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A DESIGN APPROACH TO EXTERNAL FIRE SPREAD FROM BUILDINGS WITH EXPOSED MASS TIMBER

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ABSTRACT: Engineered wood products (EWPs) are relatively new, innovative construction materials which, if used correctly, can serve as sustainable alternatives to more common construction types. They provide an opportunity for designers to reduce the embodied carbon of proposals. Given the climate crisis, it is vital that the sector decarbonises.
However, lessons must be learnt from previous sustainability-driven design decisions that did not sufficiently consider safety implications. Often there is a desire from building owners, occupiers and/or designers to expose mass timber. Doing so can provide aesthetic, wellbeing, cost and carbon benefits over encapsulation. However, exposing large areas of mass timber introduces an additional fuel load to the compartment – the structural fuel load, and compartment fire experiments to date have shown that this can lead to larger external flaming.
This paper aims to investigate potential implications of this phenomenon on: (i) large-scale 'standard' façade tests, and (ii) radiation assessments to neighbouring buildings.
First, temperature data recorded outside the opening(s) of seven mass timber compartment fire experiments is compared to temperatures in front of the façade recorded during three 'standard' industry façade fire tests. It is found that BS 8414 and the proposed harmonised European test generally expose the façade to more/as severe temperatures than observed during mass timber compartment fire experiments. Therefore, these tests are considered applicable to exposed mass timber buildings. The NFPA 285 test, which was designed for traditional buildings, is less severe than the mass timber experiments reviewed.
Heat fluxes recorded opposite openings in three mass timber compartment fire experimental series are then compared to heat flux predictions made following first principles-based radiation calculations following the enclosing rectangles and configuration factor method (as in BR 187). Using the "low" and "high" fire load assumptions in BR 187 leads to underpredictions of heat flux received. Modelling the external flame as an emitter (of the same temperature as the opening) has little impact on results. Therefore, a higher emitter temperature is recommended when carrying out radiation calculations from exposed mass timber compartments.

KEYWORDS: timber, external flaming, external fire spread, standard façade tests, radiation, compartment experiments

1 INTRODUCTION

1.1 THE CLIMATE CRISIS AND TIMBER

Buildings are responsible for approximately 40% of global CO_2 emissions, with embodied carbon accounting for around a quarter of that. Unlike operational carbon emissions, which can be reduced over time, embodied carbon is 'locked in' once an asset is constructed. As the global building stock is expected to double in terms of floor area by 2060, there is an urgent need for architects and engineers to use sustainable construction materials, such as engineered wood products (EWPs) [1], [2].
Innovations in EWPs (or 'mass timber') have presented opportunities for designers to use timber for larger structures. Timber sequesters carbon during its growth, and when it is sustainably sourced, used efficiently, and designed with the end-of-life scenario considered from the outset, can result in buildings with lower embodied carbon than those predominantly using steel and/or concrete [3], [4]. In addition, EWPs are aesthetically desirable, can have wellbeing benefits for building users [5], and may command higher rental rates [6].

1.2 EXPOSED MASS TIMBER AND EXTERNAL FLAMING

Exposing large areas of mass timber introduces additional fuel load to a compartment. The majority of small- and medium-scale compartment fire experiments conducted to date have shown that this can result in larger external flames [7], [8] and increased heat flux to both the building of fire origin and opposite [9] than from an otherwise identical compartment constructed from non-combustible materials. One experimental series, with a very high movable fuel load (of 1085 MJ/m^2), did not observe a significant increase in flame height when mass timber was

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introduced, but did report higher temperatures [10]. Significant external flaming was also observed during the large-scale *CodeRed* experimental series [11]–[13].

These observations highlight the need for existing fire safety design methods to be revisited, scrutinised and, if necessary, adjusted before they are applied to buildings with large areas of exposed mass timber. Larger external flaming may have an impact on:

(i) applicability of 'standard' large-scale façade tests,
(ii) radiation assessments to neighbouring buildings,
(iii) heat transfer analyses to external loadbearing structure.

The latter has been studied in separate work [14] so is not covered in this paper.

1.3 FIRE SAFETY OBJECTIVES

Broadly speaking, buildings are legally required to limit the risk of external fire spread:

- over the façade of the building of fire origin, and
- from one building to another,

to an 'acceptable level'. An 'acceptable level' may be determined based on a number of parameters, such as the type and scale of the building, occupancy characteristics, proximity to other buildings, etc.

Building regulations typically consider life safety. Clients and insurers may have additional objectives to limit damage to property, contents and/or business operations.

Different guidance documents exist as reference to enable designers to demonstrate compliance with fire safety objectives. In England, statutory guidance in the form of the approved documents "provide guidance for common building situations". "Compliance with the guidance set out in the approved documents does not provide a guarantee of compliance with the requirements of the regulations because the approved documents cannot cater for all circumstances, variations and innovations" [15]. Mass timber is a recent innovation within the construction industry that has not yet been widely adopted in the UK, so its use does not yet represent a "common building situation" [16].

Whilst there will always be some knowledge gaps, and "satisfactory engineering solutions may be achieved with partial information" [17], research is needed so that built environment professionals can understand mass timber further, and design, construct and maintain safe, sustainable buildings.

1.3.1 Limiting fire spread over external walls

Designers typically have two options for limiting fire spread over the façade of the building of fire origin:

(i) selecting materials which meet prescriptive reaction-to-fire performance requirements, or
(ii) conducting a large-scale 'standard' façade fire test and passing specified performance criteria.

This paper focuses on the latter. Large-scale façade tests submit a multi-storey test sample of the façade to a large fire, represented by wooden cribs or a gas burner. The 350kg wood crib specified in BS 8414 as part of the large-scale test, for example, gives a total energy output of ~4500 MJ over a 30 minute period, with a peak heat release rate of 3 ± 0.5 MW [18]. The intent of these tests is to simulate a realistic worst-case fire scenario, such as the flame projecting from a compartment fire post-flashover, or from a burning skip positioned close to the façade [19]. NFPA85 uses gas burners.

Data has been sourced by the authors from the proposed harmonised European test, the NFPA 285 test and the BS 8414 test for comparison with data from seven large-scale timber compartment experiments.

1.3.2 Limiting fire spread from one building to another

It is generally acknowledged that the risk of fire spread between buildings should be limited, however there is no internationally agreed method for doing so. Most national building codes (e.g., National Construction Code (NCC) [Australia], NFPA 5000 [USA], International Building Code (IBC) [USA], The Model Building Code [Germany], etc.) set out prescriptive separation distances based on building type. However, there is little scientific reasoning provided in support of these methods, which are often based on historical observations [20], [21]. The national building codes of some countries permit a calculation-based methodology to be used by designers to quantitatively assess the emitted radiation from a severe post-flashover fire onto an adjacent building/boundary such that they can ensure a maximum heat flux is not exceeded. BR 187 – *External fire spread – Building separation and boundary distances* [22] is one such method, which is the focus of this paper. The BR 187 method is based on research carried out by Margaret Law in the 1960s [23], [24]. The fire compartment is assumed to be a radiating emitter with a uniform temperature of either 830 °C (low fire load) or 1040 °C (high fire load). The typical acceptance criteria for incident radiation on an exposed building is 12.6 kW/m^2, the threshold for piloted ignition of wood.

The 2014 revision of BR 187 notes that some compartments, such as those that are well insulated, can result in higher temperatures. A document released as part of The Grenfell Tower Public Inquiry highlighted the need for further guidance on higher compartment temperatures and external flaming from well insulated compartments [25]. However, no guidance is currently provided on this topic, and it is therefore often not considered by designers. Similarly, no guidance currently exists on whether the assumptions within BR 187 are suitable for compartments with large areas of exposed mass timber.

1.4 STRUCTURE AND CONTENT OF THIS PAPER

This paper presents novel data from *CodeRed*, supplemented by data from the RISE [26] and Épernon experiments [27]. Temperatures recorded above and heat fluxes recorded opposite the openings in the experiments are used to understand the impact of exposed mass timber on externally venting flames and radiation from the compartments. First, temperature data is compared to temperatures from a selection of 'standard' façade fire tests (the proposed harmonised European test, NFPA 285 and BS 8414), to evaluate whether the tests are sufficiently severe. Then, the heat fluxes recorded opposite the openings are compared to heat fluxes calculated following a common radiation calculation method (BR 187).

2 THE *CODERED* EXPERIMENTS

Arup designed and commissioned a purpose-built facility for the *CodeRed* experimental series which took place at CERIB's Centre d'Essais au Feu (Fire Testing Centre).

The experiments aimed to study the fire dynamics in large, open-plan compartments with an exposed timber surface. The test geometry is shown in Figure 1.

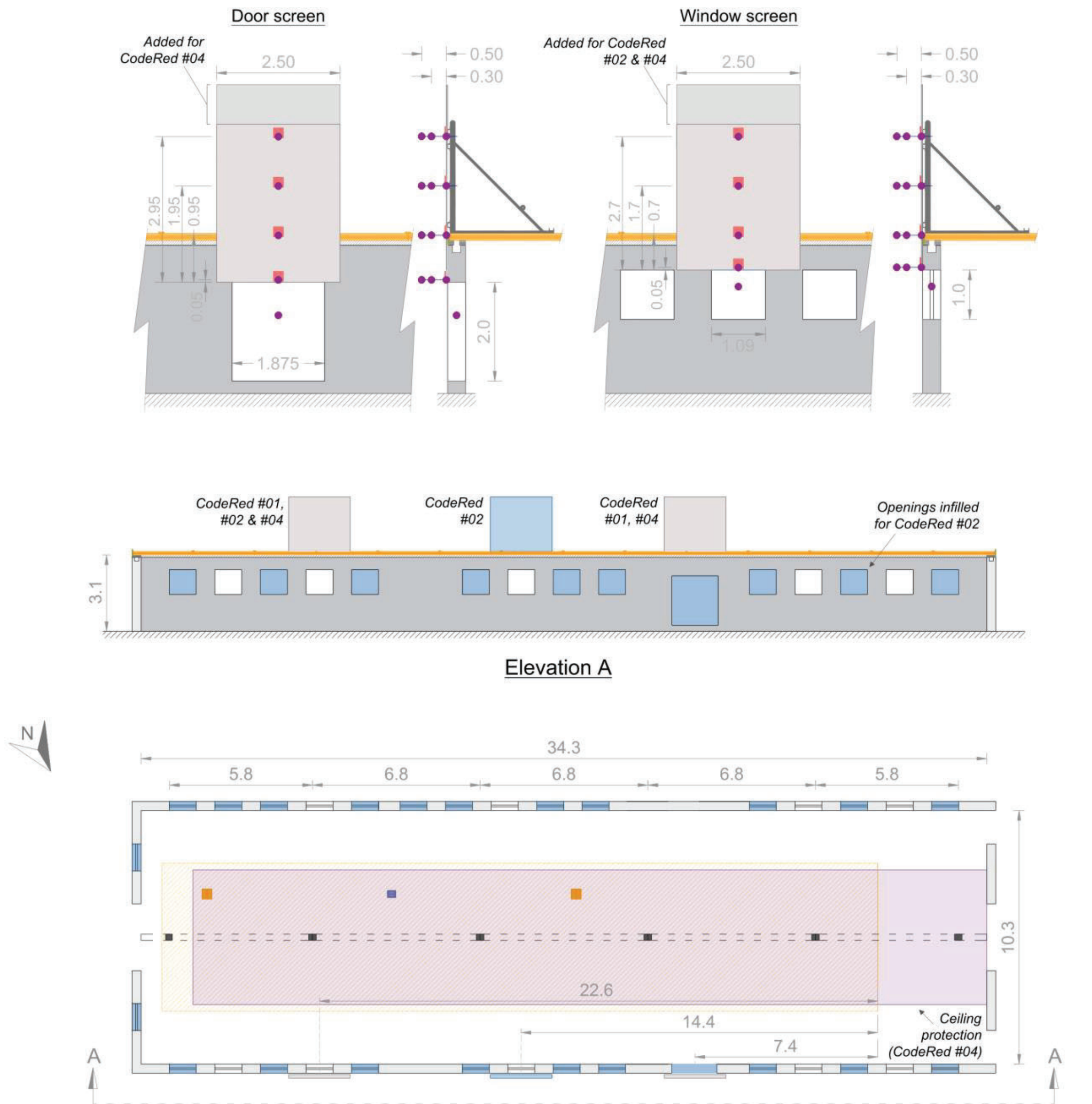

Figure 1: *Plan of CodeRed compartment, with elevations showing instrumented doors and windows. Openings coloured blue were infilled during CodeRed #02. Purple shading on plan indicates the area of encapsulation on the CLT ceiling in CodeRed #04.*

The compartment had an internal floor area of 352 m^2. The fuel bed was identical in all experiments and consisted of continuous wood cribs with a fuel load density of ~380 MJ/m^2 over a floor area of 174 m^2. The fuel load was chosen to enable comparison with earlier experiments studying travelling fire dynamics in equivalent non-combustible compartments *x-ONE* [28], *x-TWO* [29]. Table 1 summarises the key parameters of the *CodeRed* experiments without suppression.

2.1 INSTRUMENTATION

The fire development in the *CodeRed* experiments, both inside and outside the compartment, was captured via an extensive arrangement of instrumentation. A brief overview of the instrumentation used to capture the data presented within this paper is presented in this section. A more detailed description of the instrumentation used for each experiment can be found in the literature [11]–[13].

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Table 1: *Summary of the key parameters of the three CodeRed experiments without suppression.*

Experiment		***CodeRed #01***	***CodeRed #02***	***CodeRed #04***
Date		09 Mar 2021	01 Jun 2021	14 Dec 2021
Internal floor area, A_F	[m^2]	352	352	352
Total area of openings, A_w	[m^2]	56.6	**28.3**	56.6
Exposed CLT area, A_{CLT}	[m^2]	352	352	**176.7**
Total internal surface area of compartment (floor, ceiling and walls), **inc. opening area**, A_t	[m^2]	980	980	980
Total internal surface area **exc. opening area**, A_T	[m^2]	923	952	923
Area-weighted average window height, h_{eq}	[m]	1.488	1.818	1.488
Opening factor as per Eurocode [30] $A_t/(A_w h_{eq}^{1/2})$	[m$^{-1/2}$]	14.2	25.6	14.2
Opening factor as per L&O'B [31] $A_T/(A_w h_{eq}^{1/2})$	[m$^{-1/2}$]	13.4	24.9	13.4
Modified opening factor as per [32] $(A_T\text{-}A_{CLT})/(A_w h_{eq}^{1/2})$	[m$^{-1/2}$]	8.3	15.7	10.8
Instrumented openings		W1, D1	W1, **W2**	W1, D1
TC in openings?		No	**Yes**	**Yes**
HFG opposite openings?		No	**6m, 8m**	**6m, 8m**

2.1.1 Internal instrumentation

To measure the gas temperature distribution within the compartment, 57 thermocouples (TCs) were distributed across the compartment, organised into 17 thermocouple trees. To account for the radiative heat flux from the fire, the recorded temperatures were corrected using a methodology referred to as the *β-method*, which was consistent across *x-ONE* [28], *x-TWO* [29] and *CodeRed*.

2.1.2 External instrumentation

Outside the compartment, non-combustible screens were installed above two openings as shown in Figure 1. The screens were annotated to allow approximation of flame geometry. Thermocouples and plate thermometers were installed on each façade screen. In *CodeRed #02* and *#04*, thermocouples were also positioned within the openings.
The thermocouples recorded data every 10 seconds (i.e., a frequency of 0.1 Hz) for *CodeRed #01* and every 5 seconds for *CodeRed #02* and *#04* (i.e., a frequency of 0.2 Hz). To reduce noise, all data from the thermocouples was smoothed using the Savitzky-Golay filter [33] available within SciPy, with a time frame of 60 s.

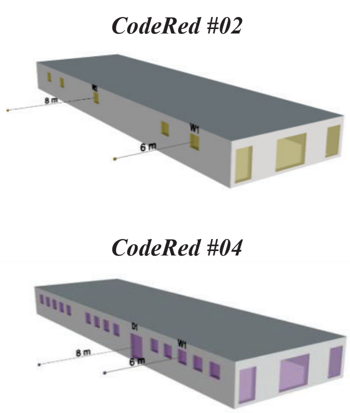

Figure 2: *Isometric models of CodeRed #02 and #04 showing instrumented openings.*

Unlike the internal thermocouple data, the temperatures recorded by the external thermocouples were not corrected to account for radiation received from the compartment fire, because the radiation received is expected to be small.
Heat flux gauges (HFGs) were installed opposite the centroid of the instrumented openings in both *CodeRed #02* and *#04*, as shown in Figure 2.
Two cameras were positioned opposite each instrumented opening to observe the external flame extension above the openings. Various other stationary cameras were placed around the compartment. Drones and handheld cameras were also used to give a dynamic view of the fire.

3 EXPERIMENTAL DATA

Papers covering the *CodeRed* experiments have been published which include detailed plots of internal and external temperature and heat flux data [11]–[13]. The following section presents additional data which has not yet been published.

3.1 HEAT FLUX OPPOSITE THE OPENINGS

Heat fluxes measured opposite the instrumented openings for *CodeRed #02* and *#04* are plotted in Figure 3. As expected, the heat flux measured by the HFG positioned 6 m opposite opening W1 recorded slightly higher heat fluxes in both experiments than the HFGs placed 8 m away from openings W2 / D1.
The peak heat flux recorded opposite W1 in *CodeRed #04* was 11.6 kW/m^2, compared with 7.9 kW/m^2 in *CodeRed #02* – an increase of 47 %. Despite the ceiling in *CodeRed #04* being partially encapsulated ceiling, it caused a higher heat flux opposite the same W1 opening. This is thought to be due to the greater number of openings in *CodeRed #04* radiating to the HFG.
The heat flux reading opposite the larger D1 opening was lower than the measurement opposite the window, contrary to expectations when considering the openings as uniform temperature emitters (i.e., ignoring external flames). The D1 opening had smaller external flames than the window openings which suggests the external flames were responsible for the higher measurement opposite the window opening W1 [13].

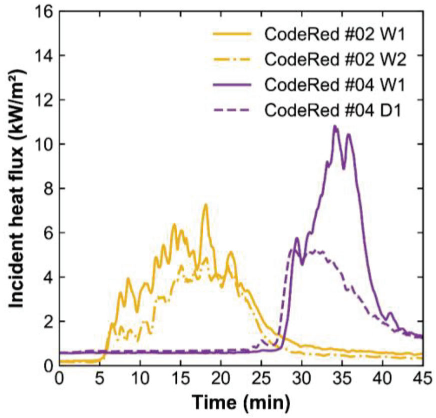

Figure 3: *Heat fluxes recorded at 6 m opposite opening W1 and 8 m opposite openings W2/D2 in CodeRed #02 and #04.*

Figure 3 also shows that peak heat fluxes occur later in *CodeRed #04* compared to *CodeRed #02*, due to the encapsulation slowing the growth phase and delaying the involvement of the CLT ceiling in the fire.

The fire duration in *CodeRed #02* was longer due to the reduced ventilation [12]. This is reflected in Figure 3, where an incident heat flux was registered opposite the openings for a period of around 20 minutes, compared to 10-15 minutes for *CodeRed #04*.

3.2 GAS TEMPERATURE IN THE OPENINGS

The temperatures recorded in the openings (shown in Figure 4) largely mirror the heat fluxes recorded opposite. Peak temperatures in the openings during both *CodeRed #02* and *#04* are very close to the 1040 °C that BR 187 assumes for "high fire load" compartments.

The temperatures in the window openings were broadly similar in each experiment. The door opening in *CodeRed #04* had a lower peak temperature, nearer 830 °C. This may be because the thermocouple for this opening was positioned lower in the opening (see Figure 1).

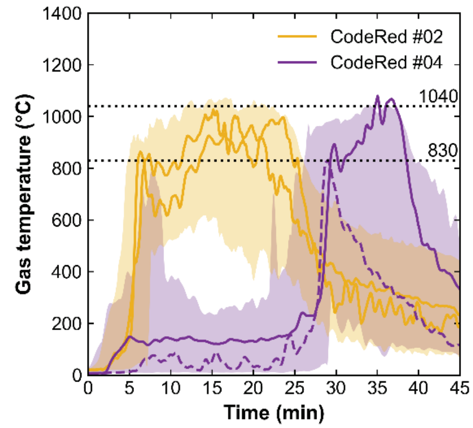

Figure 4: *Gas temperatures recorded during CodeRed #02 and #04. Lines show temperatures recorded within the windows (solid lines) and door (dashed line). Clouds show the range of corrected gas temperatures recorded inside the compartment.*

4 ANALYSIS

4.1 COMPARISON WITH 'STANDARD' LARGE-SCALE FAÇADE FIRE TESTS

As discussed in Section 1.3.1, large-scale testing of façade systems containing combustible materials (such as insulation or cladding) is a route to compliance for limiting external fire spread on the building of fire origin.

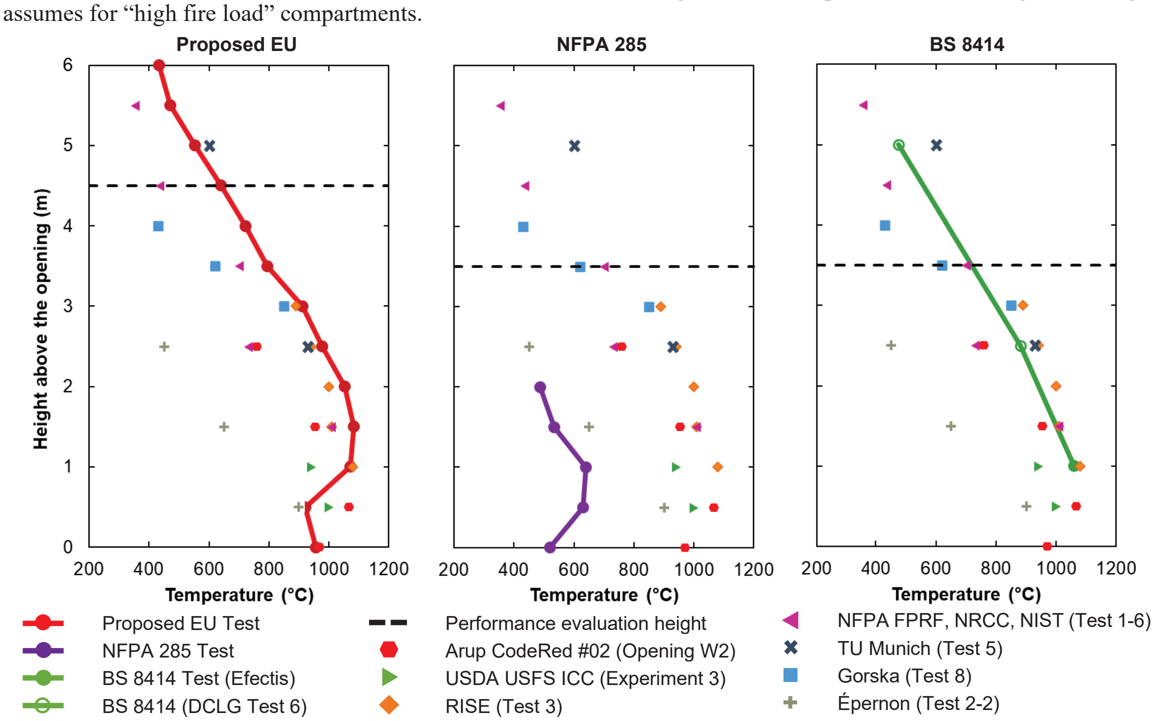

Figure 5: *Temperatures recorded outside timber experiments compared with those experienced during 'standard' large-scale tests.*

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To understand whether the existing 'standard' test fires are severe enough to represent the external flaming observed in large scale experiments with exposed timber, the external temperature data from *CodeRed* and other notable mass timber experiments with external instrumentation has been compared to available data from large-scale industry 'standard' façade fire tests. Namely:

- the BS 8414 test.
- the NFPA 285 test, and,
- the proposed large-scale harmonised European (EU) test, which is broadly based on the BS 8414 test [34].

These tests were chosen as they are widely applicable, and data was available from tests which had either no façade system installed [34]–[36] or a limited combustibility façade installation only [37], such that the façade system itself did not contribute to the temperature data.

Figure 5 plots the 'standard' façade fire test data on top of maximum temperatures recorded at different heights outside the openings of a range of small- to large-scale mass timber compartment fire experiments.

The proposed EU test represents a relatively accurate upper bound of the external temperature data recorded during the mass timber compartment fire experiments. The only minor inaccuracy is at around 0.5 m above the top of the opening, which may be due to the thermocouple being placed outside the flaming region (e.g., if the flame did not adhere to the façade).

The BS 8414 test performs similarly, however has slightly lower temperatures than the proposed EU test. Some timber compartment fire external flame temperatures slightly exceed the BS 8414 test temperatures, by approximately 50-100 °C.

The NFPA 285 test, on the other hand, exposes the façade to much lower temperatures than those seen during timber compartment fire experiments. This is not surprising given the room gas burner follows the ASTM E119 *Standard Test Methods for Fire Tests of Building Construction and Materials* time-temperature curve. The temperatures recorded during calibration of the NFPA 285 test are lower than all external temperatures recorded during the mass timber compartment experiments chosen for this analysis. These findings are similar to those reported by [38].

4.2 COMPARISON WITH THE BR 187 RADIATION ASSESSMENT METHOD

As discussed in Section 1.3.2, one route for demonstrating compliance in terms of limiting fire spread from one building to another is completing a quantitative assessment of the expected incident radiation on a neighbouring building or boundary in case of a post-flashover fire. BR 187 describes one such method.

4.2.1 Temperature of emitter

BR 187 recommends adopting 830 °C for "low fire load" spaces (office, residential) and 1040 °C for "high fire load" spaces (industrial, retail) when selecting the emitter temperature. It also notes that "further work is required to investigate whether a higher temperature should be used for … buildings with higher levels of insulation" [22].

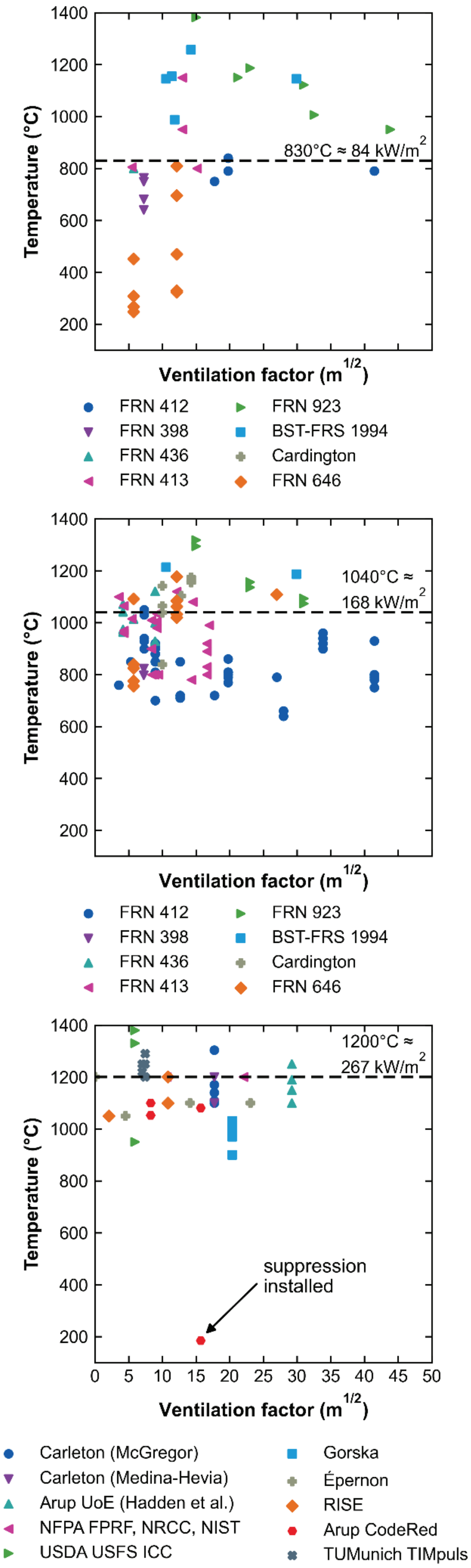

Figure 6*: Maximum internal temperature versus ventilation factor for compartment experiments with (i) low fire load, (ii) high fire load, and (iii) exposed mass timber structure.*

Figure 6 presents the original data that the 830 °C and 1040 °C values within BR 187 are based on. A wide scatter of the underlying data from various small- and medium-scale compartment fire experiments is notable.
To determine a more suitable emitter temperature for mass timber compartments, a similar plot has been made for ten mass timber compartment fire experimental programmes. A general shift towards higher temperatures is evident through the three subplots. This suggests that a higher emitter temperature may be appropriate when conducting BR 187 assessments for buildings with exposed mass timber which do not benefit from e.g., sprinkler protection. 1200 °C has been chosen as a representative temperature for the analysis in this paper.

4.2.2 Geometry and emissivity of emitter(s)

BR 187 presents three methods to evaluate fire spread risk between buildings, namely, in BR 187 Section:
2.2.1. Enclosing rectangles,
2.2.2. Aggregate notional areas (or protractor method),
2.2.3. An alternative approach using look-up tables.
The enclosing rectangles method is typically used for modern buildings with a majority glazed façade whereby the entire glazed façade is modelled as an emitter.
Appendix A of BR 187 outlines the radiation calculation which is then made following configuration factor theory. Appendix B of BR 187 summarises Law and O'Brien's seminal work on external flaming [31], though in the experience of the authors, this is rarely applied in practice. BR 187 states that, when Appendix B is followed, the results are very similar to the 'conventional' analysis [22].

4.2.3 Parametric study of radiation to other buildings

A parametric study has been completed to evaluate various emitter temperatures, geometries and emissivities.

4.2.3.1 Scenarios modelled

Scenario 1 (BR 187 Appendix A)
In this scenario, all openings are modelled as radiating emitters, following BR 187 Section 2.2.1 and Appendix A. All other construction is assumed to be 'protected' i.e., constructed from fire resisting construction and not emitting radiation to the nearby building. The temperature of the emitters was taken as 830 / 1040 / 1200 °C.

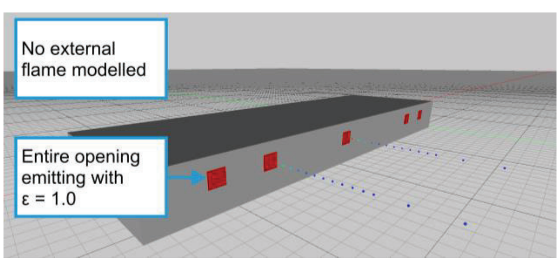

Figure 7: *Scenario 1 modelling parameters for CodeRed #02.*

Scenario 2 (BR 187 Appendix B)
Following BR 187 Appendix B, whereby the upper ⅔ of the opening(s) and an external flame are modelled as radiating emitters, both with the same emitting temperature. The emissivity of the opening, $\varepsilon_o = 1.0$. The emissivity of the flame, ε_f, calculated as per BR 187 / Law and O'Brien using $\varepsilon_f = 1.0 - exp(-0.3X_{ef})$, where X_{ef} is the thickness (depth) of the flame. Flame height was calculated based on the crib fuel load only (i.e., no CLT contribution was considered), as no generally agreed analysis method currently exists that determines the impact of the structural (CLT) fuel load on external flame height. Temperature of emitters is also varied as per (1).

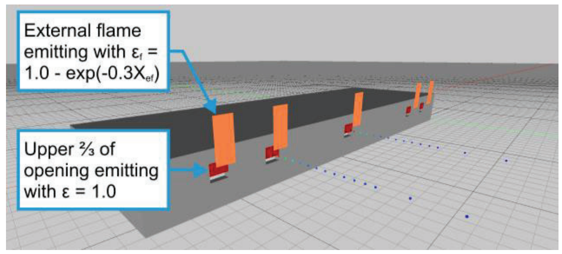

Figure 8: *Scenario 2 modelling parameters for CodeRed #02.*

Scenario 3 (BR 187 App. B, with $\varepsilon_f = 1.0$)
The same as (2), but with an assumed worst-case emissivity of the external flame, $\varepsilon_f = 1.0$, used.

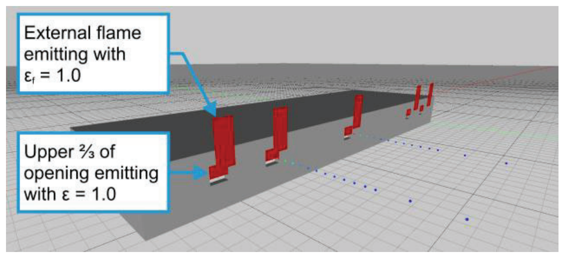

Figure 9: *Scenario 3 modelling parameters for CodeRed #02.*

Only Scenarios 1 and 3 are presented in this paper, due to the quantity of data and because the predictions in Scenario 2 were very similar to Scenario 1. This aligns with BR 187 Figure B4, which also shows very similar predictions between the two methods.

4.2.3.2 A note on flame emissivity, ε_f

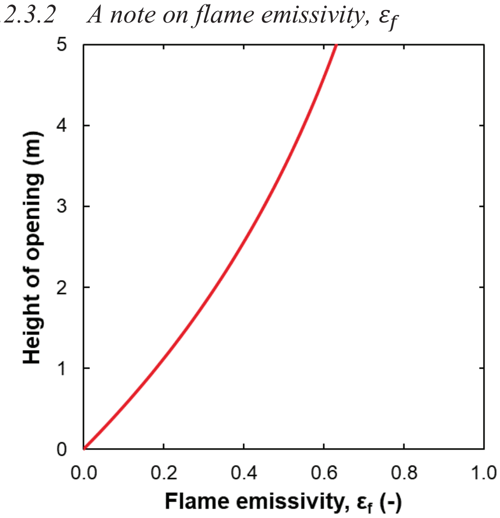

Figure 10: *Relationship between opening height and ε_f.*

Figure 10 shows the BR 187 correlation between the emissivity of the flame and the height of the opening (which determines the flame thickness (depth), X_{ef}).

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In *CodeRed*, the window openings were 1.0 m tall, which results in a calculated flame emissivity of 0.18, meaning the contribution of the external flames to the incident heat flux calculated opposite is minimal when following BR 187 Appendix B. This is also the case for most real-world design scenarios. For example, a fire in a single-storey compartment with 3.0 m tall floor-to-ceiling glazing (assuming full glass breakage) would result in flames with an emissivity of 0.45. This would reduce the heat flux calculated from the flame emitter by over half.

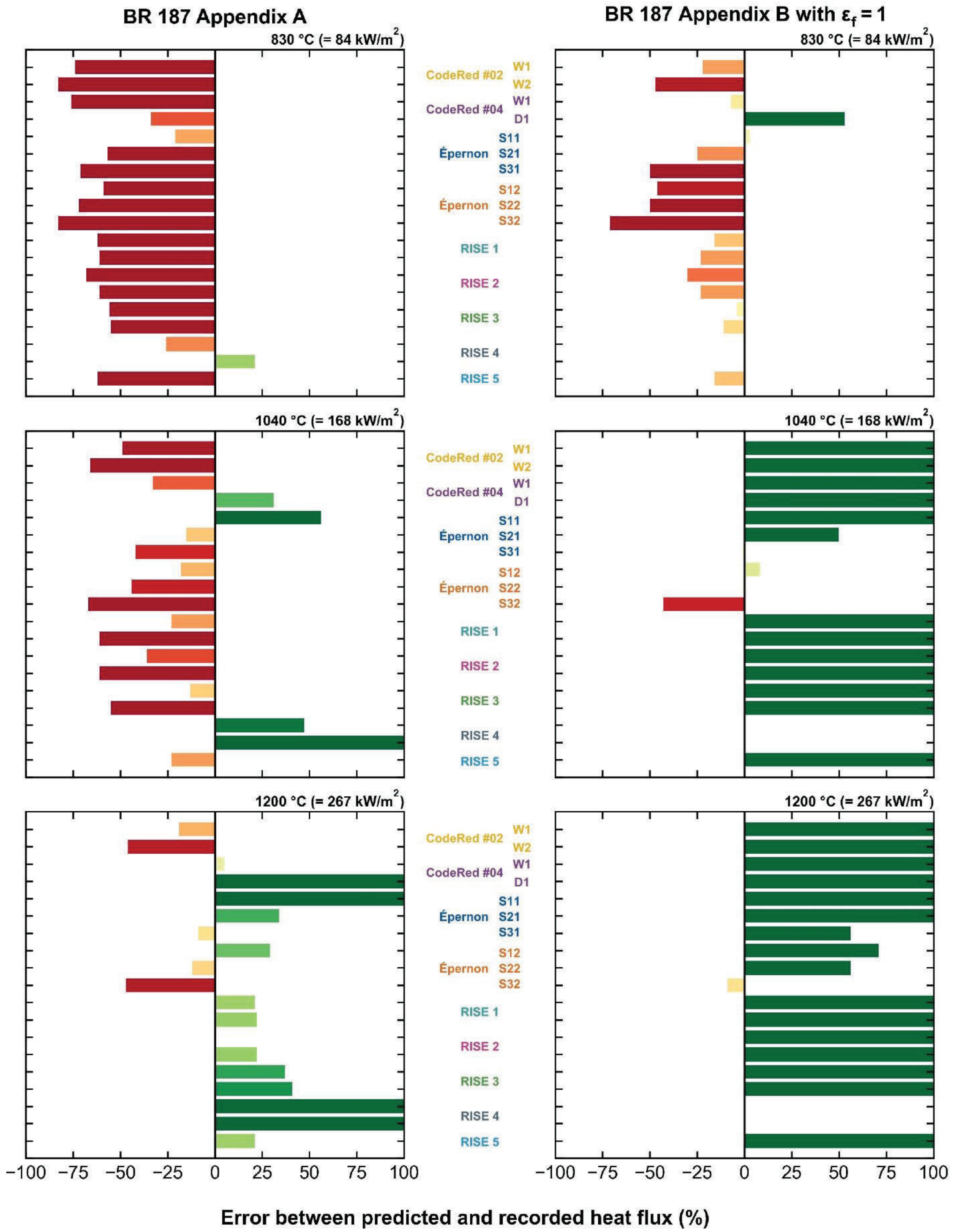

Figure 11: *Bar charts showing percentage error between predicted heat fluxes and the peak heat fluxes recorded during a range of timber compartment fire experiments. An error of +100% represents a heat flux prediction which is twice the recorded heat flux.*

4.2.3.3 Compartment experiments analysed

The parametric study was applied and compared to:

- Large-scale experiments *CodeRed #02* and *#04*, which had external HFGs as per Section 2.1.2.
- Medium-scale timber compartment fire experimental programmes by RISE and Épernon, which also had external HFGs as per [26], [27].

RISE Test 4 was not modelled following BR 187 Appendix B because the flame height calculated was so low as to be negligible. Sprinklers are not considered in this work as none of the compartment experiments analysed had them installed.

4.2.3.4 Comments on results

Figure 11 presents the results from the parametric analyses using bar charts. The plots visualise the performance of the predictions made following BR 187 compared to the actual heat fluxes recorded during the experiments, as percentage error between predicted heat fluxes and the peak heat fluxes recorded during a range of timber compartment fire.

Figure 11 shows:

- Using an emitter temperature of 830 °C resulted in significant underpredictions of heat flux across the experiments analysed. 18 out of 19 predictions were low when modelling the opening only as an emitter. 15 out of 17 predications were low when following BR 187 Appendix B (i.e., modelling the external flame) and conservatively assuming the flame emissivity is 1.
- Using an emitter temperature of 1040 °C made only a small improvement to the predictions. When modelling only the opening, three predictions were satisfactory (i.e., overpredicted with a reasonable factor of safety). However, one prediction largely overpredicted, and the other 15 predictions were low.
- When the modelled geometry was adjusted following Appendix B (i.e., with a flame at the same temperature as the opening (1040 °C) and with an emissivity of 1), the predictions swung the other way. 12 predictions overpredicted significantly. The same observation (albeit slightly worse) is made for the 1200 °C emitters following Appendix B.

The best predictions for heat flux received opposite the mass timber compartments analysed were from the models which assumed emitters representing the opening geometry only (i.e., without external flames) at a temperature of 1200 °C. 10 out of 19 of these predictions (i.e., more than 50%) were satisfactory (made overpredictions by a reasonable factor of safety). In four cases, significant overpredictions were made while underpredictions were made in only five cases.

5 DISCUSSION

5.1 APPLICABILITY OF EXISTING LARGE-SCALE 'STANDARD' FAÇADE TESTS

External temperature data recorded during seven mass timber compartment fire experiments has been gathered and presented. This data has been compared to temperatures recorded in front of the façade during three 'standard' industry façade fire tests – namely BS 8414, NFPA 285 and the proposed harmonised European test – to evaluate if the existing tests subject façade system to an appropriate fire severity where a building contains exposed mass timber.

The comparison showed that the proposed harmonised European test has the most severe external flame, which envelopes the data from mass timber compartment experiment well: 89% of the data points from mass timber compartment experiments were exceeded by the test.

The BS 8414 test also showed relatively good enveloping of the data: 65% of the data points from mass timber compartment experiments were exceeded by the test.

However, it should be noted that the BS 8414 data was more limited than the proposed European test data. Only three data points were available, from two different sources. Therefore, the observations are less robust than those made when comparing to the proposed European test. The proposed European test is based on BS 8414, and broadly represents that test, so similar observations should be expected (as was evident in this work).

The NFPA 285 test was shown to have a lower external flame severity than all the mass timber compartment experiments reviewed (i.e., it didn't envelope any of the data points). NFPA 285 is referenced in the IBC and NFPA 5000, for use with buildings that include combustibles as part of the exterior wall, located over 18m in height. The applicability of the NFPA 285 test for analysing the performance of façades of buildings that include large areas of exposed mass timber structure (interior to the building) is therefore questionable and future editions of this standard will need to address the available experimental data.

5.2 APPLICABILITY OF EXISTING RADIATION CALCULATION METHODS

The underlying data behind the "low fire load" and "high fire load" assumptions within BR 187 for compartment temperature has been presented. This has been compared to a new dataset, of the peak internal compartment temperatures recorded during a selection of ten mass timber compartment fire experimental programmes. The general upward shift indicates a hotter emitter temperature may be appropriate for buildings with large areas of exposed mass timber and no beneficial fire protection measures such as sprinkler protection. 1200 °C was chosen as a "very high fire load" compartment temperature. This enveloped most of the timber compartment experiments reviewed, with a scatter no greater than seen in the underlying data for non-combustible compartment experiments.

Based on this, a parametric analysis has been undertaken to evaluate the accuracy of existing BR 187 calculation methods when applied to mass timber compartment fire experiments. The analysis evaluated three different emitter temperatures (830 °C, 1040 °C and 1200 °C), two geometry combinations (openings only, openings and flame) and three emissivity combinations ($\varepsilon_o = 1.0$, $\varepsilon_o = 1.0\ and\ \varepsilon_f = 1.0 - exp(-0.3X_{ef})$, and $\varepsilon_o = 1.0\ and\ \varepsilon_f = 1.0$). A total of 53 calculations were made across three different mass timber compartment fire experimental series.

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The analysis showed that, if the existing assumptions within BR 187 for temperatures of "low fire load" and "high fire load" compartments were applied to spaces with large areas of exposed mass timber, underpredictions can be expected, even when modelling the external flaming following Appendix B. Adjusting the Appendix B external flaming method to include a flame emissivity of 1.0 was found to be overly conservative.

The best predictions for heat flux were made following the existing BR 187 enclosing rectangles method using a "very high fire load" compartment emitter temperature of 1200 °C. Whilst the authors recognise the 'crudeness' of the BR 187 method, it has been the focus of this paper because it is a popular method for assessing the risk of external fire spread between buildings in the UK. The findings are based on first principles radiation analyses, so could be adopted elsewhere where similar quantitative design methods are permitted [21].

Other more sophisticated approaches, such as the probabilistic method outlined in BR 187 IP 3-16 [39], will require further investigation to determine if these methods are appropriate on timber buildings, or if further amendments are needed.

It is noteworthy that the current draft of EN 1995-1-2 [40] proposes a modified version of the existing external flame correlation in EN 1991-1-2 [30] and BR 187 Appendix B to account for the structural fuel load present in timber buildings. This method has not been assessed as part of this study though further review against the available datasets are recommended.

6 CONCLUSIONS

Many timber compartment fire experiments, including *CodeRed*, have shown that large external flames and higher compartment temperatures can be expected from compartments with exposed mass timber where there is no automatic fire suppression installed. This paper investigates the impact of this phenomenon on: (i) the applicability of large-scale 'standard' façade tests, and (ii) radiation assessments to neighbouring buildings.

Firstly, novel external temperature and heat flux data from the *CodeRed* experiments is presented. Then, this data is supplemented with temperature data from a collection of ten medium- and large-scale compartment fire experiments with varying areas of exposed mass timber, and compared to temperatures recorded outside three industry 'standard' large-scale façade fire tests. Two of the large-scale tests, the proposed large scale harmonised European test and the BS 8414 test, generally enveloped the timber data points well. These large-scale tests therefore are reasonable tests to use for façade systems on buildings with large areas of exposed mass timber. NFPA 285 did not envelope any of the timber compartment fire data points.

The second focus of the paper is existing radiation calculation methods for assessing the heat flux that may be expected on neighbouring buildings/boundaries. When carrying out such a calculation, the temperature of the emitter is a key parameter. Temperature data which underlies existing assumptions within BR 187 is presented and compared with temperature data from a selection of 10 mass timber compartment fire experiments. An obvious trend towards higher peak internal temperatures is observed, which indicates that a higher emitter temperature may be appropriate for buildings with large areas of exposed mass timber.

Based on this, a parametric analysis has been completed to assess the performance of the BR 187 calculation method (the current design method in the UK for evaluating the external fire spread risk between buildings). Heat flux data recorded opposite three mass timber compartment fire experimental programmes is compared to predictions made following BR 187. It was found that simply increasing the emitter temperature to 1200 °C yielded the best results based on the test data available to the authors. Should further data come to light that contradicts the findings of this analysis, then this temperature may need to be revaluated.

Whilst this paper has focused on the BR 187 method, the findings are based on first principles, therefore will apply to other countries which have similar quantitative analysis methods.

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REFERENCES

[1] Architecture 2030, "Why The Building Sector?," 2022. https://architecture2030.org/why-the-building-sector/ (accessed Mar. 26, 2022).

[2] WBCSD and Arup, "Net-zero buildings - Halving construction emissions today," 2023.

[3] W. Hawkins, "Timber and carbon sequestration," *Struct. Eng.*, vol. 99, no. 1, pp. 18–20, 2021.

[4] Arup, "Net Zero Carbon Buildings: Three Steps to Take Now," 2020.

[5] D. R. Fell, "Wood in the human environment: restorative properties of wood in the built indoor environment," University of British Columbia, 2010. doi: 10.14288/1.0071305.

[6] L. Wingo, "The obstacles and opportunities of mass timber construction in the US," *Arup Perspectives*, 2021. https://www.arup.com/perspectives/the-obstacles-and-opportunities-of-mass-timber-construction-in-the-us (accessed Mar. 26, 2022).

[7] J. Sjöström, A. Temple, D. Brandon, E. Hallberg, and F. Kahl, "Exposure from mass timber compartment fires to facades," Brandforsk, 2021.

https://doi.org/10.52202/069179-0228

[8] C. Gorska, “Fire Dynamics in Multi-Scale Timber Compartments,” University of Queensland, 2019. [Online]. Available: https://espace.library.uq.edu.au/view/UQ:ec263ab/s4408332_final_thesis.pdf

[9] A. Bartlett *et al.*, “Heat fluxes to a facade resulting from compartment fires with combustible and non-combustible ceilings,” in *FSF 2019 – 3nd International Symposium on Fire Safety of Facades*, 2019, pp. 62–69.

[10] T. Engel and N. Wether, “Impact of Mass Timber Compartment Fires on Faade Fire Exposure,” *Fire Technol.*, 2022, doi: 10.1007/s10694-022-01346-8.

[11] P. Kotsovinos *et al.*, “Fire dynamics inside a large and open-plan compartment with exposed timber ceiling and columns: CodeRed #01,” *Fire Mater.*, pp. 1–27, 2022, doi: 10.1002/fam.3049.

[12] P. Kotsovinos *et al.*, “Impact of ventilation on the fire dynamics of an open-plan compartment with exposed timber ceiling and columns: CodeRed #02,” *Fire Mater.*, pp. 1–28, 2022, doi: 10.1002/fam.3082.

[13] P. Kotsovinos *et al.*, “Impact of partial encapsulation on the fire dynamics of an open-plan compartment with exposed timber ceiling and columns: CodeRed #04,” *Fire Mater.*, pp. 1–30, 2023, doi: 10.1002/fam.3112.

[14] A. Glew, E. O’Loughlin, P. Kotsovinos, D. Barber, and J. Schulz, “Application of the Law and O’Brien correlation for external flames to mass timber compartments,” in *SiF 2022 - The 12th International Conference on Structures in Fire*, 2022.

[15] HM Government, *Fire safety: Approved Document B. Volume 2: Buildings other than dwellings*, vol. (inc. 2020. 2019.

[16] HM Government, “Approved Document B: Fire safety - frequently asked questions - GOV.UK.” https://www.gov.uk/guidance/approved-document-b-fire-safety-frequently-asked-questions (accessed Sep. 21, 2022).

[17] M. Law and P. Beever, “Magic numbers and golden rules,” in *Proceedings of the Fourth International Symposium on Fire Safety Science, Ottawa, Canada, 13-17 June 1994*, 1994, pp. 78–84.

[18] S. Colwell and T. Baker, *BR 135: Fire performance of external thermal insulation for walls of multistorey buildings*, Third. Watford: BRE, 2013.

[19] J. Schulz, D. Kent, T. Crimi, J. L. D. Glockling, and T. R. Hull, “A Critical Appraisal of the UK’s Regulatory Regime for Combustible Façades,” *Fire Technol.*, vol. 57, no. 1, pp. 261–290, 2021, doi: 10.1007/s10694-020-00993-z.

[20] E. Carlsson, “External Fire Spread To Adjoining Buildings - A review of fire safety design guidance and related research,” Lund University, 1999.

[21] D. Thomson, P. Currie, and J. Mai, “A Comparative Analysis of the Use of Different External Fire Spread Calculation Methods,” in *Proceedings of the 11th conference on performance-based codes and fire safety design methods*, 2016, no. 22-25 May.

[22] R. Chitty, *BR 187 External fire spread: building separation and boundary distances*, Second. Watford: BRE, 2014.

[23] M. Law, “Fire Research Technical Paper No. 5 - Heat Radiation from Fires and Building Separation,” 1963.

[24] P. H. Thomas, A. J. M. Heselden, and M. Law, “Fully-developed compartment fires - two kinds of behaviour,” Borehamwood, 1967.

[25] R. Chitty and T. Lennon, “Department for Communities and Local Government Final Work Stream Report: BD 2887 - Compartment sizes, resistance to fire and fire safety project,” Watford, 2015. [Online]. Available: https://assets.grenfelltowerinquiry.org.uk/CLG00006271_BRE_ DCLG Final Work Stream Report - Compartment sizes%2C resistance to fire and fire safety project - Work stream 6 - Space Separation dated 3 March 2015_4.pdf

[26] D. Brandon, J. Sjöström, E. Hallberg, A. Temple, and F. Kahl, “Fire Safe implementation of visible mass timber in tall buildings – compartment fire testing,” 2020.

[27] The University of Edinburgh and CERIB, “Épernon Fire Tests Programme,” 2020.

[28] E. Rackauskaite *et al.*, “Fire Experiment Inside a Very Large and Open-Plan Compartment: x-ONE,” *Fire Technol.*, 2021, doi: 10.1007/s10694-021-01162-6.

[29] M. Heidari *et al.*, “Fire experiments inside a very large and open-plan compartment: x-TWO,” in *SiF 2020 – The 11th International Conference on Structures in Fire*, 2020, no. November, pp. 479–491. doi: 10.14264/b666dc1.

[30] The British Standards Institution, *Eurocode 1: Actions on structures Part 1-2: General actions – Actions on structures exposed to fire*. 2013.

[31] M. Law and T. O’Brien, “Fire Safety of Bare External Structural Steel,” *Constrado*, 1981.

[32] C. Gorska, J. Hidalgo, and J. Torero, “Fire dynamics in mass timber compartments,” *Fire Saf. J.*, 2020, doi: 10.1016/j.firesaf.2020.103098.

[33] A. Savitzky and M. J. E. Golay, “Smoothing and Differentiation of Data by Simplified Least Squares Procedures,” *Anal. Chem.*, vol. 36, no. 8, pp. 1627–1639, Jul. 1964, doi: 10.1021/ac60214a047.

[34] J. Sjöström, J. Anderson, F. Kahl, L. Boström, and E. Hallberg, “Large scale exposure of fires to facade - Initial testing of proposed European method,” 2021.

[35] Thomas Bell-Wright, “NFPA 285 - 2019 calibration data.” Thomas Bell-Wright, Dubai, 2019.

[36] Efectis, “FIRE TESTS REPORT n° EUI-20-000358, Regarding: The characterization of: Large exposure cribs,” 2020. doi: 10.1002/fam2667.

[37] BRE Global Ltd, “BRE Global Client Report - BS 8414-1:2015 + A1:2017 test referred to as DCLG test 6,” Watford, 2017.

[38] J. Sjöström, R. Mcnamee, and A. Temple, “External fire plumes from mass timber compartment fires — Comparison to test methods for regulatory compliance of façades,” no. January, pp. 1–12, 2023, doi: 10.1002/fam.3129.

[39] S. Koo, *BR 187 IP 3/16 External fire spread - Supplementary guidance to BR 187 incorporating probabilistic and time-based approaches*. Watford: BRE, 2016.

[40] Comité européen de normalisation, *prEN 1995-1-2:2025 (Final Draft). Eurocode 5: Design of timber structures Part 1-2: General — Structural fire design*. 2021.

https://doi.org/10.52202/069179-0228