Numerical simulation of the fire behaviour of facade equipped with aluminium composite material-based claddings—Model validation at large scale

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1 INTRODUCTION

The recent fire events in buildings involving combustible cladding systems have raised concerns regarding the risk that these systems can pose. Understanding such facade fires is complex as they involve a combination of various products and system. Facade fire propagation tests at ISO 13785-1 intermediate scale were performed on different combinations of aluminium composite material (ACM) claddings and insulants. Simulations were addressed to reproduce these tests and were validated in terms of thermal conditions in the system. This allowed additional investigation and understanding of fire propagation on the facade and more accurate determination of the fire behaviour of the overall system. In this paper, the scaling influence on the fire behaviour of ACM clad systems is investigated with simulations performed to reproduce fire tests at the BS8414-1 larger scale on three different combinations of ACM and insulants. The contributions of the cladding and insulant were numerically investigated. The fire behaviour of each component and of the overall system is validated by comparison with experiments. Simulations and tests show that the ACM cladding is the most important element driving the global fire behaviour of the systems. In particular, ACM-PE-based cladding systems, whatever the insulant, show extensive fire propagation while its degradation affects the integrity of the cavity.

KEYWORDS
BS8414-1, facade insulation, fire propagation, large scale fire test, numerical simulation, ventilated facade
than the performance of each individual component. A facade system includes not only the cladding and the insulant’s characteristics but also those of cavities, cavity barriers, mounting and fixing, substrate, and any singularities, such as window frames. All these elements interact strongly when involved in a fire.

In the context of fire safety, it should be noted that for systems such as external thermal insulation composite systems (ETICS) or ventilated facades, the materials used (cladding or insulation) may be combustible. In addition, in ventilated facades, the air gap may be a vector of fire propagation via the chimney effect. Thus, both the materials taken independently and the system as a whole (combination of materials and assembly) can potentially contribute to fire propagation.

At the present time, the use of fire barriers or compartmentation systems, as requested by national regulations, can hinder these problems, but they, too, constitute additional variables in the system.

Assessment of a specific facade system’s fire performance can be undertaken using large-scale testing, in accordance with local regulations. However, these large-scale tests are pass/fail oriented; and they give very little quantitative information for further interpretation of the fire behaviour of the tested system; if the flames pass over the top of the frame, the test will be stopped and this will not allow a thorough performance investigation.

Following the fire at Grenfell Tower in London on 14 June 2017, the UK government established an Independent Expert Advisory Panel to advise on immediate measures that should be put in place to help make high rise residential buildings safe. On 6 July, the Independent Expert Advisory Panel recommended that a series of large-scale BS 8414-1 tests be carried out in order to help building owners make decisions about any further measures that may need to be put in place. This series of tests included seven combinations of cladding systems. Previous studies report on the three facade fire tests that were performed, according to the BS8414-1 standard on various combinations of two grades of aluminium composite material (ACM) and two different insulants, similar to those subsequently tested in Guillaume et al.

Several studies have shown the feasibility and usefulness of numerical simulation for facade fires using different test facilities or methods and using different simulation codes. Published results have shown the feasibility of modelling such test methods using large eddy simulation (LES), especially when incombustible claddings were considered. However, great attention must be paid to the numerical model sensitivity, in particular to correctly representing the behaviour of the flames near the facade system, and thus the thermal stresses received by the facades.

A series of intermediate facade fire propagation tests according to the ISO 13785-1 standard with additional heat release rate (HRR), and gas analysis using FTIR was addressed in Guillaume et al. The test series comprised nine different combinations of three grades of ACM and three different insulants.

Based on the ISO 13785-1 facade fire tests detailed in Guillaume et al., a preliminary numerical study was carried out with the Computational Fluid Dynamics (CFD) code Fire Dynamics Simulator (FDS), developed by the American Institute NIST and widely used in the fire safety community. Thermal characteristics of the system components were input into the model. On the basis of comparison with the experimental results obtained from the ISO13785-1 facade fire tests, the model’s consistency and relevance were verified, in terms of thermal properties, fire propagation, HRR, smoke, and chemical species release. Thus, the numerical model was validated at intermediate scale. The numerical simulations and the tests both showed that the ACM cladding was the most important element driving global fire behaviour of the tested facade systems. In particular, ACM-PE-based cladding systems, whatever the insulant used in the system, showed very marked fire propagation and the consumption of the ACM, while burning, affected the integrity of the cavity.

This paper details the extension of this previously validated numerical model and input dataset from Dréan et al. to evaluate the scaling influence. The previously validated model was implemented on the large scale of the BS8414-1 test, in order to confirm the input dataset and fix several numerical parameters such mesh size or gradients for future upscaling.

The fire test protocol in BS8414-1 is representative of an external fire source, or a fully developed (post flashover) fire in a room, venting through an opening such as a window aperture that exposes the cladding to the effects of external flames. Indeed, 8 to 9 m of facade are tested at this scale. The propagation of the fire on more than two floors can then be studied.

The objective of the present study is to accurately numerically reproduce the thermal load to which the tested system is exposed, the thermal behaviour of the system and the fire propagation via the facade. The simulations are carried out with FDS software, based on the numerical hypothesis and input dataset previously validated. Iterative calculations are performed to verify the model’s consistency with, and relevance to, the experimental results obtained during the reference fire tests referenced on various combinations of two grades of ACM and two different insulants, similar to those subsequently tested at intermediate scale.

In the first step, the BS8414-1 test is numerically modelled, to reproduce the fire test behaviour of a facade system comprising ACM-PE cladding and PIR insulant. In order to accurately reproduce the fire propagation on the system, the simulations are performed with a fine numerical grid similar to that used in the previous step, detailed in Dréan et al. Comparisons are made between numerical and experimental results for temperatures based on a previous study.

The second step of the study consists in using coarser numerical cells, that are more commonly encountered in large-scale simulations and engineering studies. Using such a coarse grid is necessary because of the difficulties and time taken in modelling larger scales, such as a full-scale facade on a high rise building. However, a numerical hypothesis must be fixed in order to apply the model developed using an accurate fine grid, to a model developed with a coarser grid. The main objective is to reproduce the thermal gradients in gas and solid phases achieved with the initial model. For example in the coarser grid model, the air cavity now has the same thickness as the cell size. The exchanges between the materials and the gas phase are also evaluated in larger cell.

In the third step, the numerical model is modified to verify the combustion behaviour of each part of the system. These additional
investigations allow the verification of the robustness of the numerical model. To do that, a second simulation is performed with the original cladding [ACM-PE], but with a non-combustible insulant mineral wool (MW). Then, a third calculation is performed using the original insulant [PIR], but with an inert non-combustible cladding [ACM-A2 like]. The basic structure of the test rig remains the same for all the tests simulated. These two tests are detailed in previous studies.\textsuperscript{14,15}

The aim of this study is to obtain a robust numerical model that could predict the behaviour of whole systems at a larger scale, for later upscaling studies. Special attention is given to flow and thermal conditions at all locations in the tested systems. This allows for additional investigation and understanding of the relative contribution of insulant and ACM cladding. In particular, the relative contribution of each component to the fire behaviour of the system can be numerically assessed. The contribution of the ACM cladding and of the insulant to global fire behaviour is investigated separately. Thus, the fire behaviour of each component of the overall system is validated numerically and the scaling influence evaluated.

2 | EXPERIMENTAL SET-UP

2.1 | Test facility

The facade fire tests of the previous study,\textsuperscript{13} performed according to BS8414-1,\textsuperscript{12} allow the evaluation of large-scale facade system fire behaviour, as required by UK regulations for building safety.

The set-up of the experimental facility was developed according to BS8414-1 specifications.\textsuperscript{12} This is a large-scale facade build-up as detailed in previous studies.\textsuperscript{13-15} It consists of two frames with dimensions 2600 × 8000 mm for the back wall (main face) and 500 × 8000 mm for the side wall (wing) with calcium silicate (CalSil) boards as a support for the tested system and on which the system is installed (Figure 1A).

A wood crib with a HRR close to 3.0 ± 0.5 MW is installed in the combustion chamber of the facility, and its dimension are close to 1500 × 1000 × 1000 mm (l × w × h). The complete system is then placed under a large hood to collect the effluents.\textsuperscript{11,12}

The instrumentation used during the test is fully detailed in previous studies\textsuperscript{13-15} and indicated in Figure 1B. During the test, surface temperatures are measured with an uncertainty estimated as ±2.5 K at different locations. Level 1 corresponds to the top of the panel above the combustion chamber. External measurements are done 50 mm in front of the finished face. Level 2 corresponds to the top of the second raw of panel above the combustion chamber. Measurements are done externally 50 mm in front of the finished face, at midpoint of cavity between panel and insulation and at midpoint of the insulation layer. The location of the cavity barriers is also schematized in Figure 1C.

2.2 | Tested systems in the experimental reference

In the reference test reports,\textsuperscript{13-15} facade fire tests have been performed on three combinations of two different compositions of ACM and two different insulants (Table 1). Information regarding these insulants, such as density or thermal conductivity, is available on product datasheets from their respective manufacturers. The

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{Overview of the (A) facility and (B) instrumentation installed during the facade fire test\textsuperscript{13} according to BS8414-1 [Colour figure can be viewed at wileyonlinelibrary.com]}
\end{figure}
different thicknesses of combustible insulants or MW were chosen to achieve similar levels of thermal performance. The ACM–PE panels comprise a 3-mm-thick PE core with 0.5-mm-thick aluminium facings on either side. These tests were performed just after the Grenfell disaster, by BRE, for DCLG. The intention was to assess the compliance of such systems with the criteria given in BR135. The tests were stopped if the “flame height” fail criterion of BR135 was exceeded.

However, attention must be paid to the test repeatability and to the variability of the heat released by the fire source since a wood crib was used.

Concerning mounting and fixing, the cladding systems were assembled on calcium silicate boards. The cladding was made of 3 × 4 panels for the back wall (1B to 3E in Figure 1) with two additional panels around the combustion chamber (0B and 0C in Figure 1) and four panels (0A to 3A in Figure 1) for the side wall (or test wing). Gaps between cladding panels were 20 mm wide.

A set of four horizontal intumescent cavity barriers, with a 25 mm thickness of intumescent, were installed. Vertical cavity barriers were placed: two for the back wall and one for the side wall (see Figure 2).

### Table 1: Tested combinations of facade systems selected

| Tested System | Designation | Cladding/Thickness | Air Gap Thickness, mm | Insulant/Thickness |
|---------------|-------------|--------------------|-----------------------|-------------------|
| 1<sup>2</sup> | [ACM-PE + PIR] | ACM standard cladding with nonfire-retarded polyethylene (PE) core 4 mm | 55 | Foil-faced poly-isocyanurate (PIR) insulation 100 mm |
| 2<sup>14</sup> | [ACM-PE + MW] | ACM standard cladding with nonfire-retarded polyethylene (PE) core 4 mm | 55 | Dual density wool insulation (MW) 180 mm |
| 3<sup>13</sup> | [ACM-A2 + PIR] | ACM cladding with an A2 mineral core limited combustibility (Euroclass A2) 4 mm | 55 | Foil-faced poly-isocyanurate (PIR) insulation 100 mm |

Abbreviations: ACM, aluminium composite material; MW, mineral wool.

### Figure 2
Overview (A) of the cavity barriers and (B) of the final mounting of the facade system for the BS8414-1 fire test<sup>13</sup> [Colour figure can be viewed at wileyonlinelibrary.com]
of cavity barriers was found. Unfortunately, a large part of the fire development may have continued after the “flame height” fail criterion of BR135 was exceeded, at which point the tests were extinguished. So the available experimental test data only covers the period from ignition until the tests were extinguished.

3 | NUMERICAL SET-UP

Preliminary numerical development was carried out by means of iterative calculations, which were performed to verify the model's consistency and relevance with the experimental results obtained during the BS8414-1 fire tests. The objective of this study is to accurately numerically reproduce the thermal load to which the tested system is exposed, the thermal behaviour of the system and the fire propagation via the facade. The thermal characteristics of the system components are integrated in the model.

Once the thermal behaviour of the facade system is validated for the [ACM PE + PR] configuration at large scale, local phenomena is evaluated with confidence and specific numerical studies of the flow around the cavity barrier can be detailed. The individual contribution of the cladding and the insulation is addressed through further validation of the numerical model. Simulations of the system including a non-combustible MW insulant and of the system including an inert non-combustible cladding as tested in Guillaume et al allow a deeper analysis of the material contribution to the fire spread in the facade systems.

3.1 | Numerical tools

The numerical simulations are performed with the CFD code FDS version 6.7.0. FDS is a computational code in fluid dynamics that incorporates a combustion model and a large scale model (LES) for the description of turbulent flows. This tool allows 3D modelling of the computational domain. It considers heat transfer at walls, ventilation conditions for the removal of hot gases and air intake. The Navier-Stokes equations are solved in the limit of low Mach number, thermally driven flow with an emphasis on smoke and heat transport from fires. The radiative heat transfer is included in the model through the solution of the radiative transport equation for a grey gas. Detailed information is provided in previous study.

The default submodels of FDS were used for the gas phase radiation exchanges even if a sensibility analysis performed with 100 (default value), 500, and 800 solid angles was addressed in Appendix B (see Supporting Information). The combustion model with primitive and lumped gas species definition, to solve a transport equation for each species to be tracked, was also investigated, as well as the use of a single step reaction for CO production. This was because of uncertainty in the occurrence of this phenomenon and of well-ventilated conditions for the combustion observed experimentally and numerically. The fuel burnout in each solid numerical cell is accounted for by the specification of the combustible mass and heat of combustion of the object through the bulk density parameter. Thus, when the mass contained in each solid cell is consumed, the solid disappears from the calculation cell by cell. This feature is used to account for the destruction of the cladding, as observed experimentally with ACM-PE experiments. The default Deardorff model is used for the LES subgrid modelling. The default near-wall model with a wall function for smooth wall is used. The heat transfer at walls is simulated with a subsequent heat of vaporization to account for the energy loss due to the vaporization of the solid fuel.

3.2 | Description of the numerical domain

3.2.1 | Numerical domain

The total dimensions of the numerical domain are 3000 × 3800 × 10000 mm, with open boundary conditions for the pressure at the sides and at the top of the computational domain. The numerical domain is considered large enough to account the test facility and the fire plume resulting from the system combustion.

Mesh size is taken at 20 × 20 × 20 mm for the facility, so that the grid is refined to capture accurately the combustion and turbulence phenomena of the system. A total of 11.25 million cells are used.

In the FDS reference guide and literature, a criterion for the quality of the mesh resolution is given for simulations involving buoyant plumes. It is assessed using the nondimensional D*/Δx ratio, where Δx is the size of the grid cells and D* is the characteristic fire diameter. Following this expression, for the typical HRR of the wood crib (maximum of Q = 3.5 MW), the adequate fine mesh size Δx to obtain reliable predictions of the radiative heat flux should be close to 100 mm. However, for the total HRR achieved numerically for the wood crib and facade system (Q = 7 MW), the mesh size should be close to 130 mm. Thus, the 20 mm considered grid size is sufficiently fine to capture accurately the combustion and turbulence phenomena of the system from ignition to fully developed fire.

Attention must be paid to the 20-mm gap at the junction between cladding panels. Regarding the mesh size, only one fluid numerical cell is used to represent the gap, with a size adapted to the meshing (ie, 20 mm). The 55-mm air cavity between ACM cladding and insulant is modelled with a 60-mm cavity, so that three cells are used to calculate the aeracoustic phenomena in the air cavity. No sensibility analysis was performed regarding the fine mesh size selected and the global fire behaviour mainly lead by the surface propagation of the fire in this application.

This technical choice is made to conserve reasonable calculation costs and regarding the later upscaling application of this numerical model. Compromises were needed to develop a robust numerical model able to be used for this application. The selected cell size is enough to capture the main features of local effects, not in details, but sufficiently to reproduce the fire behaviour in the present application. Furthermore, quickly after the beginning of the test, the fire propagation from the burner to the system leads to its combustion. Thus, the cladding panels, and thereby the gaps between them disappear in the first minutes of the test.
In the numerical model, virtual instrumentation consisting of thermocouples are placed at the same locations as during the real test (Figure 1).

### 3.2.2 | Numerical model for thermal analysis

The thermal characteristics of the system components are integrated in the numerical model in terms of density, thermal conductivity, heat capacity, emissivity, heat of combustion, ignition temperature, mass loss rate, and species release rates, for every material involved. All thermal and combustion properties considered, for the material making up the systems, are taken from the numerical model validated at intermediate scale. A justification for the numerical model used for thermal degradation analysis of the materials and overall combustion is deeply discussed in Dréan et al.

The burning rates of the materials are indeed imposed. The burning rate of the facade is however more complex as flame spread occurs. The most challenging point of this approach was to find the suitable parameters, with a physical meaning. This parameters included thermal parameters (so the heat transfer is correctly modelled) and the right combustion properties (ignition temperature and mass loss rate). These complete sets of parameters have to be found for several materials with strong interaction from one to another. Thus, the numerical results achieved will not fit correctly the experimental ones because mass loss rate is prescribed but because the thermal properties and the fire properties are suitable. Indeed, the materials properties, ignition temperature, and burning rates of the materials are imposed. However, each of those parameters are exactly taken from literature and selected according to appropriate environmental conditions. None was calibrated for the numerical results achieved to fit correctly the experimental ones.

In the numerical model, the aluminium frame and cavity barriers are implemented at same location as during the tests. The cavity barriers include an intumescent coating. The expansion of the intumescent part of the cavity barrier is assumed to occur at 260°C. The intumescence is modelled as the appearance of an additional thickness of the solid obstacle representative of the cavity barrier when the local temperature criterion is reached.

A failure mechanism for the aluminium frame is implemented in the numerical model. Each part of the solid disappears if its surface temperature reaches 550°C. This temperature corresponds to the loss of the mechanical properties for the aluminium.

The thermal properties of the calcium silicate (CalSil) supports are implemented to ensure a correct thermal transfer in terms of loss from the facade system backing. Exposed boundary conditions are thus considered.

### 3.2.3 | Numerical model for the fire source

The model of the fire source evolution of the basic test rig was previously validated by comparison with several calibration tests (plasterboard facade) as presented in Appendix C (see Supporting Information). The numerical model assumed the HRR indicated in Figure 3 for the wood crib combustion. According to the previous study, this heat source releases a nominal total heat output of 4500 MJ over 30 minutes with a peak rate of \((3 \pm 0.5)\) MW. The HRR is comparable with that indicated in Anderson and Jansson.

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**FIGURE 3** Heat release rate used in the model for the BS8414-1 wood crib

**FIGURE 4** Overview of the numerical model developed for the BS8414-1 fire test—cladding (grey), wood crib (red volume), cavity barriers (pink), and insulant (yellow) [Colour figure can be viewed at wileyonlinelibrary.com]
A sensitivity analysis of the influence of this uncertainty on the HRR of the wood crib is addressed later in this paper. Illustrations of the numerical model are given in Figure 4.

4 | NUMERICAL FIRE PERFORMANCE TEST: RESULTS AND VALIDATION

4.1 | Comparison between experimental and numerical values for the [ACM-PE + PIR] configuration

The comparisons between numerical and experimental results for temperatures are analysed. Experimental data and numerical results are smoothed using a rolling average over 30-second periods. During the test, the crib was extinguished at 395 seconds because the “flame height” fall criterion of BR135 was exceeded. However, the numerical simulation was performed up to 10 minutes.

The overall uncertainty of a numerical prediction is the combination of the uncertainties of both the numerical model and of the input parameters. The numerical uncertainties are evaluated following McGrattan and Toman and are indicated in Table 2. Numerical parameter uncertainty is an important consideration to assess the reliability of the results and the impact of the input parameters of a model. In this study, the input parameters are taken from the literature and used to fit the experimental results. Thus, no input uncertainties are evaluated. However, a sensibility analysis was performed for the ignition temperatures of the cladding and the insulant.

4.2 | Fire behaviour observations

A comparison of the experimental fire behaviour of the system with numerical observations is presented in Figure 5 at different elapsed times. The visualization begins at 2 minutes and is shown for every minute thereafter and illustrates the fire development and the system behaviour during the simulated test. Unfortunately, no experimental

| TABLE 2 | Numerical and experimental uncertainties |
|----------|------------------------------------------|
| Quantity | Experiment | Numerical |
| Surface temperature | 5% | 8% |
| Gas temperature | 5% | 8% |
| Heat flux | 7% | 15% |
| Heat release rate | - | 17% |

FIGURE 5  Numerical model of the fire behaviour of the system during the BS8414-1 test of the [ACM-PE + PIR] system [Colour figure can be viewed at wileyonlinelibrary.com]
observations were available. Thus, the modelled fire behaviour helps to understand the flame propagation over the tested system.

It can be seen that the fire propagation from the wood crib to the external cladding starts early, at around 2 minutes. Then the fire propagates to the whole system, and flames are visible through the gap between the first and second row of panels above the combustion chamber, at around 3 minutes. A quick propagation of flames on the cladding surface appears between 4 and 7 minutes, and the side wall starts to contribute after 5 minutes. Some counter-current fire propagation at side wall is visible after 6 minutes. Then, the fire intensity tends to decrease, corresponding to the lack of combustible materials. Slowing propagation is observed on the side wall between 6 and 10 minutes. Furthermore, the real test was ended after 395 seconds. These numerical observations allow understanding what was missed after this time.

The gas temperature inside the cavity of the back wall is assessed numerically in Figure 6. The aluminium frame at the bottom of the panel located just above the combustion chamber is lost at around 4 minutes, leading to fire propagation inside the cavity. The horizontal and vertical cavity barriers reduce propagation of the fire to panels located laterally and above the first row of panels. At the second row of panels, the fire enters the cavity at around 7 minutes and stays confined under the horizontal cavity barrier.

It should be noticed that the wood crib is extinguished at 395 seconds. Thus, fire behaviour of the system after 7 minutes is not available experimentally. The “flame height” fail criterion of BR135 was exceeded at 395 seconds, corresponding to flame emission from the bottom of the third row of panels across the full width of the wall and its vertical edge and at the mid-height of the panel junction through the ventilation gap. This behaviour is observed numerically at 4 minutes.

The comparison between observations from the test and the numerical model of the cladding after the end of the test (395 seconds) is addressed in Figure 7. A similar shape for the apparent thermal degradation of the cladding was observed.

The same observation was made for the insulant on the back and side walls.

At the side wall, reduced degradation of the insulant was observed, both numerically and experimentally. At the back wall, thermal degradation is observed at the first row of panels and locally at the second row of panels. It can be seen that there is a close correlation between the numerical modelling results and observations from the experimental tests involving [ACM-PE + PIR].

In the illustration, the black line corresponds to a temperature of 352°C and is only used for observation. However, this value is representative of the lower bound of ignition temperature of the tested system with 8% of uncertainty. It can be used as the upper boarder of the charring zone.

The contribution of the insulant to the fire is evaluated numerically. The maximum insulant surface contributing to the fire is close to 2.2 m² for the back wall and 0.1 m² for the side wall.

4.3 | Comparison with experimentally measured values

The simulated temperatures at the back and side walls at external L1 level (Figure 8) and L2 level (Figure 9) are comparable in magnitude and evolution with the experimental temperatures over time and at each thermocouple location.

Similar conclusions can be drawn for the temperature in the air cavity at L2 level of the back and side walls (Figure 10), meaning that thermal, dynamic, and aeraulic phenomena are properly represented by the numerical model.

Some differences are visible around 350 and 400 seconds between numerical and experimental results and concern mainly the...
thermocouples at back wall. The test was ended at 395 seconds because the BR135 criterion was reached at this time, and the wood crib was then extinguished. In the corresponding test report, level 2 external thermocouples reached the external fire spread criterion at 360 seconds. Thus, this criterion seems to be reached numerically 30 seconds before the experiment at some location. The main differences observed can be attributed to the fact that thermocouples can slightly move in the cavity due to local turbulence during the test or to the thermocouple inertia when the crib is extinguished. Furthermore, only one test was performed, so attention must be paid to its repeatability. Furthermore, the numerical model does not take into account mechanical changes of the system (local distortions were observed after the test) or displacement of thermocouples inside the cavity. Regarding the 5% and 8% uncertainties on gas temperature evaluated experimentally and numerically, respectively, the simulated temperature are very comparable with the experimental data or comprised in the confidence range. However, the heat source from wood crib is 3 ± 0.5 MW, thus 3.5 or 2.5 MW as a range, it is around 36% and it is acceptable in the standard.

However, the numerical simulation illustrates the full development of the fire, after the time at which the "flame height" fail criterion of BR135 was exceeded and the crib was extinguished. This

**FIGURE 7** Experimental and numerical observations of the fire behaviour of the system at the end of the BS8414-1 test (395 s) of the [ACM-PE + PIR] system [Colour figure can be viewed at wileyonlinelibrary.com]
phenomenon is missed during the experiment. The simulated temperatures at the back-wall surface at L2 level (Figure 11) are comparable in magnitude and evolution with the experimental temperatures over time and at each thermocouple location.

The global thermal behaviour of the system is captured using simulation, and the thermal properties used are suitable. The good agreement between experimental and numerical results for surface temperatures validates the material thermal properties used in the study. The numerical model developed when modelling the intermediate scale experiments is thus validated at larger-scale for the [ACM-PE + PIR] configuration. However, both numerical and experimental uncertainties must be deeply considered regarding such complex systems because numerical models fail to represent the displacement of thermocouples in front or in the cavity of burning elements.

4.4 | Numerical evaluation of the HRR during the test for the [ACM-PE + PIR] configuration

The total HRR during the BS8414-1 test was evaluated numerically. The HRR evolution indicated in Figure 12A corresponds to the heat released by the tested system and by the fire source (wood crib).
The system contribution starts after 4 minutes of test. Then, a maximum value of \((7.3 \pm 1.2)\) MW (17% uncertainty) is predicted and reached at 7 minutes 30 seconds of test. Without the contribution of the wood crib, the HRR of the [ACM-PE + PIR] system only is indicated in Figure 12B. A maximum value around \((4.5 \pm 0.8)\) MW at 7 minutes 30 seconds of the test is observed. The energy released by the tested system without the contribution of the wood crib is also indicated.
The maximum cladding surface contributing to the fire is close to 2.8 m² for the back wall and 1 m² for the side wall. However, these surfaces are not burning at the same time. The maximum cladding surface burning simultaneously is about 2.2 m² at back wall and 0.5 m² at side wall. The maximum insulating surface contributing to the fire is close to 2 m² for the back wall and 0.1 m² for the side wall. The corresponding HRRs are, respectively, 0.3 MW from the back wall and 0.014 MW from the side wall. The contribution of the insulant represents 7% (max.) of the numerically evaluated system HRR during the test. The main results of the numerical simulation show that for the tested system, the cladding is the most important parameter driving global fire behaviour.

The cladding and insulant surfaces involved during the test lead to a corresponding maximum HRR of the total system close to 4.65 MW and are close to the evaluated HRR. Comparable total HRRs per unit area for similar tested systems are found in Dréan et al. and Agrawal.\textsuperscript{34}

### 4.5 Variance of the numerical model for the [ACM-PE + PIR] system

The method\textsuperscript{35} described in ISO 16730-1:2015 is used to further validate the numerical model against the experimental results. The relative difference (hybrid method), and the cosine associated with each quantity to be validated, are presented in Table 3. The minimum cosine value evaluated, close to 0.87, is associated with the maximum relative difference value close to 41% and concerns the external system temperature at the side wall in position L2. This low cosine value and high relative difference value can be attributed to the fact that thermocouples can slightly move in front of the system due to local turbulence during the test or to the thermocouple inertia when the crib is extinguished. Furthermore, only one test was performed, so attention must be paid to its repeatability. However, this relative difference is in the range of the numerical and experimental uncertainties.

For all the other temperatures at the back and side walls, as well as the air cavity temperatures, cosines are in all cases higher than 0.86, and relative differences lower than 34%. The values for the relative differences are also in the range of both numerical and experimental uncertainties. For the external gas temperature at L1 level at back wall, the relative difference is very low (9.5%), associated to a cosine close to 0.94. Thus, the numerical predictions at this location are accurate enough to properly represent the flame load from the fire source and the ignition of the tested system in this area.

As a preliminary conclusion, the numerical model applied to the [ACM-PE + PIR] system is valid and can be used for further investigations.

### 5 NUMERICAL EVALUATION OF THE MODEL FOR THE [ACM-PE + PIR] SYSTEM, USING A COARSER GRID

Once the small 20-mm grid numerical model validated, a model is created with coarser numerical cells, which are more commonly encountered in large-scale simulations and engineering studies.

Using such coarse grid is necessary because of the difficulties and time taken in modelling larger scales. For example, the CPU time to model 770 seconds of a BS8414-like test of the [ACM-PE + PIR] system is increased eightfold when using 20-mm cells instead of 250-mm cells. Several studies have shown the usefulness of numerical simulation for facade fires, to provide deeper analysis of the fire propagation inside the system or the fire spread from the fire compartment to the facade. These studies are of prime importance because they allow the evaluation of larger scales such as compartment fires or real scale building facades.

#### 5.1 Numerical set-up

The total dimensions of the numerical domain are 3000 × 3800 × 10000 mm, with open boundary conditions for the pressure at the lateral sides and at the top of the computational domain. The numerical domain is considered large enough to account the facility and the fire plume resulting from the system combustion.

Mesh cell size is taken as 125 × 125 × 125 mm for the combustion chamber and 250 × 250 × 250 mm for the system and the facility. A total of 0.25 million cells are used.

In the FDS reference guide\textsuperscript{27} and literature,\textsuperscript{29} a criterion for the quality of the mesh resolution is given for simulations involving buoyant plumes. It is assessed using the nondimensional $D*/\Delta x$ ratio, where $\Delta x$ is the size of the grid cells and $D*$ the characteristic fire diameter. Following this expression, for the total HRR achieved numerically for the wood crib and the tested system (maximum of $Q = 7$ MW), the adequate fine mesh size $\Delta x$ to obtain reliable predictions of the radiative heat flux should be close to 130 mm. However, for the

| Thermal Behaviour | | Dynamics |
|-------------------|-------------------|----------|
|                   | System temperature L1 (average) | System temperature L2 (average) | Temperature inside the air cavity L2 (no velocity measurement) |
|                   | Back wall | Side wall | Back wall | Side wall | Back wall | Side wall |
| Relative difference, % | 9.5 | 27.7 | 33.9 | 40.8 | 17.5 | 15.17 |
| Cosine | 0.94 | 0.86 | 0.90 | 0.87 | 0.93 | 0.94 |

**TABLE 3** Relative difference and cosine associated with each quantity to be validated in the numerical model following ISO16730-1:2015 for the [ACM-PE + PIR] system.
total HRR achieved numerically for the wood crib and facade system (Q = 7 MW), the mesh size should be close to 130 mm. Thus, the considered grid size (0.125 m for the combustion chamber, 0.25 m for the system) should be sufficient to still capture accurately the combustion and turbulence phenomena of the system.

Numerical hypothesis must be considered for the model developed for the accurate fine grid to be applied to the coarser one. The main objective is to reproduce the thermal gradients achieved with the initial model, in the gas phase. As discussed in Janardhan and Hostikka,\textsuperscript{36} the change in the ignition temperature or other thermal parameter is needed while changing the mesh resolution. The investigated approach for the use of coarse mesh in fire spread simulations is to consider artificially an area adjust coefficient reported in thermal parameter.

One of the main difficulties using such a mesh size is the location of virtual captors, like thermocouples, since they will measure quantities such as temperature in a $0.25 \times 0.25 \times 0.25$ m$^3$ volume, and cannot be accurately placed in the model. This can lead to an overestimation of temperature, if the flame envelope is passing through the cell. The temperature will be an average of the flame envelope and the real temperature in the cell. For example, the air cavity has now the same thickness as one cell size, ie, 0.25 m.

The second main difficulty is that, with the coarse grid (25 cm), exchange between the solid and gas phases will be evaluated in a larger cell. Thus, to reproduce the numerical results that were validated against the test data using a fine grid (20 mm), the only parameter that can be modified in order to reproduce the results with larger mesh size are the computed ignition temperature for the insulant and the ACM cladding. This parameter is half-physical and half-numerical when modelling flame spread in a finite volume model such as FDS and is affected by simplifications to fluid and 1D heat transfer in solid submodels. Decreasing artificially the computed ignition temperature of the materials allows maintenance of a correct thermal gradient for the exchange between solid and the gas phases when large cells are used.

Thus, the main hypothesis consists in the modification of the computed ignition temperatures for insulant and ACM cladding established for the fine grid model, so that the coarser grid model reproduces the output of the fine grid model. These modifications were chosen after iterative simulations and consist in a decrease of 100°C in the computed ignition temperature for PE (initially $T_i = 380$°C, now $T_i = 280$°C) and for PIR (initially $T_i = 370$°C, now $T_i = 270$°C). A sensitivity analysis for the computed ignition temperatures of PIR and PE is addressed in Appendix A (see Supporting Information).

### 5.2 Comparison between experimental and numerical values for the [ACM-PE + PIR] system using a coarse grid

The simulated temperatures at the back and side walls at external L1 level (Figure 13) and L2 level (Figure 14) using the coarse grid are comparable in magnitude and evolution with the experimental temperatures over time and at each thermocouple location. Similar conclusions can be drawn for the temperature in the air cavity at L2 level of the back and side walls (Figure 15), meaning that thermal, dynamic, and aeraulic phenomena are properly represented by the numerical model. The main differences observed can be attributed to the fact that thermocouples can slightly move in the cavity due to local turbulence during the test or to the thermocouple inertia when the crib is extinguished. Furthermore, only one test was performed, so attention must be paid to its repeatability. However, the numerical simulation illustrates the full development of the fire, after the time at

![FIGURE 13](image-url)

Comparison of numerical and experimental (points) temperature on the back and side walls (external level 1) of the system during the BS8414-1 test of the [ACM-PE + PIR] system evaluated on fine (straight lines) and coarse (dotted lines) grid
which the "flame height" fail criterion of BR135 was exceeded and the crib was extinguished. This phenomenon is missed during the experiment. The simulated temperatures at the back-wall surface at L2 level (Figure 16) are comparable in magnitude and evolution with the experimental temperatures over time and at each thermocouple location.

The global thermal behaviour of the system is captured using simulation, and the thermal properties used are suitable. The good agreement between experimental and numerical results for surface temperatures validates the material thermal properties used in the study. The numerical model developed when modelling the intermediate scale experiments is thus validated at larger scale for the [ACM-PE + PIR] configuration. The numerical simulation illustrates the full development of the fire, after the time at which the "flame height" fail criterion of BR135 was exceeded and the crib was extinguished. This phenomenon is missed during the experiment.

5.3 Numerical evaluation of the HRR for the [ACM-PE + PIR] configuration on coarse grid

The total HRR during the BS8414-1 test is evaluated numerically using the coarse grid (Figure 17). Its evolution corresponds to the heat

![FIGURE 14](https://example.com/figure14) Comparison of numerical and experimental (points) temperature on the back and side walls (external level 2) of the system during the BS8414-1 test of the [ACM-PE + PIR] system evaluated on fine (straight lines) and coarse (dotted lines) grid

![FIGURE 15](https://example.com/figure15) Comparison of numerical and experimental (points) temperature inside the cavity of the back and side walls (level 2) of the system during the BS8414-1 test of the [ACM-PE + PIR] system evaluated on fine (straight lines) and coarse (dotted lines) grid
It is compared with the value modelled using the fine grid. There is good overall agreement between these results.

The THR evaluated with the fine and the coarse grids are also compared. Good overall agreement is found, indicating that fuel stoichiometry and the fuel mass released are correctly taken into account in the simulation with the coarser grid.

5.4 Variance of the numerical model for the [ACM-PE + PIR] system

The relative difference (hybrid method) and the cosine associated with each quantity to be validated are presented in Table 4. The minimum cosine value evaluated, close to 0.93, and the maximal relative difference value, close to 28%, concerns the external system temperature at the back wall in position L2 and the external system temperature at the side wall in position L1, respectively.

For all the other temperatures at the back and side walls, as well as the air cavity temperatures, cosines are in all cases higher than 0.95, and relative differences lower than 27%. The values for the relative differences are also in the range of both numerical and experimental uncertainties. For the external gas temperature at L1 level at back wall, the relative difference is very low (16.7%), associated to a cosine close to 0.96. Thus, the numerical predictions at this location are accurate enough to properly represent the flame load from the fire source and the ignition of the tested system in this area, even if a coarse grid is used.

As a preliminary conclusion, the coarse grid numerical model of the [ACM-PE + PIR] system is valid and can be used for further investigations.

5.5 Investigation into the influence of the wood crib

According to the testing conditions given in BS8414-1, the HRR of the fire source (wood crib) can commonly range between 2.5 and 3.5 MW (3.0 ± 0.5 MW). Thus, a significant uncertainty exists. It can be partially related to the transient shape of the wood crib while burning (collapse of some wood sticks leading to a change in local ventilation of the fuel), or slightly to the moisture content of the wood, which can range between 10% and 15% following the test standard.

| TABLE 4 | Relative difference and cosine associated with each quantity to be validated in the numerical model following ISO 16730-1:2015 for the [ACM-PE + PIR] system simulated with the fine and coarse grids |
|---|---|---|---|
| | Thermal Behaviour | System temperature L1 (average) | System temperature L2 (average) | Dynamics |
| | | Back wall | Side wall | Back wall | Side wall | Temperature inside the air cavity L2 (no velocity measurement) Back wall Side wall |
| Relative difference, % | Fine grid | 9.5 | 27.7 | 33.9 | 40.8 | 17.5 | 15.17 |
| | Coarse grid | 16.7 | 27.8 | 21.9 | 26.1 | 16.6 | 26.8 |
| Cosine | Fine grid | 0.94 | 0.86 | 0.90 | 0.87 | 0.93 | 0.94 |
| | Coarse grid | 0.96 | 0.96 | 0.93 | 0.97 | 0.95 | 0.98 |
The influence of the wood crib HRR on the numerical model of BS8414-1 with the coarser grid was investigated, using three different values of the wood crib HRR: 2.5, 3, and 3.5 MW. In the numerical simulations described above, the assumed HRR for the wood crib was close to the maximum HRR allowed by BS8414-1 (eg, 3.5-MW plateau).

### 5.5.1 Influence on the HRR of the overall system

The overall HRR during the BS8414-1 test of the [ACM-PE + PIR] system was evaluated numerically using the coarse grid for three values of the peak HRR of the initial wood crib. The HRR evolution indicated in Figure 18 corresponds to the heat released by (a) the tested system and the fire source and (b) the tested system only.

The HRR achieved with the 3.5-MW wood crib shows that the combustion of the system starts more quickly due to more important flame above the fire room. The overall kinetics is similar whatever the peak HRR of the crib. The maximum total HRR values are close to 8 MW (± 0.5 MW) for all three cases investigated. The contribution of the evaluated system appears to be only time shifted when this range of wood crib HRRs is considered.

### 5.5.2 Influence on the system temperature

Examples of comparisons between numerical and experimental results for external temperatures at level L1 on the back and side walls are presented in Figure 19 for the three different wood crib peak HRRs. They correspond with the most thermally impacted level of the system. The differences are mainly due to timing, because the L1 thermocouples are low on the test wall they are mainly in the flames and register similar temperatures.

The average, minimum, and maximum temperatures evaluated numerically at external Level L1 on the back and side walls are indicated in Figure 20. At this location, the numerical model is able to reproduce the main experimental phenomena in terms of maximum values and global kinetics. The same observation was made at level 2 and in the air cavity.

Thus, the uncertainty allowed for wood crib HRR in BS8414-1, has no significant influence on the results achieved for the [ACM-PE + PIR] system. The HRR used in the simulations has a peak value of 3.5 MW. Thus, during the test, this value will not be constant and can be lower. This explains some of the differences observed when numerical and experimental results are compared. The sensitivity analysis performed shows that once the combustion of the system starts above the fire room, whatever the peak HRR of the wood crib, it has little influence on fire propagation. The lower wood crib peak HRR, of 2.5 MW, is sufficient to trigger the fire ignition and development.

### 6 FURTHER VALIDATION OF THE NUMERICAL MODEL ON OTHER FACADE COMPOSITIONS

Further validation of the numerical model has been performed. The model was modified to verify the combustion behaviour of each of the two main components of the system and of the system itself. These additional investigations allowed the verification of the robustness of the numerical model and to investigate the use of inert cladding or MW insulation instead of ACM-PE or PIR.

The first derivative model used the same [ACM-PE] cladding as the [ACM-PE + PIR] system, but with an inert insulant (MW). It was designated as the [ACM-PE + MW] system. A second derivative model used the same [PIR] insulant as the [ACM-PE + PIR] system but with an inert non-combustible ACM cladding [ACM-A2]. It was designed as the [ACM-A2 + PIR] system.

Only the thermal and fire properties of either the cladding or insulant, depending on the derivative, were changed in the model. The numerical model of the test rig remains the same for all the tests simulated. The numerical model for [ACM-A2] cladding used the same thermal properties as for the [ACM-PE] cladding but no combustible properties. Thus, in this configuration, the ACM cladding will not have any contribution to the heat released. Furthermore, no fire retardants were considered in the ACM cladding. The simulations were performed using the coarse grid described previously. The experimental results for these systems can be found elsewhere.\(^\text{14,15}\)

The comparison between numerical and experimental results for temperatures and HRR achieved for the [ACM-PE + MW] and [ACM-A2 + PIR] configurations are presented from Figures 21–27.

![FIGURE 18 Numerical evaluation of heat release rate (HRR) during the BS8414-1 test for the [ACM-PE + PIR] system evaluated on coarse grid for three peak HRR values for the wood crib. A, Overall system; and B, without the wood crib contribution](image-url)
Experimental data and numerical results are smoothed using a rolling average over 30-second periods as proposed in ISO 13785-1.

### 6.1 Comparison with experimentally measured values

During the [ACM-PE + MW] test, the crib was extinguished at 310 seconds because the “flame height” fail criterion of BR135 was exceeded. However, the numerical simulation was performed up to 800 seconds. The simulated temperatures at the back and side walls at the external L1 and L2 levels are comparable in magnitude and evolution with the experimental temperatures for the [ACM-PE + MW] system (Figures 21 and 22) over time and at each thermocouple location, up until the crib was extinguished. After the wood crib was extinguished the fire develops fully, resulting in higher temperatures.

The lower numerical temperature evaluated at TC 3014 location (L1) can be related to its position close to the gap between panels, which can have moved during the test.

The same conclusion can be made for the [ACM-A2 + PIR] system (Figures 23 and 24). The wood crib was not extinguished in either the experiment or the simulation. The temperatures achieved are comparable with those measured during the calibration test of the BS8414-1 facility and follow the wood crib-only temperature evolution. At external L1 level, experimental and numerical temperatures are in an excellent agreement during the first 900 seconds of the test (corresponding to the time criterion to comply to BR135). Then, distortions of the panels above the fire source and geometrical changes of the crib due to its combustion were observed during the test. This can lead to the differences observed at this time experimentally.

The global thermal behaviour of the system is captured by the model, validating the thermal properties of the materials used for both
systems. The fire behaviour of the insulant is thus correctly simulated. The main differences observed can be attributed to the fact that the numerical model does not take into account mechanical changes of the system (local distortions were observed after the test) or displacement of thermocouples inside the cavity.

The same conclusions are made for the temperature in the back and side wall air cavities in both systems. For both systems (Figures 25 and 26), the main differences observed can be related to the thermocouple moving in the cavity due to local turbulence during the test. The good agreement between experimental data and numerical results for the surface and air cavity temperatures thus validates the thermal properties assumed for each material used in the study and in particular for the cladding.

6.2 Heat release rate

The HRR curves from the numerical analysis of the tests of the three configurations are presented in Figure 27. The comparison of the HRR for the [ACM-PE + PIR] and [ACM-PE + MW] systems show that
when PIR is used, we observe a higher peak of HRR (by approximately 1.5 MW) and the peak is delayed by approximately 2 minutes 30 seconds for the system with MW compared with the system with PIR. This higher value is due to the small heat release contribution from the PIR. The delay is related to the quicker start of combustion in the MW system and to the energy absorbed by the PIR for charring, thermal cracking and pyrolysis, leading to a competition between thermal and thermochemical effects.

For the [ACM-A2 + PIR] system, there is a local increase in the HRR at 8 minutes 30 seconds. It is related to limited combustion of the insulant and to pyrolysis gases released by the PIR burning out of the system. In the numerical model, the PIR insulant surface burns quickly until the fuel mass is consumed in the numerical cell. This contribution from the insulant can be due to the limited thermal degradation of the cladding not being taken into account numerically: all the heat is kept in the air cavity without participating to the cladding degradation. This leads to more aggressive combustion of the insulant. However, the PIR contribution is low (300 kW). Thus, the numerical approach allows the evaluation of the contribution of the PIR during the test.
This study aimed to understand and to model the fire behaviour of different facade systems at the large scale of BS8414-1. Systems comprising [ACM-PE + PIR], [ACM-A2 + PIR], and [ACM-PE + MW] were numerically modelled following previous BS8414-1 experiments. In a preliminary study, the fire behaviour of different facade system comprising [ACM-PE + PIR], [ACM-A2 + PIR], and [ACM-PE + MW] was tested to the medium scale ISO 13785-1 test. Based on the thermal and combustion properties of each material of which these insulated facade systems comprised, it was possible to numerically model each of the experimental tests, with excellent agreement between the model outputs and the experimental data. More precisely, HRR, wall cavity gas temperature, and the surface temperature of the insulant were predicted with very good agreement between the model outputs and the experimental data. In this paper, the behaviour of the different facade systems was predicted at a large scale through the modelling of the above-mentioned BS8414-1 tests. Gas temperatures and the general behaviour of system were predicted with good agreement between the model outputs and the experimental data.
The thermal properties of each material were then validated using a coarser numerical grid that would be more representative of what could be used to model at larger scales, such as, for example, high rise buildings. The above-mentioned BS8414-1 test data were compared with numerical model outputs achieved with the coarser grid. The use of these parameters for a larger scale was thus validated.

In all the simulated configurations, the strong combustion of polyethylene cored ACM cladding leads to the quick consumption of the material soon after its ignition. The ACM cladding burns in well-ventilated conditions because of its external location, and it disappears at early stage of the fire and thus reduces the cavity performance. The insulant is exposed to the fire contribution of the cladding and to the flames in the cavity, even if the cladding has disappeared. During the fire test, the insulant can then burn in well-ventilated conditions because it is quickly exposed to the external environment once the cladding has disappeared. Furthermore, the ACM-PE represents more than 90% of the value of the peak of HRR and of the total energy released.

An additional sensitivity analysis was performed on the [ACM-PE + PIR] system, to evaluate the influence of the wood crib on HRR. It can be concluded that once the combustion of the system above the fire room starts, the allowed variance in the heat output of the wood crib has only a minor influence on the fire propagation of the system. The lower bound of wood crib HRR (2.5 MW) is sufficient to trigger cladding system ignition and fire development. The wood crib HRR used in the numerical models was of the maximum allowed (3.5 MW). During real tests, this value can be lower. This can explain some of the differences observed when numerical and experimental results are compared.

A sensitivity analysis (in Appendix A in Supporting Information) to investigate the influence of the ignition temperature of the PIR insulant showed that the ignition temperature of PIR does not play a significant role in the overall behaviour of the system as the predicted maximum HRR value is always in the margin of uncertainty of the measurements. Conversely, the ignition temperature of PE is a very influential parameter. Due to the very low impact of PIR ignition temperature and the very high impact of that of PE, it can be concluded that the performance of the ACM-PE is the driving component leading to the failure of the whole system.

The robustness of the numerical model has been further validated. The model was modified to verify the combustion behaviour of each part of the system through additional investigations: the modelling of [ACM-A2 + PIR] and [ACM-PE + MW] systems was also conducted and excellent agreement was found between the model outputs and the experimental data.

The numerical simulations and the experimental tests show that the ACM cladding is the most important element driving global fire behaviour of the facades. In particular, ACM-PE-based cladding systems, whatever the insulant used in the system, show very rapid fire propagation and the degradation of the ACM-PE, while burning, affects the integrity of the cavity. The numerical modelling approach can help to understand the relative contribution of the materials of which complex systems comprise.

These conclusions on the ACM-PE-based cladding system are similar to those made in work based on the intermediate scale ISO 13785-1 test, detailed in Guillaume et al.26 27 Thus, scaling has minor influence on the fire behaviour of such facade systems. However, no singularities like windows were included in either test and will have a major influence on the fire propagation over a ventilated facade and for penetration of fire into the building.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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