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Letter to the Editor: Design Fires for Open-Plan Buildings with Exposed Mass-Timber Ceiling

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Dear editor,

Over the past decade, the design and construction of mass timber buildings using cross laminated timber (CLT) and glulam have significantly increased globally. This is mainly due to the benefits of timber construction in the global fight against climate change and a decarbonised economy. In addition, it meets architectural aspirations, can result in a reduced cost and improved speed of construction, in comparison to conventional, typically non-combustible construction forms. Many recent proposals by architects include high-rise mass timber buildings for office and public uses with large open-plan floor areas that are greater than 1000 m^2 with aspirations of maintaining as much timber exposed as possible.

For the structural fire design of high-rise buildings, a key issue to be addressed is the requirement for the building to withstand burn-out of a fully developed fire. When the load-bearing member is combustible and is exposed there is a feedback loop between the fire severity and structural response (through timber charring) resulting in more onerous fire conditions. The uncertainty of the types of fires that are therefore likely to occur in large-open plan compartments with exposed load-bearing timber, and how the timber may contribute to the fire, is a complex area that has not received enough attention from regulators, standardisation bodies, the industry or the research community.

A conservative measure to mitigate the inherent risk combustible load-bearing elements pose, for design safety purposes is that of complete encapsulation of the timber. The purpose being to limit the additional contribution from the combustible structure to the fire throughout its duration. This is a relevant design safety assurance solution, once the encapsulation systems have been appropriately detailed, and fire tested for the specific application.

It is important to understand the effect of the exposed mass timber on compartment fire dynamics to actively incorporate exposed load-bearing timber into a robust design solution; and this understanding is also relevant when determining the acceptable exposed area when quantifying the fire resistance of the structure,

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and when analysing if the compartment floors and walls are not compromised for the design fires being considered.

In addition to the quantity of exposed timber area, the overall compartment fire dynamics may also be impacted by the number and orientation (e.g. walls vs. ceiling) of exposed mass timber surfaces [1]. However, this aspect is outside the scope of this letter, which focuses on the fire severity within buildings with a single exposed mass timber surface (i.e. ceiling).

1. The Compartment Fire Framework and Exposed Timber Structures

Globally, there is no design methodology for quantifying the effect of exposed mass timber on the fire dynamics which has been thoroughly validated even for small compartments that have been studied extensively from the 1960s. The largest compartment fire tests carried out to date with exposed mass timber surfaces are only 84 m^2 [2] in floor area and are primarily representative of rooms in residential and hotel uses. There is no large-scale open plan test or experimental data available at present that is representative of typical office configurations. As a result, it is difficult to draw conclusions with respect to the fire dynamics of high-rise mass timber structures where open plan spaces are being proposed.

Figure 1 illustrates a huge discrepancy between the available timber compartment fire experiments and high-rise mass timber buildings currently being designed and built. This figure represents the increasing compartment surface area to volume ratio with increasing compartment floor area. The higher the ratio the more likely flashover is to develop within the enclosure due to increased re-radiation from the walls [3].

Open-plan compartment floor areas (1000 to 4600 m^2) for currently proposed mass timber buildings identified in Fig. 1, are 10 to 55 times higher than timber compartments for which experimental data is available at this time. The expected fire dynamics are likely to be different and more complex in these large open plan floors than in small rooms, for which experimental data is available.

2. Small Compartment Fires With Exposed Mass Timber

A recent approach in research and industry is to consider post-flashover design fires used for non-combustible structures by including a charred area of exposed timber as additional fuel load. In the absence of any other available guidance, increasingly the approach is based on a range of different Eurocode Parametric fires (i.e. EN 1991-1-2 [4], Barber [5], and Brandon [6]). This approach is iterative in nature and based on several assumptions. For example, the methodologies are not appropriate for timber that may have debonding (seen in some CLT panels) due to fresh timber becoming exposed, multi-level interconnected compartments (e.g. atriums), and compartments over 500 m^2 (which is the limit for the Eurocode 1 parametric fire). Similarly, additional fuel from charred timber may result in the final fuel load exceeding the limitations set out for the tested range of the afore-

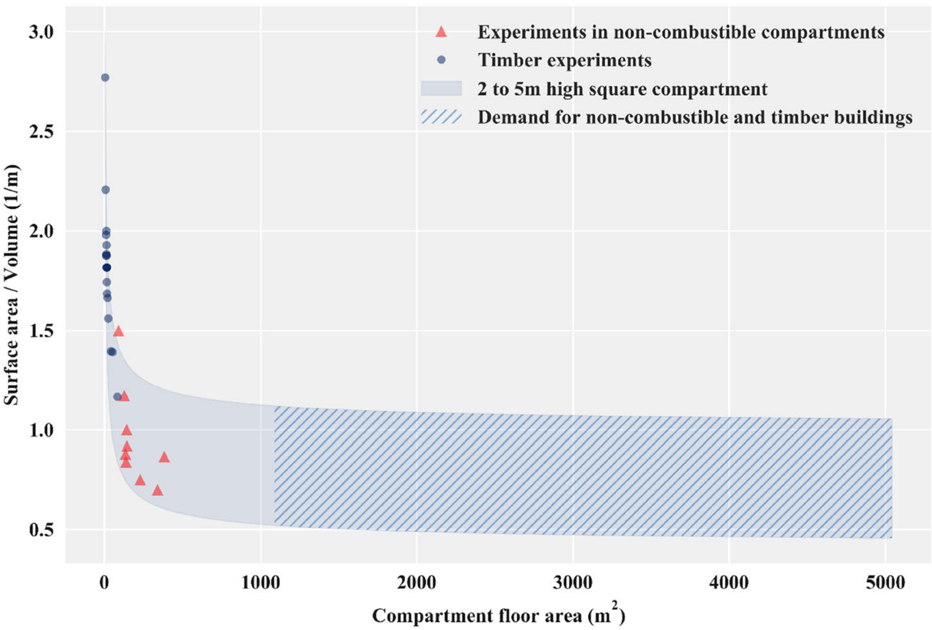

Figure 1. Comparison of typical surface area to volume ratios of timber and non-combustible compartments within which experiments have been carried out to date; and current demand for non-combustible tall buildings and high-rise mass timber buildings being designed and built in UK and USA. Figure adapted from Rein [3].

mentioned design fires. Alternative approaches utilising zone based models have also been proposed for small compartments that need to be explored further [7].

A further improvement is being explored by the authors in this letter by utilising the method of Zehfuss & Hosser [8] currently included as an alternative to the parametric fires, in the German National Annex to BS EN 1991-1-2 [4]. The Zehfuss & Hosser method was developed to address the evidence of limitations with the growth and decay representation when using parametric fires, for some ventilation ranges; the method has recently been found to be more accurate than iterative parametric fires in predicting decay in exposed mass timber compartments as well [9]. However, further research is necessary.

For demonstration purposes, a comparison of the design fires obtained utilising some of the aforementioned methodologies is presented in Fig. 2. The analysis is based on and compared with the experimental data reported by Zelinka et al. [2] for an 84 m^2 compartment with a partially exposed CLT ceiling.

Although, the selected methods predict the peak fire temperatures reasonably for the specific experiment, the iterative parametric fires do not accurately account for the slower decay that occurs in compartments with exposed mass timber.

For the scenario examined, the methodology proposed by Zehfuss & Hosser shows more representative decay behaviour although further validation is neces-

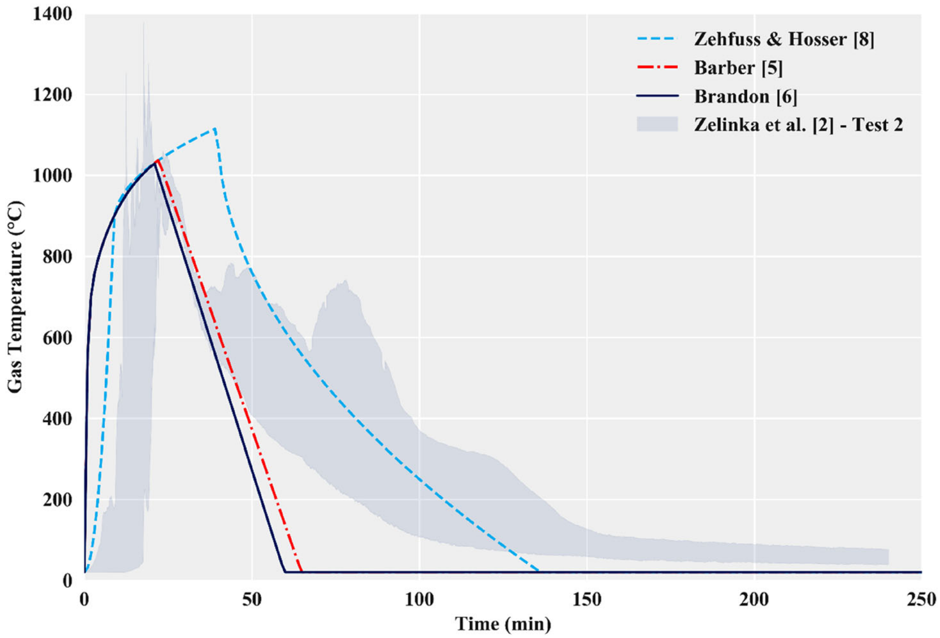

Figure 2. Comparison between fire experiment results in 84 m^2 compartment with partially exposed CLT ceiling (Zelinka et al. [2] —Test 2) and design fire curves which would typically be considered for a similar compartment taking into account the additional fuel load from timber.

sary. It is clear from the graph that the tail end of the decay needs further refinement still, as the Zehfuss & Hossner method currently under-predicts those temperatures. The limitation of design fires to represent decay may not have attracted enough attention for non-combustible structures due to their ability to continue carrying the load. For example, steel starts losing its strength at ~ 400°C and would still maintain ~ 50% of its strength at 550°C. In addition, its material properties are largely recoverable. However, for exposed mass timber structures, the timber, if the material reaches 100°C, would have lost 35% and 75% of its strength in tension and compression respectively [10]. In addition, the material properties of timber are not recoverable. As a result, the fire decay phase needs to be addressed to determine low temperature charring and loss of strength.

Thus, even for small compartments, the fire prediction methodologies currently used for non-combustible structures have not been shown to be valid, when applied to exposed mass timber buildings. The limited methodologies that have been developed for small exposed mass timber compartments need further validation, including beyond the current limit of 84 m^2. The methods are also based on compartments with a limited amount of ventilation (ventilation controlled fires) and, therefore further research is required on their accuracy when applied to large open plan and/or well-ventilated compartments where fuel controlled fires may be more likely.

3. Open-Plan Timber Compartments and Travelling Fires

In structural fire design, an approach taken for non-combustible high-rise structures with large open-plan floor areas would be to consider a range of uniform and non-uniform design fires such as a standard fire used in furnace testing, Eurocode parametric fire, and travelling fires [11, 12]. These provide a robust range within which to test analytically, the proposed structural design.

In large open-plan compartments, travelling fires have been observed, i.e. fires burning over a localised area and spreading along the compartment. Over the past decade, various design fire methodologies have been formulated to account for and represent travelling fires for open-plan compartments, and these are now accepted as relevant methodologies in design [13–17]. These methodologies are not predictive in nature but are used as a design tool by structural fire engineers to consider a more holistic range of potential fire scenarios. However, none of the currently proposed travelling fire methodologies have been developed with the purpose to consider compartments with an exposed mass timber structure.

A common finding of the research programmes conducted to date [1] which focus on compartments with exposed mass timber, is the effect of increased area of exposed timber on both the amount of available fuel, and raising the heat release rate of the compartment fire overall. As a result, the presence of timber impacts both the growth and decay phases of a fire. Fire test evidence has shown that for some types of CLT where the CLT is susceptible to debonding (i.e. char that has formed falls off, and fresh timber becomes exposed as new fuel to the fire), the fire either regrows, or continues to burn at a quasi-steady heat release rate, and the onset of fire decay is delayed (i.e. increased burning time).

Similarly to the parametric fires, none of the above-mentioned effects of an exposed mass timber structure on the fire dynamics can be accounted for using the current travelling fire methodologies. For the travelling fire methodologies to be applied to an exposed timber compartment, they need to be significantly adapted to incorporate these fundamental behaviours, and this requires further fundamental research and experimental data. This is data of fires in large compartments with exposed mass timber. As a result, the authors' opinion is that the current travelling fire methodologies cannot be used for compartments with large areas of exposed timber structure and particularly not as a basis for design in practice at this time.

4. Research Needs

Further research is necessary to expand current travelling fire methodologies to account for exposed mass timber. Travelling fire methodologies split fire exposure into two fields: the near-field and the far-field. Near-field represents flames directly

Table 1
Review of Key Parameters, Which Represent The General Concepts and Principles of Most Published Travelling Fire Methodologies, In Relation to Mass Timber Structures

Parameter	Implications and further research
Fire size	A travelling fire size is defined by the distance between the leading (i.e. fire front) and trailing edges (burnt out edge) along the fuel bed (see Fig. 3). Even for non-combustible compartments, currently available experimental evidence is limited and insufficient to enable detailed predictions about the expected fire spread and burn-out rates; and thus, the likely fire size for a specific compartment. In addition, although current travelling fire methodologies assume a constant spread rate for design purposes, in real fires it has been observed to not be constant. In the design of non-combustible structures these uncertainties are currently addressed by considering a range of design fires with different spread rates to capture the effect of different heating regimes. Any methodology for structures with an exposed mass timber ceiling would have to take into account the potential for fire spread across the ceiling. Thus, it would need to consider the likely spread rates of the leading and trailing edges of the flames at the ceiling which could be different to those across fuel at floor level. There is also the distinct possibility of ignition of timber ahead of the flame front on the fuel bed available in the floor. Figure 3 provides a visual representation of the phenomena expected when an exposed mass timber ceiling is introduced. Future research should also consider the impact of changes in ventilation during the fire and the effect of wind on the direction and rate of fire spread.
Fuel load density	Fuel load density is a design variable and depends on the expected end use for the space of interest. However, for structures with an exposed timber ceiling, additional fuel is in reality introduced from the pyrolysis of the timber at either the near-field or far-field. This is likely to significantly affect the fire dynamics and the additional fuel from the combustible structure should be considered explicitly and separately from the fuel load density related to compartment occupancy.
Heat release rate (HRR) per unit area	For non-combustible structures, HRR is a design variable and depends on the occupancy assumed for the space of interest. For structures with an exposed timber ceiling, HRR is likely to be affected too due to the pyrolysis of the exposed timber. Whilst some experiments exist for small enclosures, further research is needed for open-plan compartments to estimate appropriate HRR for this arrangement in design.
Near-field region	In different methodologies, the near-field is represented by either likely maximum temperatures reported in experiments (e.g. 1200°C [14, 15]), or based on heat fluxes from localised fires with [17] or without [16] consideration of flame extensions under the ceiling. For an exposed mass timber ceiling it is likely that a heat flux definition is more appropriate rather than a temperature definition as is conventionally assumed for non-combustible structures [20]. Further research needs to consider the impact of an exposed timber ceiling in comparison to a standard concrete ceiling in open plan compartments, with respect to maximum likely flame temperatures, heat fluxes and flame extension under the ceiling, and their dependency on different possible fire sizes.

Table 1
continued

Parameter	Implications and further research
Far-field region	For non-combustible structures, the Alpert's correlation is used as a simple tool to describe smoke temperatures ahead of the flames and behind the flames (i.e. burn out areas) in some travelling fire methodologies [14, 15, 17]. Other methodologies use zone models [17] or localised fire models in combination with Alpert's correlation [16]. For an exposed mass timber ceiling to be considered, additional parameters need to be added to the methodology which would enable consideration of decay phase and smouldering of timber post-fire. A simple approximation for smouldering should be developed for design purposes taking into account oxygen concentration after the fire has burnt out to determine scenarios where smouldering may be critical and whether alternative approaches to emergency response are necessary. This is because smouldering could potentially result in comparable charring rates to flaming.

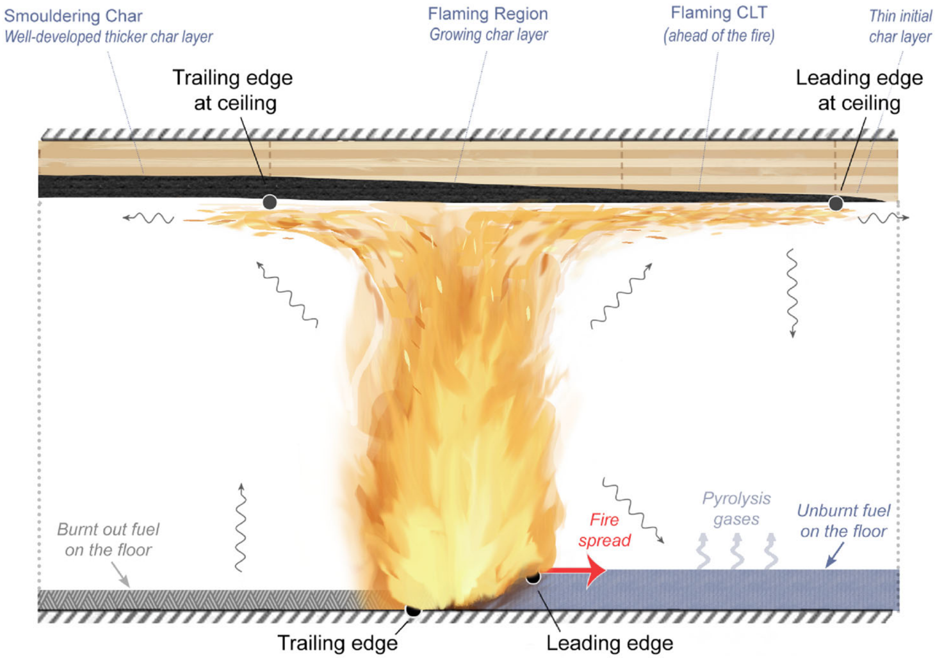

Figure 3. Visual representation of the travelling fire dynamics phenomena expected when an exposed mass timber ceiling is introduced to a large scale open-plan compartment. Arrows indicate radiation from fire and heated surfaces preheating fuel and timber ahead of the flames, and continuing heating of charred timber behind the flames in addition to the heating from smoke (not indicated in this figure for clarity).

impinging on the ceiling whilst the far-field represents cooler smoke temperatures further away from the flames.

The authors have reviewed each key parameter, which represent the general concepts and principles of most published travelling fire methodologies (TFM) [15–17] developed on the basis of TFM [14], to determine its relevance and suitability for compartments with an exposed mass timber ceiling (see Table 1).

This forms one basis to create a research roadmap to fill current analysis capabilities, and so fill the current knowledge gap. The outcomes from this review acts as a proof of concept methodology to investigate the additional experimental and numerical research now needed to make the travelling fires methodology fit for purpose when relying on it in design safety assurance.

The discussion above also assumes that the CLT does not suffer from excessive debonding [18]. As per recent changes in manufacturing standards in the USA [19], CLT that does not have char debonding behaviour, even under prolonged fire exposure, displays predictable charring, and similar to that of solid timber.

Currently, Arup has partnered with Imperial College London sponsoring two PhD students with the intention to fill some of these gaps in knowledge, and improve best practice in industry to progress efforts in achieving this important goal for a decarbonised economy. We offer this as an alternative perspective to the current methods at this time.

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