed tests have shown acceptable result in terms of reaction to fire behaviour also using a thick plaster layer over a combustible material as EPS (Expanded Polystyrene). Figure 5 compares the tests of an ETIC with EPS system with the classical 7 mm plaster and with the application of a 2 cm plaster layer. Anyway, the use of a plaster layer could be advisable only for building with incombustible structural frame (not for timber-made buildings).



Fig. 5. View of the executed tests of ETICS with EPS. a) test with the standard plaster (7 mm about); b) test with the thick plaster layer (2 cm).

As stated previously, for the identified vulnerable parts of the façade, some constructive details have been worked out. Figure 6 shows, as an example, a horizontal section of the part of the façade around a window. This is one of the vulnerable parts of the façade because, in case of fire that breaks out inside the building, it's directly affected by the fire coming from inside. The proposed solution makes use of incombustible insulation materials (see Figure 6, a)) or, alternatively, it could be used a thick plaster layer above combustible insulation, protecting with incombustible insulation the possible interstices.

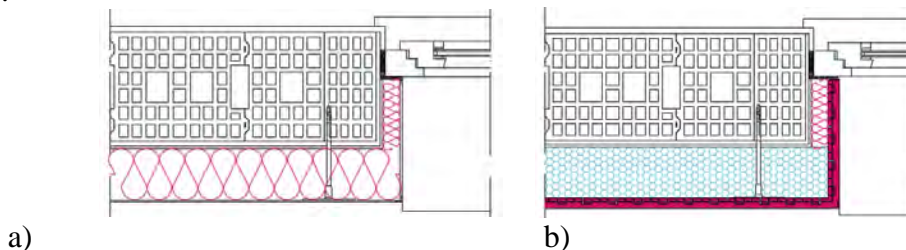


Fig. 6. Two typical solutions for the horizontal joint façade-window. a) solution with an incombustible insulation material; b) solution with a combustible insulation material under a 2 cm plaster layer.

The main considered parameters used for the checklist of this final part of the assessment (Step 3) could be summarized in:

- fire reaction performance classification in the identified vulnerable parts of the building;
- state of deterioration and thickness of the of the plaster layer on the ETICS in case of presence of combustible insulation materials;

- observed behaviour to internationally recognized intermediate-large scale fire tests;
- compliancy with the provided constructive details and schemes;
- presence or absence of possible ignitions sources (photovoltaic panels, chimneys, etc.).

As an example, Figure 7 d) shows as an example a question concerning the fire performance classification of the ETIC system at the ground floor (important to estimate the likelihood of occurrence of “fire at the base” scenario).

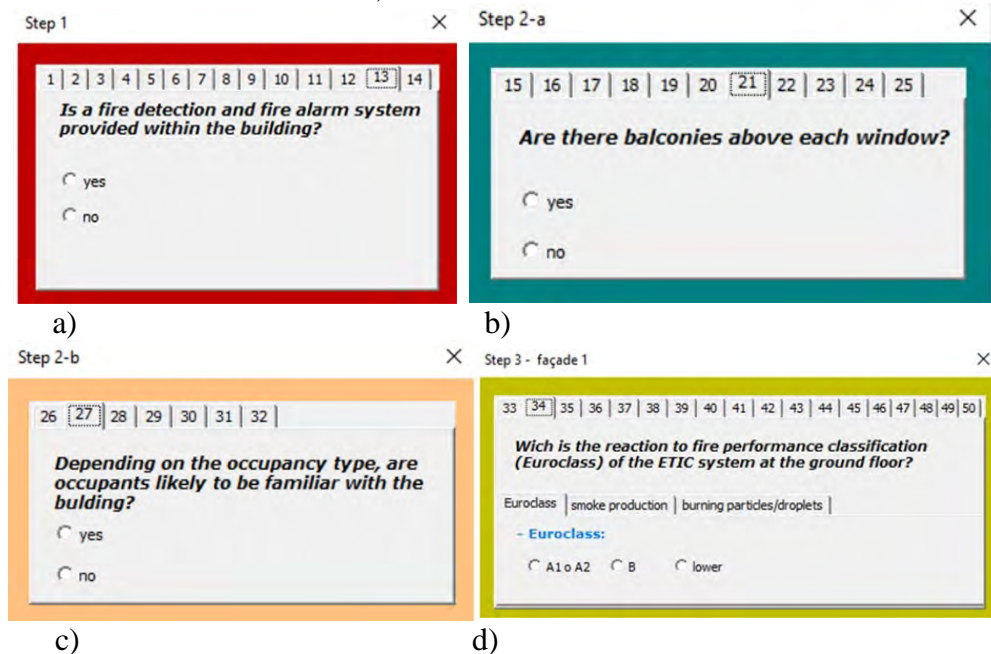


Fig. 7. Example of questions of the check-list. a) Step 1; b) Step 2 -a; c) Step 2-b; d) Step 3.

This last part of the process makes use of the matrix below (see Figure 8), to combine the output level of risk obtained from the previous part of the process (Step 2).

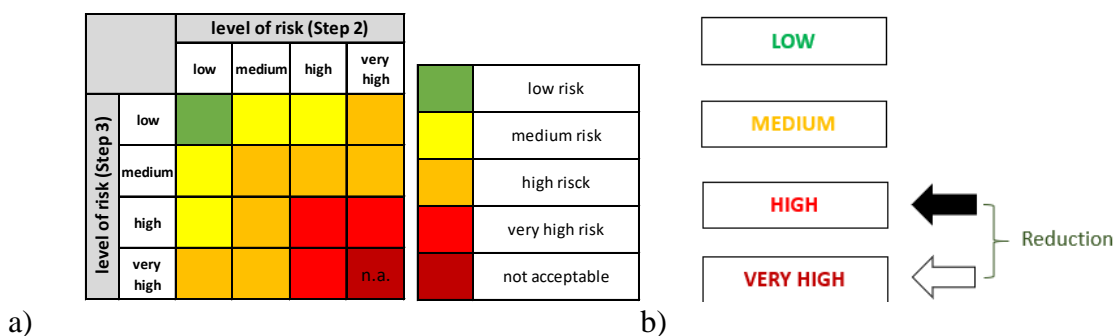


Fig. 8. a) final matrix; b) variation of the risk level in output from Step 2.

At the end the reached final level of risk could be acceptable or not acceptable, depending on the prefixed acceptability threshold. As an example, in case of a façade renovation aimed at an energy efficiency upgrade of the building, the threshold could be fixed at the baseline level in the Step 1 output from. This means that the new façade will not cause a risk aggravation. Otherwise, in case a new building design, every step of the process could advise the designer to minimize the risk level and the threshold could be fixed operating a cost-benefit analysis. However, the cost-benefit analysis must take into consideration the legislative requirements. The acceptability threshold can thus change depending on the considered design phase of the building, the aim of the intervention, the legislative requirements and, last but not least, the financial resources.

3 CONCLUSIONS

The fire risk assessment proposed methodology for buildings with combustible façade systems has been organized adopting matrices for combining the parameters that affect the level of risk, both in terms of likelihood and damage (magnitude). The main advantage of this approach is that the same level of safety could be obtained acting in different ways. This means that in a building with an incombustible structure and where occupants are most likely awake and familiar (e.g. offices, working places), it could be acceptable to have a façade with a lower fire performance behaviour. In a similar building where occupants could be asleep and unfamiliar with the places (e.g. hospitals, hotels) it will most likely be required a high fire-performance façade system.

The method has been based on the NFPA guideline, adapting the checklist to the Italian legislation, but especially simplifying the check-list to be useful also for reduced height buildings and for Cross Laminated Timber buildings: buildings with a different structure as buildings with a low-massive timber frame could be analysed by subjecting specimens to tests.

The proposed risk assessment structure, organized in two processes, allows a possible future extension and generalization to other façade systems different from ETICS (e.g. ventilated façades). In this case, it will be required to rely on appropriate test methods able to faithfully reproduce the fire behaviour of the system.

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A EUROPEAN FRAMEWORK TO ENSURE FIRE SAFETY IN TALLER BUILDINGS

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ABSTRACT

The Modern Building Alliance presents a framework which proposes a comprehensive and structured list of elements for consideration by Member States in their regulatory approach to ensure fire safety in high and mid-rise buildings. This framework fits with the EU subsidiarity principle and aids in structuring the exchange of information and best practices between Member States within the European Fire Information Exchange Platform (FIEP) established by the EU Commission in October 2017. A holistic approach enables consideration of, not only the building design and construction but also technical installations and fire safety management throughout the lifetime of the building, including clarification of the roles and responsibilities in the value chain. For façade system components, the use of large scale testing of the system is recommended as a starting point, complemented by clear information about the systems and applications in which products may be used. This paper also identifies the role of product manufacturers and of EU standards. The ultimate goal of such a framework is to provide a clear basis to Member state regulators and the construction sector, allowing identification of gaps and best practices for fire safety.

1 INTRODUCTION

The Modern Building Alliance gathers different trade associations and companies representing the plastics industry in the construction sector with the mission to support the EU in ensuring safe and sustainable construction. Plastics (thermoplastics and thermosets) are widely used in construction applications because of their properties contributing to energy efficient and sustainable buildings, from window frames and durable pipes to state-of-the-art insulation solutions. Ensuring fire safety is a prerequisite to deliver the maximum benefits of polymer products with regard to performance and sustainability. It's a driving force behind product design and manufacturing and a joint responsibility of the whole value chain involved in building and construction. Fire safe buildings need construction materials and products to be approved, installed and maintained responsibly and in accordance with all regulations. Indeed, many major fire incidents have in common a lack of compliance with regulations or standards [1]. It also became apparent that in some countries regulations might not be clear, and roles and responsibilities are not explicitly described [2] leaving room for interpretation and errors. Another factor is that it may not be clear how to assess the performance of a system, since different components are produced by various manufacturers, while the system assembly can be made by a third party. This system then may not comply with the appropriate regulation or there is a lack of evaluation of the system performance. Added to that is the fact that many EU countries have adopted a different large scale façade testing method with a variety of national criteria that are more or less adapted to specific building contexts. For example in the UK BS8414 [3] is a large scale test with a corner but no window opening, whereas the French test LEPIR2 [4] is also large scale but without a corner and with a window opening, and the German test DIN 4102-20 is a large scale test, but with a lower fire load than the former two tests. Combining all these aspects will potentially result in a situation where unsuitable products are used in a building either by predesign, or due to replacement of components in the field without substantiated evidence and a clear view on the impact on the performance of the system as a whole. In many cases these choices are made to reduce time or cost. As part of a successful fire safety strategy, the installation of active and passive fire protection measures is also crucial to detect a fire in an early stage, prevent fire spread and to ensure

compartmentation and safe evacuation routes for occupants. In addition to construction and installation aspects, problems with the organisation and maintenance of the building, for instance blocked evacuation doors, sprinkler valves shut off, or covered smoke detectors or dysfunctional alarms are frequently seen. A lack of redundancy in the fire safety design can jeopardise the overall fire safety strategy if one aspect is failing. In the proposed framework, the three identified key aspects Building, Installation and Organisation (BIO) are investigated in order to provide a clear foundation to Member State (MS) regulators and the construction sector, allowing identification of gaps and best practices for fire safety. The regulatory framework for buildings, installations and organisation is defined at national (or regional) level and MS must also ensure proper enforcement and compliance. The EU is providing the set of necessary standards to assess and report the performance of products and systems, allowing MS to define application-specific performance requirements. Finally, the roles and responsibilities in the value chain are discussed.

2 A HOLISTIC APPROACH TO ENSURE FIRE SAFETY IN BUILDINGS

2.1 Buildings

The definition of building categories in national regulations is influenced by many local factors. Some countries have developed different regulatory requirements for example for small, mid height and high rise buildings, other countries have specific requirements only for normal and for high rise buildings. For instance, the height limit for high rise buildings is 22 m in Germany, 18m in the UK and 28m in France. In addition, regulatory requirements in many countries depend on the type of use of buildings (i.e. residential buildings, offices, schools, and hospitals), which can be justified. Height limits do not need to be harmonised but should be defined locally in relationship with the adequate evacuation and intervention strategy, notably the available fire-fighting equipment. A European harmonisation of typologies definitions would be highly complex and bring little benefits but we recommend to each Member State (MS) to define its regulatory safety requirements based on the height and size of a building as well as on its type of use, as is done in some MS.

Regulatory requirements can be different for all these types of buildings, with performances defined by the fire safety strategy for evacuation, compartmentation, and fire-fighting. In addition to requirements regarding reaction and resistance to fire of the installed products, there should therefore be precision regarding the protective measures implemented, such as ease of evacuation (single stairs, protected or not...) and access for fire fighters. It is necessary that there is sufficient time to evacuate everyone from the building or to safe areas within the building. These safe areas are intended to assure the safety of occupants while the fire is active and while firefighting operations are ongoing. The most common safe areas are the stairwells and other escape routes, which need to remain isolated from fire and smoke. While such considerations are easier to integrate in new constructions, it must also be addressed for existing buildings, particularly when considering a renovation. Older buildings may not have appropriate escape routes and fire-fighting access. If these cannot be improved during a renovation it may be worthwhile considering installing fire doors, sprinklers or even demolition to build a new construction instead of conducting an extensive renovation.

Redundancies are necessary for all safety systems. Typical approaches are ventilated lobbies that create a buffer zone between areas with combustible products and the stairs, or creating a pressure differential between the lobbies and the stairs, preventing smoke from entering the stairs. Another common form of redundancy is to prevent fire or smoke from escaping the sector of the building where the fire originated. This is achieved by means of fire and smoke compartmentation preventing or delaying the progression of a fire. It is important to note that robustness and redundancies are more crucial for high rise buildings than for less tall structures because of the ease of evacuation of the

latter. Additionally, for high rise buildings the evolution of a fire as it scales up becomes extremely complex [5] and the performance of both fire safety measures and the fire brigade is stretched.

For tall buildings it is critically important to avoid fast fire spread along the façade cladding or insulation system, which potentially would bypass internal compartmentation. The performance of a façade cladding system cannot be assessed based only on reaction to fire classifications of the products applied because the performance of the façade system depends on a number of factors:

- The combination of different products in a façade cladding system leads to a different fire performance than for the single products.
- Even if only non-combustible products are applied, the geometry (i.e. ventilation gaps, windows detailing) can play an important role in fire spread [6].
- Fire barriers have been developed for different types of façade systems (ventilated façade systems, ETICS, cavity walls). Small scale tests alone are not sufficient to prove the effectiveness of these barriers.

Therefore it is essential to use large scale tests as the basis for requirements for all façade systems for tall buildings— regardless of combustibility of individual components –considering all elements of a façade system. Together with the results of the test it is of utmost importance, that the tested system is described exactly and unambiguously regarding the properties of the tested materials, products and assembly. Harmonised product standards or harmonized technical specifications are needed to define what has to be reported. If for a façade cladding/insulation system, the fire performance has been verified with such a large scale test, it is necessary to make sure, that installed façade systems still meet the defined performance criteria, but on the other hand it is not feasible to perform large scale tests for every small variation of a façade system, like change of thickness of the insulation or other components. Hence, clear rules are needed for the extended application of the large scale test results of systems to assure maintenance of the fire performance with defined changes. For instance, using intermediate scale testing such as ISO 13785 to test most significant variations can be part of this process[7]. The fire safety community should be developing such guidelines. As fire regulations are in most cases developed to be robust and fit for all solutions, the safety margins of the latter are implicit and cannot easily be quantified, and this sometimes can bring an unnecessary burden for the construction sector. This is often the case for high rise buildings. Member States (MS) should therefore also consider being open to fire safety engineering solutions which can more easily quantify the safety level of their solutions and their safety margins.

2.2 Installations (in MS regulatory framework)

The fire safety concept and strategy for a building can only work, if the installations relevant for fire safety are in place, undamaged and working well. The most important technical installations are:

- Smoke and CO detectors and alarm systems are an absolute must. For larger buildings it is essential to have a sufficient number of smoke detectors in every compartment and connected alarms which make sure that occupants who are still far away from the fire as well as fire brigades are alerted immediately.
- Fire suppression installations, including sprinklers can be very effective in many situations, such as high rise buildings or large assembly buildings, as they assure that starting fires grow slowly or remain small and the consequences of fires are limited.
- Smoke dampers and smoke ventilation systems can be required to keep escape routes free of smoke.
- For the fire brigades it is important, especially important in high rise buildings that all necessary installations are in place to support the fire-fighting strategy as: adequate water supply, building plans with information on gas and electricity supply.

The fire safety concept of a building needs to verify, that the safety level can be met with these installations and that they have been tested, installed and inspected correctly.

2.3 Organisation (in MS regulatory framework) for the building maintenance and renovation process

All the requirements mentioned hereafter are not specifically defined in a legal framework; however they should be taken into account when a building is planned.

- To guarantee the safety of people in a high rise building in case of a fire, it is necessary to implement an adapted fire safety strategy. This is a concept by which various measures are taken to guarantee a societally accepted adequate level of safety for people. However, these objectives are not easily quantifiable and further analysis is needed.
- For new construction and renovation, it is necessary to provide verification that the systems and products installed correspond to the systems designed (quality control, trained/accredited installers, definition of responsibilities...). This is valid for all building components, products and installations. It starts from the market surveillance of construction products that must be organized in MSs and extends to fire inspection of installations. Non-compliant electrical components or incorrectly installed fire doors are examples of possible concerns. Fire inspections can be categorized into three types, (1) inspections of newly constructed buildings, (2) inspections of existing buildings undergoing renovations, and (3) inspections of existing buildings for routine safety checks [8]. Lack of inspection or negligent inspection practices can result in casualties and fire loss. In 2006, an assessment of the U.S. fire service found that 25.2% of responding fire departments reported that no one conducts fire-code inspections within their communities. As a result, it was estimated that 20.3 million people, or 7% of the US population, live in communities where no one conducts fire-code inspections [8].
- It is important to clearly define fire safety responsibilities, emergency procedures and emergency training for buildings where appropriate (e.g. hospitals, schools, public buildings).
- The organization of the fire brigades and adequate fire-fighting equipment should also be seen as part of the whole fire safety framework. It is not necessarily the same equipment that is needed for tackling fires in high rise buildings and in rural areas.
- For existing buildings regular control is needed, to make sure that all parts and installations of a building are still in place, undamaged and functioning correctly. Escape routes need to be free from obstructions and in no case to be blocked. All installations require regular maintenance and control, and occupants should be aware of the fire safety measures as well as evacuation plans.
- In high rise buildings, evacuation is often only made from the level where the fire takes place and from adjacent levels, while occupants on other levels can remain in place. This strategy is named “stay put”. In case of a façade fire, where the fire has spread vertically and spread over more than two floors, this strategy is jeopardised, especially if stairs are unprotected. That is often the case of old buildings that do not have to comply with current regulations. Hence, reflection should be made on whether occupants should be told or not to evacuate the building in case of a façade fire. As mentioned earlier, the performance of the façade in case of a fire is only one of many factors impacting the safety of occupants. It is important that the fire does not enter the building; that fire detection is adequate; and that safe escape ways are provided. All the elements together contribute to the level of safety. This has been

demonstrated in a number of fire incidents (some are listed in [7]) where all occupants were able to evacuate safely regardless of the façade fire spread.

- For façade systems it is especially important to ensure that the complete build-up corresponds to the system tested and approved.
- Finally, it is also important to consider the social factors in the analysis of fire statistics and to get more detailed knowledge about the relevant type of risk factors, who dies in fires and why. In Norway, it was shown for a sampled population that 39 % of all fatal fires are caused by open fires, and 34 % of these are caused by smoking. Additionally, other risk factors were systematically identified such as substance abuse, mental illness, and alcoholic influence [9]. Estonia recently shared information during the Fire Information Exchange Platform (FIEP) on their recent successful initiatives on fire safety, demonstrating the large potential for improvements thanks to well-targeted prevention measures focusing on the benefits of smoke detectors, the risk of smoking and open fires, and the danger of obstructing escape routes by providing relevant public awareness, home visits and media campaigns, child education. This targeted campaign resulted in a reduction of 50% of domestic fires in ten years.

To achieve all the objectives aforementioned, this is necessary to:

- organize control of existing buildings (maintenance and modifications);
- have accredited professionals performing the roles related to fire safety of the building (e.g. fire fighter, fire safety manager, maintenance); and
- mandate fire brigades to work on prevention (safety checks, awareness campaigns, evacuation plans).

Thanks to an improved knowledge, better engineering, and appropriate regulations, fire deaths are at their lowest level in many parts of the world. In the last decades, we have seen a reduction in the number of fires across Europe that is a result of the setup and the improvement of fire safety regulations. However, tragic fires still occur. By analysing the conditions that led to these regrettable incidents, it has become clear that there were systematically breaches of one or several existing regulations. In many cases, compliance with fire safety regulations would have avoided the ignition, propagation and the extensive loss of life. That is why fire inspections are important in buildings throughout the lifecycle of a building.

3 ROLES AND RESPONSIBILITIES IN THE VALUE CHAIN

3.1 The role of Europe and Member States

Fire safety is generally regulated nationally by Member State (MS) regulators. Buildings across MSs differ based on construction traditions in different regions and societies which influence fire strategies. A simple example is the difference between the buildings in Mediterranean and Scandinavian regions. Not only are weather conditions different, but so too are the choice of construction products and local preferences. Fire safety regulations are also historically influenced by the firefighters' means of intervention and the means of egress of a building's residents. Because of the subsidiarity principle, the EU must only act where there is clearer added value, particularly for the single market. For these reasons, the European Union is not able to impose a single set of fire regulations. Hence, the European Union needs to maintain room for local needs and local regulations, while construction products that are able to travel across borders, are therefore regulated at EU level. MSs should therefore remain free to design their fire safety regulations by taking into account the local specificities in terms of building design solutions, materials, use patterns and climate. The EU should therefore continue to respect the subsidiarity principle in order to have effective fire safety strategies. Conversely, harmonised practices in MSs facilitate the circulation of construction products in the European market. This is typically done through adequate European harmonised standards that

are referenced in MSs' regulatory framework. These standards ensure that products from all European countries are tested and classified identically. The description of the products, as well as the classes and levels for different properties, are defined in these standards in a way, which allow MSs to define their appropriate safety levels on that basis. The rules for CE marking and AVCP (Attestation and Verification of Constancy of Performance) are defined strictly at the European level and controlled by appropriate national market surveillance by MSs. On this basis, MSs are able to define regulatory requirements so that the intended safety level is met. In addition, it is important that MSs ensure that the systems and products installed correspond to the systems designed. To achieve this, not only quality control of the applied products is necessary – it is key that they are installed correctly. Therefore during construction works responsibilities have to be defined clearly and for critical installations only trained craftsmen should perform the task.

Reaction and resistance to fire tests that have been developed for CE marking are usually small and medium-scale. The European classification criteria have been linked to the performance of a large variety of construction products. All tests, regardless of their size, have to consider the fire scenario in which the construction product is burning. A benefit of small-scale tests is that the cost of these tests is limited. They facilitate development of new products and allow even SMEs to test and market their products while respecting fire safety standards. A façade fire scenario has been left aside in this harmonisation process in the past due to the complexity of the problem. There is a broad agreement that only a larger scale test, simulating exposure of a realistic façade construction to a realistic fire source, is needed to assess the fire performance of such a façade construction. The European Commission is currently preparing a decision on how and where a harmonised test method will be developed under the Construction Products Regulation. The EC facade study [10] proposes to incorporate DIN 4102-20 and BS8414 [3] or a new one based on both former tests. The plastics industry supports the harmonisation of large-scale fire tests for (insulated) façade constructions and calls for standardisation bodies to be mandated to finalise and validate the method developed by the European Organisation for Technical Assessment, which incorporates the most common used test methods in MSs. This would also benefit the development of a harmonised test method for kits involving thermal insulation of buildings such as External Thermal Insulation Composite Systems (ETICS) which are not yet available and so national provisions still apply [11]. Ideally, a large scale test is necessary to assess fire safety of the complete construction. While this test and classification system is being prepared, urgent clarification is needed on how and for which types of products it will be applied.

In many cases the single components for façade systems are tested and classified regarding their fire performance separately or sometimes as a kit e.g. in ETICS. In case a façade comprises of single products sold separately but the complete façade system is assembled by the company doing the construction or renovation of the building, it might not have been tested appropriately as the responsibility is not well defined. Already today an ETICS system can be approved and CE marked as a system, based on an EOTA Guideline. But there are no product standards for other façade cladding systems.

In 2017, the European Commission announced a new initiative to enhance fire safety cooperation across EU MSs. Under the leadership of the Commission's DG GROW, the Fire Information Exchange Platform (FIEP) gathers MS authorities and stakeholders from civil society and industry. The FIEP aims to facilitate the exchange of information between the competent MS authorities and other stakeholders, allowing them to benefit from lessons learned and best practice regarding fire safety. It is expected to enhance the capabilities of MS authorities to fulfil their tasks in full knowledge of the advantages and disadvantages of the regulatory choices they have to make. The following areas have been identified by FIEP members for further cooperation:

1. Common terminology and fire statistics
2. The application of fire prevention principles
3. The regulatory approach for new products, including high-rise buildings
4. Exchange of experience from fire accidents
5. Fire engineering approach in building regulations

The FIEP might assist in several of the above points. Sharing best practice between MSs and key stakeholders can create a better understanding of how countries already using large scale façade testing consider variations between the tested constructions and the final details of the construction. A lack of accessible, comparable statistical data is one of the critical issues which have hampered efforts to protect European citizens. While many MSs have introduced initiatives to improve fire safety nationally, the results of these are often not shared effectively and the influence of changes to the system is often unknown. This means successful projects cannot easily be replicated in other countries and it makes it difficult to learn from initiatives that are not as successful as desired. With regard to the work stream on fire statistics, the European Commission announced that it will benefit from the pilot project on fire safety statistics voted by the European Parliament in September 2018. This will help to complement other pioneering work already done in gathering EU-wide data [12,13].

3.2 The role of the product manufacturers

Product manufacturers have direct roles, contributing to fire safety of buildings:

- Contribute to the development of robust product standards
- Have their products classified and labelled according to these standards and to have adequate quality control
- Present unambiguous and clear information about their product performance and general use guidelines
- For façade system components, conduct large scale system testing and provide clear information about the systems and possible applications of the products.
- Contribute to training of designers and installers
- Manufacturers cannot be held liable for a product that has been misused or installed in its actual application in a way that is not compliant with regulation. Hence the role and responsibility of the value chain should be clarified.

Product manufacturers are also contributing via industry association activities:

- To show leadership on fire safety and contribute to their National building fire regulation developments and reviews
- To participate in the FIEP workstream, set up by the European Commission
- To propose solutions to improve fire safety in the EU

3.3 The role of other stakeholders

During planning and construction of new buildings and renovation measures, various stakeholders can and should contribute to fire safety. The contributions of architects and fire safety engineers are needed to develop a holistic fire safety plan for the complete building. Firefighters should be included in the approval process for the planned construction. They should also take a role in inspection of buildings in use, to make sure that fire prevention and detection measures are working and evacuation routes have not been obstructed. There is currently no common agreement on what is the competency required from these professionals or on competency verification approaches that should be used [2], to guarantee that those involved in the design, construction, regulatory approval, hand-over and maintenance of the building components and installations can deliver societally acceptable levels of

safety [14]. The complexity of building systems and the quality of regulatory approval should be recognised.

4 CONCLUSIONS

- In this paper we have listed a number of important aspects separated into three categories: Building, Installation, Organisation, which should be considered when developing and reviewing the building regulations of a country. While fire safety regulations remain a Member States' competence, structuring the key aspects in such a framework can facilitate the exchange of information between Member States.
- Even if sometimes regulations have been robust over the last decades, they need to be reviewed systematically to make sure that they are still relevant and proportionate regarding current practices and the impact on the construction sector. More importantly, regulators should consider feasible solutions applied to old buildings. Often these buildings do not fall under new or amended fire safety regulations but are more prone to fire events simply due to lack of maintenance.
- The roles and responsibilities of National regulators, the European institutions and product manufacturers have been presented. However, the connections between other stakeholders of the value chain needs further clarification in each country to ensure that objectives are reached and that gaps are identified.
- The Fire Information Exchange Platform (FIEP) was set up by the European Commission and gathers Member State authorities together in order to facilitate the exchange of information between these authorities and other stakeholders. The EC intends the platform to be used to promote best practices across Europe.
- MBA calls upon Member States to ensure the strict enforcement of existing regulations and standards.
- As fire regulations are most of the time developed to be robust and fit for all solutions, the safety margins of the latter are implicit and cannot easily be quantified, which sometimes can bring unnecessary burden for the construction sector. Member States should also consider being open to fire safety engineering solutions which can more easily quantify the safety level of their solution and their safety margins.

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PERSPECTIVES FOR ONGOING REVISION OF THE BELGIAN FIRE SAFETY REGULATION FOR FACADES AND PRACTICAL SOLUTIONS FOR TIMBER FRAME FACADES

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ABSTRACT

In the light of the recent façade fires that took place in high-rise buildings, and more particularly the tragic events of June 2017 in London, the High Council Fire Safety of the Ministry of Interior in Belgium has recently approved (March 2019) a new regulation regarding the fire safety of façades. The new requirements will be compulsory for all new buildings in Belgium as soon as the Royal Decree will be updated (foreseen in 2020). The measures that need to be taken according to the new Belgian regulation to reduce the fire spread via the facades will be detailed in this paper.

A research project concerning optimization of the performances (thermal insulation, airtightness, acoustical insulation and fire-behavior) of timber frame facades led to the development of new solutions for wooden claddings with class D-s3, d1 in end-use conditions (requirement for low-rise buildings in Belgium). The research project led also to the development of fire-resistant timber frame facades that are positioned against a concrete floor. The performed fire-resistance tests according to the standards EN 1364-4 and some of the solutions are presented in the paper.

1 INTRODUCTION

Fire spread via the facades mainly occurs in one of the following three schematic manners [1].

1. **Fire spread via the surface of the facade cladding:** to slow down this type of spreading, one generally needs to take measures relating to the reaction to fire of the facade cladding (*Fig. 1*)
2. **Fire spread from one compartment to another** (from floor to floor, for example): either internally, via the junction between the floor and the facade element or externally, when the flames are coming out of the facade by passing, for example, through glazed elements that are not fire-resistant. To remedy this type of spreading, it is necessary to ensure the fire resistance of the junction (between the floor and the facade) and that of the facade element at floor level (*Fig. 2*)
3. **Fire spread within the facade system** via combustible components (e.g. exposed insulation), the ventilated air cavity located behind the cladding (chimney effect), ... One can reduce this risk by using, amongst others, non-combustible or low-combustible elements, by protection the combustible element (panels with K₂ 10 or K₂ 30 protection classes), by interrupting the combustible insulation layers, the ventilated air cavity,

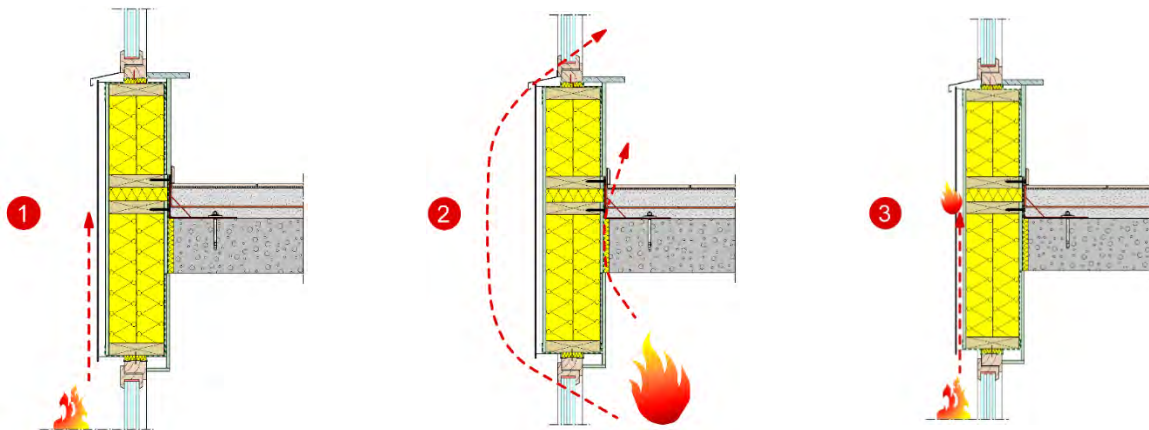


Fig. 1 Schematic manners of fire spread via the facades [1]

2 REGULATORY FIRE SAFETY FRAMEWORK IN BELGIUM AND ONGOING REVISION FOR FACADES

2.1 Belgian Royal Decree ‘General Fire Safety Requirements’

The Belgian Royal Decree of 7 July 1994 (and its modifications) [2] stipulates the general requirements for fire and explosion prevention with which all new buildings must comply. The Decree makes a distinction between the heights of the buildings: low-rise buildings ($h \leq 10$ m), mid-rise buildings ($h \leq 25$ m) and high-rise buildings ($h > 25$ m).

This Royal Decree ‘General Fire Safety Requirements’ applies to all new buildings. The regulations therefore do not apply to existing buildings, nor to renovation works on existing buildings, neither to single-family dwellings. The Belgian Regions and Communities have the competence to issue other decrees supplementing the Royal Decree, in order to take the specific nature of certain buildings into account.

2.2 Existing regulatory requirements applicable to facades

The Belgian Royal Decree of 7 July 1994 defines the requirements intended to limit or to slow down the fire spread via facade claddings. These requirements relate to the reaction to fire of the facade cladding and allow to avoid the risk ① (fire spread across the facade surface) identified in chapter 1.

The facade claddings on low-rise buildings have class D-s3, d1. The facade cladding on mid-rise and high-rise buildings have class B-s3, d1. A maximum of 5% of the visible surface of the facades is not subject to these requirements.’

It is important to stipulate that the requirements apply to the façade claddings in their **end-use conditions**, with the consideration of the possible impact of underlying layers of materials and their method of fixing. The facade cladding on which the reaction-to-fire requirement applies cannot therefore be considered individually, but as it is executed on site.

The Belgian Royal Decree establishes measures intended to limit or to slow down the fire spread from one compartment to another via the facades both vertically (towards the top) and horizontally. These measures aim to limit the risk ② (internal and external fire spread from one compartment to another) identified in §1.

- In order to limit the risk of internal fire spread, the junction between the compartment elements (floors for example) and the facade must have an EI 60 fire resistance, except in low-rise buildings (*Fig. 2*).
- In order to prevent the external fire spread from one compartment to another, the facade element at the level of each compartment wall (storey floor for example) must show a certain level of fire resistance for mid-rise and high-rise buildings. The facade element has an E 60 fire integrity and a minimum developed length of 1 m at the compartment floor level (*Fig. 2*).

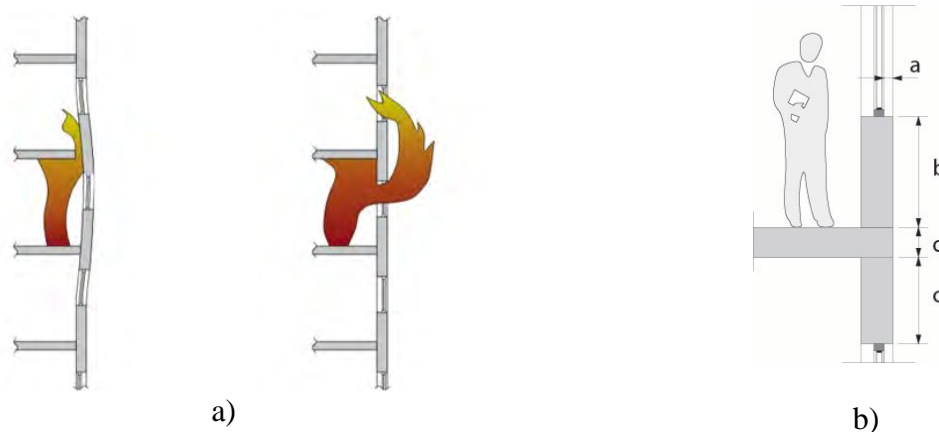


Fig. 2 a) Internal and external fire spread from one compartment to another; b) Façade element with an E 60 fire resistance with min. length $a + b + c + d \geq 1\text{m}$

2.3 Perspectives for ongoing revision of regulatory requirements applicable to facades

At present, the risks of fire spread within the facade system itself (see §1, 3) cannot be evaluated directly according to European testing standards. These are thus not explicitly covered by the regulatory requirements in Belgium. In accordance with the stipulations of the Belgian ministerial circular relating to the fire services report, the fire service may suggest recommendations on this subject within the framework of its advice related to the permit application.

The High Council Fire Safety of the Ministry of Interior in Belgium has recently approved a new regulation regarding the fire safety of façades. The new requirements (see *Table 1*) will be compulsory for all new buildings in Belgium as soon as the Royal Decree will be updated (foreseen in 2020).

Table 1 – New requirements regarding to reaction to fire of components of facades

Type component of the facades	Conditions	Type buildings		
		High-rise building ($h > 25\text{ m}$)	Mid-rise building ($10 \leq h \leq 25\text{ m}$)	Low-rise building ($h < 10\text{ m}$)
External claddings	End-use	A2-s3, d0	B-s3, d1	C-s3, d1 / D-s3, d1
Other substantial components (e.g. insulation)	As placed on the market	A2-s3, d0	A2-s3, d0 or E if fire barriers	E
		E if fire barriers and completely protected K ₂ 30	E if completely protected K ₂ 10	/

The requirements apply to **facades claddings** in their end-use conditions. The Royal Decree stipulates however that the underlying layers must not be taken into account in the evaluation of the reaction to

fire class of the claddings if they are protected by a panel with a sufficient ‘fire protection capacity’, K₂ 30 for high-rise building and K₂ 10 for mid-rise and low-rise buildings.

For the **other substantial components (e.g. insulation)**, the requirements apply to product as placed on the market.

- For **high-rise buildings**, the insulation must be non-combustible (class A2-s3, d1). The insulation can be combustible (class E or better) if it is completely (all sides) protected K₂ 30 and interrupted by a fire barrier (continuous non-combustible insulation type rock wool) every two levels
- For **mid-rise buildings**, there are three options
 1. Either the insulation is non-combustible (class A2-s3, d1)
 2. Either the insulation is combustible (class E or better) but completely protected K₂ 10
 3. Either the insulation is combustible (class E or better) if fire barriers are foreseen. The fire barrier consists in interrupting the combustible insulation and, if present, the continuous air cavity in the event of fire (*Fig. 3*). For facades with a continuous air cavity, EPS and XPS are excluded.

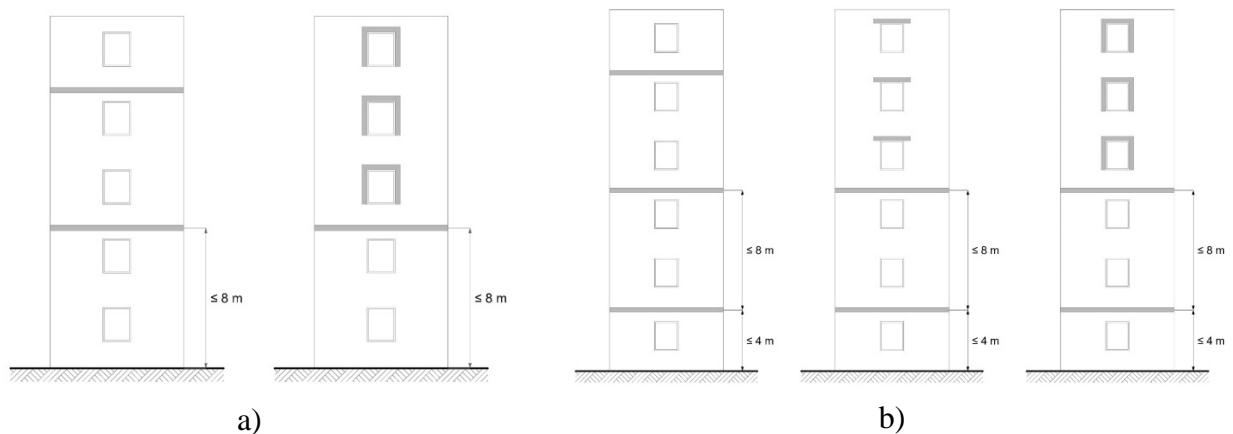


Fig. 3 a) Fire barriers for facades with continuous air cavity (ventilated facades, facade masonry);
b) Fire barriers for facades without continuous air cavity (ETICS)

Instead of the standard solutions proposed for mid-, high- and very high-rise buildings, it would also be possible to prove the conformity of the facade system by subjecting it to a large-scale laboratory test. This test would allow manufacturers to demonstrate that their system does not present any risk of fire spread. Currently, there is no standardised test of this type in Europe but a large number of national methods, which are all very different¹. The development of a harmonised method is under way at European level.

3 REACTION TO FIRE OF WOODEN CLADDINGS FOR LOW-RISE BUILDINGS

3.1 Introduction

The facade claddings on low-rise buildings have class D-s3, d1. As explained in §2.2 and 2.3, the requirements apply to facades claddings in their end-use conditions. The facade cladding on which

¹ The Belgian regulation will accept the following national tests for high-rise and mid-rise buildings: BS 8414-1 (criteria LPS 1581), BS 8414-2 (LPS 1582), LEPiR 2 (criteria “Arrêté français du 10-09-1970”) and for mid-rise buildings only: DIN 4102-20 (criteria DIBt-zulassungen für fassaden). Other national tests could be used but should be approved by the Commission of Deviation of the Minister of Interior.

the reaction-to-fire requirement applies cannot therefore be considered individually, but as it is executed on site (*Fig. 4*), i.e. including the possible impact of underlying layers of materials and their method of fixing.

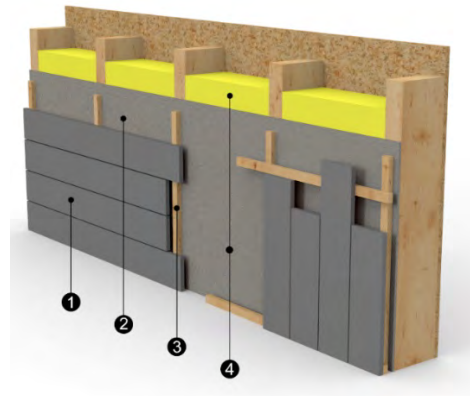


Fig. 4 – Wooden claddings in a timber frame facade – end-use conditions.
(1) cladding (2) air cavity (3) supporting

The Commission Decision 2006/213/EC established the classes of reaction to fire performance for certain configuration of wooden claddings. Wooden claddings without fire-retardant can reach the D-s2, d0 class based on the condition mentioned in this Commission Decision.

3.2 Test programs for wooden claddings without fire-retardant treatment

A test program has been performed in order to propose new solutions of wooden claddings without fire-retardant treatment and respecting the required class for low-rise buildings in Belgium. SBI-tests (EN 13823 [3]) have been performed on different configurations of wooden claddings: different types of timber frame facades (foils, boards, insulations), with and without open joints, wooden claddings (type, density and thickness), a ventilated air cavity² (different thickness).

Tests were also performed on identical cladding-systems (wooden cladding with open joints and with CaSi board as supporting construction) without waterproofing membrane or with different type of waterproofing membranes. The results confirm that foils, e.g. for protection against moisture, have an insignificant influence on the main reaction to fire class of the cladding system (*Fig. 5*)

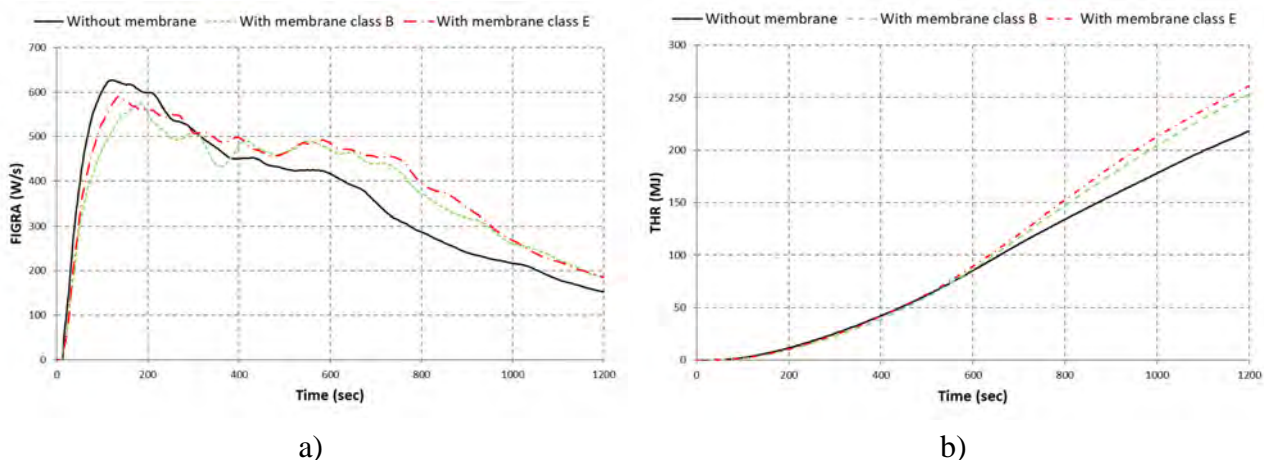


Fig. 5 a) FIGRA (W/s); b) Total Heat Release (MJ) during SBI-tests on different cladding-systems

² In Belgium, the technical Code of Good Practice NIT 243 recommend always a ventilated air cavity (min.) for wooden cladding to ensure the durability and avoid deformation.

The last confirmation tests are ongoing, and the results should be confirmed and available for September 2019. The configurations (class D-s2, d0) should have the following characteristics (to be confirmed with the last ongoing tests), based with interpretations of the results based on the Position Paper Reaction to fire of untreated and fire-retardant treated wood construction products:

- For **wooden claddings with open joints**

1. Wooden cladding: Larchwood (density about 650 kg/m³), thickness 21 mm, width 50 to 100 mm, open gap 10 mm, vertical or horizontal
2. Ventilated air cavity with wooden (counter-)battens
3. Underlying layers: board with class A2-s1, d0 and class K₂ 10

- For **wooden claddings without open joints**

1. Wooden cladding: min. density 450 kg/m³, thickness 18 mm, vertical or horizontal
2. Ventilated air cavity with wooden (counter-)battens, min. 40 mm (vertical), 20 mm (horizontal)
3. Underlying layers: particle board (density \geq 510 kg/m³, class D-s2, d0 or better, thickness \geq 10 mm) and cellulose insulation (class B)

4 FIRE RESISTANCE OF TIMBER FRAME FACADES

4.1 Introduction

The mix of materials for building construction has certain advantages and can often optimize the performances. It is not surprising that more and more buildings, both renovations and new constructions, are designed with a concrete main structure and a timber lightweight facade. If the latter is particularly well suited to meet the thermal insulation requirements of buildings, respect for the strictest fire safety measures, however, can cause problems in practice.

A research project led to the development of optimized timber frame facades which meet high thermal, acoustical and fire resistance performance. The timber frame facades, positioned against a concrete floor, have been evaluated according to the standards EN 1363-1 and EN 1364-4 [4]. A first configuration has been developed without fire resistance panels. In this configuration, the panels are optional both on the inside and on the outside to ensure fire resistance. They shall be selected according to other considerations, notably their acoustic, hygrothermal and/or aesthetic properties.

This solution has been completed with a series of other configurations for timber facade elements with an E 60 fire resistance. The latter are made up of specific inner and outer panels surrounding an insulation material (rock wool, glass wool or cellulose). Some configurations include rectangular timber studs, others I-shape wood joists (more commonly known as I-joists). One must ensure that these solutions are implemented while respecting all parameters, in accordance with the tests conducted (type and thickness of inside/outside panels, type of insulation, type and section of timber elements, type of sealing, ...).

4.2 Fire resistance tests on timber frame facade

Curtain walls with spandrels placed in front of the floor (upstand, downstand or combination of both) have to be tested in according to EN 1364-4 (or EN 1363-3). Traditional curtain walls have already been tested but very few timber lightweight façades have been evaluated by test. Fire tests according to EN 1364-4 have been performed. The tested configuration is illustrated at the *Fig. 6*.

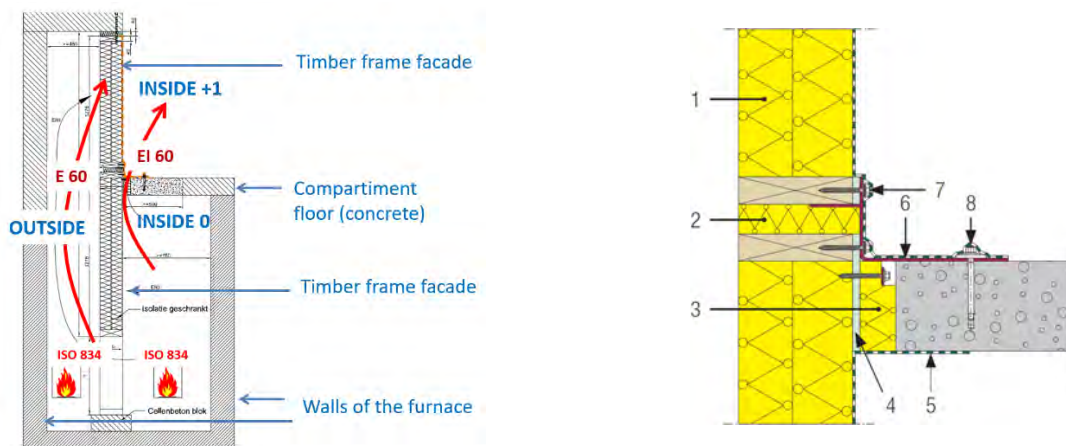


Fig.6 Tested configuration according to EN 1364-4

Specific attention has been given in order to respect the fire requirement but also the thermal, air tightness and acoustical requirements. Attention has also been given to the air tightness, thermal and acoustic performances. The first test having been carried out without cover panels both inside and outside, these are optional, in this configuration, to provide the required fire resistance. Their choice will be based on other considerations, including acoustic, aesthetic, hygrothermal and reaction to fire. On basis of the results and interpretations of the fire test, robust details have been developed (see Fig. 8) with the following main characteristics

- Penetration seal with stone wool (density 45 kg/m³, 20% compression, min. height 150 mm)
- Fixing of the structure of the timber façade with steel anchors positioned above the floor foreseen at each floor
- Timber façade in front of the floor (1275 mm upstand and 1275 mm downstand) – composed of timber studs (C24, min. 38 x 190 mm, every 600 mm max.) and filled with stone wool insulation (min. 190 mm, density 45 kg/m³)

The fire resistance timber facades have a developed length of minimum 1 m to fulfill the Belgian regulation [1] [2]. It can be designed as lintel, parapet or a combination of both – Fig. 7.

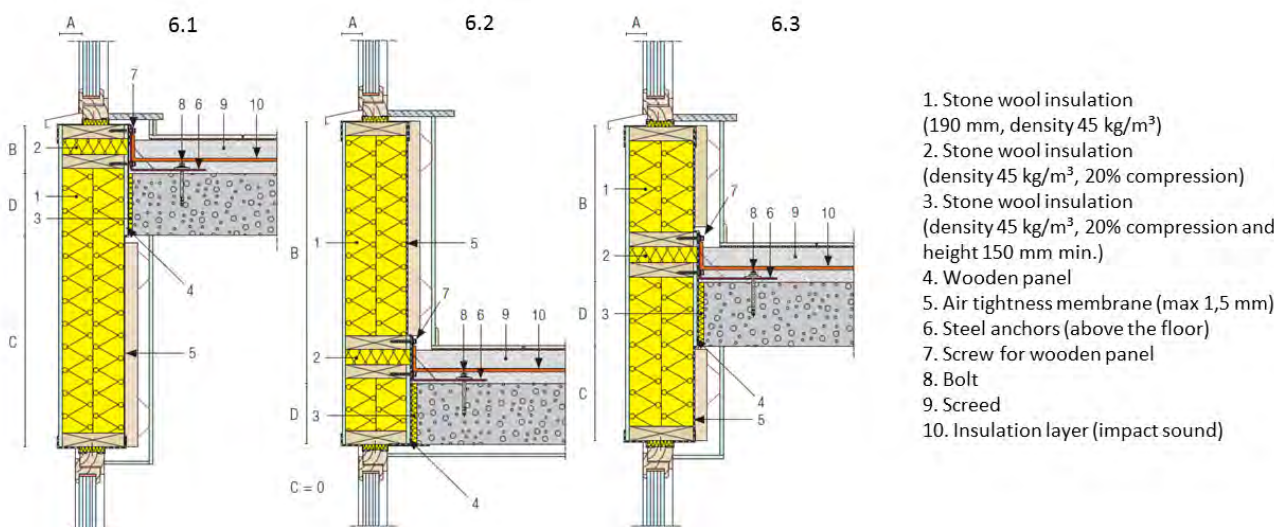


Fig. 7. Junctions of a timber frame facade with a concrete floor

This solution has been completed with a series of other configurations for timber facade elements with an E 60 fire resistance (see illustration on Fig. 8). The latter are made up of specific inner and

outer panels surrounding an insulation material (rock wool, glass wool or cellulose). Some configurations include rectangular timber studs, others I-shape wood joists (more commonly known as I-joists). One must ensure that these solutions are implemented while respecting all parameters, in accordance with the tests conducted (type and thickness of inside/outside panels, type of insulation, type and section of timber elements, type of sealing, ...).

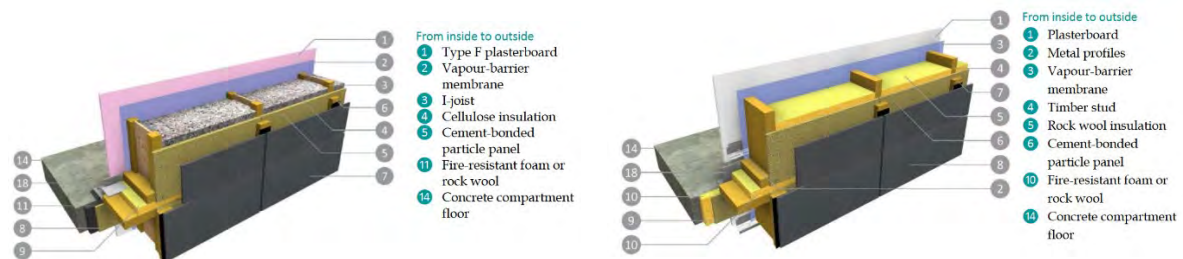


Fig. 8 Examples of details of timber façade E 60 and junction EI 60 with a concrete floor
(source – ETEX Group)

5 CONCLUSIONS

At present, the risk of fire spread within the facade is insufficiently considered in European standards. The Federal Public Service Interior is addressing the issue of this shortcoming in Belgian regulations. New requirements have been developed and will be soon compulsory for all new buildings in Belgium.

In the past, the required performances for buildings were mostly limited to the stability, the waterproof and the durability. Nowadays the buildings evolve to high complexity and a lot of performances: acoustic, thermal, ventilation, air tightness, esthetical, burglar resistance, fire safety, accessibility, environment, rapidity of executions, ... The challenge today is how to reach all the required performances, especially at the junctions. In collaboration with the sector, practical solutions of timber frame facades have developed that make it possible to satisfy regulations and to take into consideration all criteria imposed to today's buildings (airtightness, thermal insulation, acoustic performances, ...).

ACKNOWLEDGMENTS

This abstract is based upon work supported by VLAIO, the Flemish government agency for Innovation by Science and Technology under project “DO-IT HOUTBOUW” with WOOD.BE and CSTC as main partners. This publication was drafted within the framework of the Standards Service Antenna ‘Fire Prevention’ financed by the Belgian Federal Public Service Economy, SMEs, Middle Classes and Energy.

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Clemens Le Levé, Thomas Badergruber, Josef Kögl, Anton Kraler, Michael Flach
Unit of Timber Engineering, University of Innsbruck, Austria
- P.22 Fire safety of bio-based facades
Birgit Östman, Linnaeus University, Växjö, Sweden, and Esko Mikkola, KK-Palokonsultti Oy, Espoo, Finland
- P.30 Fire safety of etics with bio-based insulation materials
Christian Northe, Judith Küppers, Jochen Zehfuß
Technische Universität Braunschweig, Institute of Building Materials, Concrete Construction and Fire Safety, Braunschweig, Germany

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- P.45 Effects of Horizontal Projections on the Characteristics of Externally Venting Flames: An Experimental Study
Christos Kontis, Christoforos Tsihlias, Dionysios I. Kolaitis
Fire Engineering Unit, Laboratory of Heterogeneous Mixtures and Combustion Systems, School of Mechanical Engineering, National Technical University of Athens, Greece
- P.54 Influence of the thermal breaks on the behaviour of a balcony under fire external flames experiments, project trepos
Camille Sautot¹, Amor Ben Larbi², Maël Couchaux³
^{1&2} CTICM, ³ INSA Rennes,
- P.62 Heat Fluxes to a Facade Resulting from Compartment Fires with combustible and non-combustible ceilings
Alastair Bartlett¹, Angus Law¹, **Robert Jansson McNamee**², Jochen Zehfuss³, Siyimane Mohaine⁴, Christophe Tessier⁴, Luke Bisby¹
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⁴ CERIB Fire Testing Centre, Épernon, France

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- P.71 **The Material Library for Cladding Materials in Queensland, Australia**
Martyn S. McLaggan¹, Juan P. Hidalgo¹, Jeronimo Carrascal¹, David Lange¹, Cristián Maluk¹, Andres Osorio¹, Michael Heitzmann², José L. Torero³
¹ School of Civil Engineering, University of Queensland, St Lucia, Australia
² School of Mechanical and Mining Engineering, University of Queensland, St Lucia, Australia
³ Civil, Environmental & Geomatic Engineering, University College London, London, UK
- P.78 **Fire exposure on facades of buildings with exposed cross-laminated timber / Fire safety risks and measures**
Kathinka Leikanger Friquin¹, Nina Kristine Reitan², Ragni Fjellgaard Mikalsen²
¹SINTEF Building and Infrastructure, Trondheim, Norway
²RISE Fire Research AS, Trondheim, Norway
- P.86 **Preliminary study on the round robin proposals for assessing fire performance of facades**
Istvan Moder, Markus Eichhorn-Gruber
IBS, Linz, Austria
- P.95 **Different Standard Tests of Facade Fire Spread Applied for Identical Aluminum Composite Panel Specimens - MSZ 14800-6 (full-scale) and JIS A 1310 (intermediate-scale)**
Tamás Bánky^{1*}, Hideki Yoshioka^{2*}, **Péter Tóth**¹, Yuhei Nishio³, Takafumi Noguchi⁴, Kyoichi Kobayashi³, Manabu Kanematsu³, Tatsuo Ando⁴, Yoshihiro Hase⁵, and Tetsuya Hayakawa⁶
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Hideki Yoshioka¹, Miki Nakamura², Manabu Kanematsu³, Yuhei Nishio³, Takafumi Noguchi⁴, and Tatsuo Ando⁴
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² Japan Testing Center for Construction Materials (JTCCM), Japan
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- P.114 An engineering method for the contribution of wood: application to facade fires
Bertrand Girardin, Mathieu Duny, Gildas Auguin
Efectis, Route de l'Orme des Merisiers, 91193 Saint-Aubin, France
- P.122 Numerical investigation of fire development in a medium scale ISO 9705 compartment-facade configuration
Antoine Afflard¹, El Mehdi Koutaiba¹, **Eleni Asimakopoulou**², Dionysios Kolaitis³, Jianping Zhang², Paul Lardet¹
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² FireSERT, School of Architecture and the Built Environment, Ulster University, UK.
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- P.130 Experimental and numerical investigation of externally venting flame developing in a corridor-facade configuration
Eleni Asimakopoulou¹, Konstantinos Chotzoglou², Dionysios Kolaitis³, Jianping Zhang¹, Michael Delichatsios⁴
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Johan Anderson and Lars Boström
RISE Research Institutes of Sweden, Borås, Sweden

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Susan Lamont, Arup, Dubai, UAE, and
Birgitte Messerschmidt, National Fire Protection Association (NFPA), Quincy, USA
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Piergiacomo Cancelliere¹, Paolo Setti², Samuele Sassi², Angelo Lucchini³, Alberto Stefanazzi³,
Silvio Messa⁴, Eleonora Anselmi⁴, Arianna Villotti⁵, Mauro Madeddu², Paolo Canzani²
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Quentin de Hults, Mohamad El Houssami
Modern Building Alliance, Brussels, Belgium
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for timber frame facades
Yves Martin¹, Margo Colson², Kurt De Proft³
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Technique de la Construction (CSTC), Brussels, Belgium
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