Fire Safety and Performance of Engineered Timber in Modular Construction: Addressing Knowledge and Research Gaps

Transforming
Timber

CONTENTS

OVERVIEW

Designers and architects wanting to take advantage of the innovations possible through modular timber construction must also be aware of, and take account of, the corresponding safety and regulatory limitations when constructing with engineered timber products.

In any building, safety is obviously a paramount priority, and fire safety concerns are natural especially given the aftermath of major urban fires. Yet innovative design approaches that can have ecological and economic benefits should not be unnecessarily constrained by regulations that may not be current or appropriate to the new materials or methods of construction. Indeed, the use of all novel construction materials, such as modern engineered timber products, introduces “innovation risk,”[1] in which these novel materials may satisfy existing regulations despite introducing new, unacknowledged or unknown hazards, which also may not be reflected within existing testing methods or regulatory framework. Failure to identify innovation risks at an early stage can, in the event of subsequent building failures, result in complete bans or other widespread restrictions either due to a focus on life safety or property protection; or, equally problematically, may produce a ‘compliant’ solution whilst neglecting the underlying fire dynamics and controlling physics; this may allow novel hazards to be embedded within the final design solutions, and generate latent safety risks within the built environment.

When employing engineered timber products in building design, it is important to remember that the current building regulations system assumes that the building’s structure will not contribute to the severity of a fire.

---

[1] V. M. Brannigan, ‘The Regulation of Technological Innovation: The Special Problem of Fire Safety Standards’, Proc. Fire Saf. Eng. Appl. to Fire Build. Saf. Single Eur. Mark. Novemb. 12, pp. 20–33, 2008.

Thus, the combustible nature of structural and exposed timber elements presents challenges to the existing regulations and guidance, as well as to our current design philosophies and notions of fire behaviour of structures. Additionally, the research gap regarding the effect of exposed and structural components on the fire dynamics of engineered timber products can result in significant limitations on the ability to confidently incorporate timber elements safely and conservatively in design.

Fortunately, many of these challenges are widely-acknowledged in an active and developing research field, with relevant theoretical and experimental studies underway to redress the knowledge deficit. These efforts are based on more than a century of research into the burning behaviour of wood which can inform future detailed testing of novel engineered timber products. Similarly, existing fire safety engineering principles can be used to inform a future approach in which the unique challenges posed by combustible timber elements are explicitly acknowledged and addressed. By highlighting current limitations in fire science and engineering, research can be targeted toward providing the physics-based insights required to allow the development of credible design methodologies which will underpin the future of engineered timber construction.

This summary of three reports highlights knowledge gaps alongside their implications for timber modular construction, focusing on the challenges and issues within the existing regulatory framework, and shows how those gaps informed fire data analysis and large-scale fire performance testing on engineered timber products within the broader Transforming Timber project.

FIRE SAFETY OF BUILDINGS: WHAT IS KNOWN AND UNKNOWN

Fire behaviour and flammability parameters of natural timber have been researched for decades. For instance, fire phenomena in buildings (i.e. the way fires develop, spread, and consume building materials) is well understood.

These phenomena inform the way that buildings are designed to ensure both firefighter safety and adequate provision for the safe evacuation of occupants. Indeed, the boundaries and structural elements of buildings are, depending on their size, height, and occupancy, intended to prevent fire spread and promote fire extinction, such as through compartmentalization. However, the burning behaviour and fire performance of engineered timber is different to natural timber. This has contributed to a knowledge gap and a corresponding lack of consensus about fire performance of buildings constructed from engineered timber products, especially where timber structural elements and/or exposed timber elements are included within a building's overall structural design.

For instance, while the combustion behaviour and structural performance of wood has been studied extensively over many decades, research gaps remain surrounding the ignition, charring, and structural response of many engineered timber products. This results in a lack of the kind of detailed thermal and structural models for timber which may ultimately inform simplified engineering design methods. Further understanding of the influence of a range of physical and geometric properties on the ignition and combustion processes is also required. A study of ignition properties would also provide greater insight into flame spread on timber elements and fire growth in timber-lined compartments, as well as into the relative impacts of smouldering and flaming combustion on the performance of engineered timber, both of which have implications for structural performance in fire.

FIRE BEHAVIOUR CHALLENGES FOR TIMBER PRODUCTS

Careful consideration of the response of timber to fire exposure and heating is required in order to understand the implications for ignition, fire growth, fire spread and structural performance. This must include consideration of the additional fundamental hazards introduced into buildings by the use of engineered mass timber which have previously been summarised as [2]:

- Timber will burn.
- Additional energy release from burning timber will affect the fire dynamics.
- Additional energy release from burning timber will affect the fire growth and fire spread from the area/compartment of origin.
- Burning of timber may continue, until no structure remains.

When engineered timber products are used in modular construction, the use of combustible compartment boundaries and structural elements may delay or prevent fire extinction after combustion of the building contents, and may also invalidate existing methods for assessing structural performance during fire exposure, which rely on the concept of ‘fire resistance’. A performance specification rooted in a fire resistance framework is typically based on an assessment of the fire’s severity up to the point at which total burnout of the fuel load occurs; this may not apply to cases in which the structural elements are themselves combustible. Similarly, there are considerations regarding the residual – post-fire – structural performance of combustible elements. Unless extinction of the combustible elements also occurs, then this could lead to complete consumption and/or structural failure as the strength/volume of the remaining elements decreases.

---

[2] A. Law and R. Hadden, ‘We need to talk about timber: Fire safety design in tall buildings’, Struct. Eng., vol. 98, no. 3, pp. 10–15, 2020.

A char layer forms on burning engineered timber products, which on the one hand might promote auto-extinction of the fire. On the other hand, delamination or char fall-off can occur, in which fresh layers of timber beneath the char layer progressively become exposed, thereby promoting continued burning. In addition, char fall-off is complex and remains difficult to characterise and predict, and the rate at which char oxidation occurs and at which the char layer develops is also only partly understood.

The performance of different adhesives is also critical for understanding the potential for delamination and char fall-off, given that two failure modes are present (either within the adhesive or within the adhesive-timber interphase) at elevated temperatures.

RESEARCH GAPS FOR BUILDING APPLICATIONS

Research gaps also exist related to the fire performance of timber components in specific building applications. These are outlined in the full report *Fire Safety Considerations for Modular Timber Construction: A Review and Gap Analysis.* Broadly, they fall under these areas:

- Compartment fire dynamics, including compartment fire phases and the effect of combustible compartment boundaries;
- Encapsulation, the strategy used to remove much of the uncertainty surrounding exposed timber elements by using non-combustible encapsulation systema which themselves must be tested for fire protection and performance;
- Auto-Extinction, and particularly the potential for auto-extinction of structural engineered timber compartment boundaries and load-bearing elements;
- Structural performance of timber elements at all phases of a fire including throughout the decay and cooling phase;
- Timber composites which use engineered wood products alongside glass, steel, and concrete and therefore interact and perform in ways that have an effect on reaction-to-fire and fire resistance; and
- Connections such as mechanical fasteners that can affect performance and therefore requires further consideration.

IMPLICATIONS FOR BUILDING REGULATIONS

Dame Judith Hackitt's 2018 independent review of building regulations and fire safety calls for a shift in mindset from simply following prescriptive guidance to taking ownership and responsibility for the life cycle of a building. She suggests this shift could be prompted by adopting a new regulatory system driven by an outcomes-based approach, rather than the current box-ticking exercises. Regardless of what happens within the evolution of UK fire safety regulation, fire safety concerns will continue to exert an influence on the regulatory environment, especially as the demand for timber-based construction continues and extends to taller buildings, modular, and offsite construction. While standard approaches to fire safety may satisfy existing building regulations, it is important to consider the potentially very different contexts in which the pre-existing regulatory approaches were developed.

The building regulatory regimes of Scotland and England provide technical guidance in the form of a framework originally built upon concepts of fire resistance durations and design for burnout, which may not necessarily be appropriate for combustible elements and complex timber buildings. The full report, *Fire Safety Considerations for Modular Timber Construction: A Review and Gap Analysis*, contains a detailed summary of Scottish technical handbook specifications on domestic and non-domestic buildings, resistance to fire, reaction to fire, vulnerability of roof coverings and functional requirements, as well as a summary of key points in the English system including the Approved Documents that provide practical guidance for compliance with the Building Regulations 2010 for England.

Given that compliance with these suggested approaches does not absolve the designer of responsibility (or liability), and given the growing evidence highlighting limitations of existing approaches for complex timber buildings, it is hoped that a growing number of designers and manufacturers will instead consider the fundamental effects of the inclusion of combustible timber elements on their designs. With any new technology it is of course necessary to carefully examine which of the existing paradigms of design are suitable, and which are not. By undertaking this due diligence exercise, designers can get the best value from existing techniques, whilst hopefully avoiding the pitfalls of applying inappropriate methods and guidance to new technologies.

CONTEXT FOR TESTING TO ADDRESS GAPS IN KNOWLEDGE

Where assessments of the structural fire resistance of engineered timber panels exists, these have often involved standard fire curve furnace tests without the consideration of system configurations and adhesive types[3], the influence of environmental conditions[4], or the thermal and mechancial performance during decay and cooling phases. Additionally, testing and material classification has typically been performed at small scales which may not adequately represent the complex behaviour within real fire scenarios, or reflect the performance of the final system[5].

Although often studied at intermediate scale[6], limited large-scale testing has previously been conducted with a particular focus on the extent and arrangement of exposed timber surfaces. There is also a need for further large-scale testing in which the fire behaviour of a system (e.g. compartment or building) and connections is investigated, rather than individual elements or samples. Further research is required across a variety of timber layouts to further characterise the effect on compartment fire dynamics, including the effects on re-radiation between surfaces, overall energy release rate, and external flaming[7].

---

[3] F. Wiesner, ‘Structural behaviour of cross-laminated timber elements in fires’, 2019.
[4] D. Morrisset, R. M. Hadden, A. I. Bartlett, A. Law, and R. Emberley, ‘Time dependent contribution of char oxidation and flame heat feedback on the mass loss rate of timber’, Fire Saf. J., vol. 120, p. 103058, 2021.
[5] A. Law, A. Bartlett, R. Hadden, and N. Butterworth, ‘The Challenges and Opportunities for Fire Safety in Tall Timber Construction’, in 2nd International Tall Building Fire Safety Conference, 2014.
[6] C. Gorska, J. P. Hidalgo, and J. L. Torero, ‘Fire dynamics in mass timber compartments’, Fire Saf. J., vol. 120, no. April 2020, p. 103098, 2021. [85] A. I. Bartlett, R. McNamee, F. Robert, and L. A. Bisby, ‘Comparative energy analysis from fire resistance tests on combustible versus noncombustible slabs’, Fire Mater., vol. 44, no. 3, pp. 301–310, 2020.
[7] Arup, ‘Rethinking Timber Buildings’, London, UK, 2019.

To address these research gaps, a research programme was devised where four medium-sale fire experiments were performed on 1 m3 mass timber boxes. Results from these experiments then informed experimental configurations to be used – and experimental parameters to be varied – in further full-scale fire experiments. These are described below.

a. Fire Data Analysis to Inform Full-Scale Experiments

First, the experiments on the 1m3 mass timber boxes were conducted to develop an understanding of the response of mass-timber lined compartments in the event of a fire, to quantify the differences in fire dynamics and prognosis for ongoing burning after consumption of the movable fuel load within the compartments. These four compartments were produced with varied configurations and types of CLT surfaces. One fully non-combustible compartment with no exposed timber was tested to provide a baseline for comparison with the other scenarios, which were four compartments with three different engineered timber products: CLT, Glulam, and NLT panels in different configurations and thicknesses. Exact specifications of the tested compartments can be found in the full report, including the generic compartment configuration, compartment opening, and variation of exposed CLT configuration.

In each compartment, six kg of PP pellets were ignited using an accelerant. Several video cameras recorded every experiment in order to allow for visual analysis of fire dynamics and external flaming. Additional instrumentation allowed for quantitative analysis of total heat release rate, mass loss, gas phase temperatures, solid phase temperatures, and flow measurements through the compartment openings.

Time to flashover and peak heat release rate for each compartment are detailed in the full report, Fire Data Analysis Report to Inform Full- Scale Experiments. Three of the four compartments experienced auto- extinction, whereas reignition occurred for the one compartment with two exposed timber side walls and ceiling. Graphs in the report show total heat release rate, mass loss rates, and average compartment temperatures.

The data collected during these medium-scale experiments led to the conclusion that the most effective compartment configuration to use in studying possible differences in burning behaviour of the three respective mass timber products being developed within the Transforming Timber project is the configuration with the back wall and ceiling exposed.

b. Large Scale Fire Data Analysis

Once the experimental parameters and timber box configurations were determined through the medium-scale experiment, three large-scale outdoor fire experiments were performed. These experiments were undertaken on 13.8m3 mass timber boxes to investigate the compartment fire dynamics within a mass timber compartments and to explore the responses of exposed timber elements. These experiments also sought to evaluate the performance of three different engineered timber products when used as exposed ceiling elements.

In each compartment the exposed timber ceiling was formed from either a Cross-Laminated Timber (CLT), Nail-Laminated Timber (NLT) or Glue-Laminated Timber (Glulam) slab, always paired with an exposed CLT back wall. In all three compartments, the other compartment linings (excluding ceiling and back wall) involved no exposed timber and were composed of layers of plasterboard with a sandwich layer of stone wool.

Specific details of the compartment configurations and their openings, as well as the materials and their dimensions and thermal properties can be found in the full report, Fire Data Analysis Report for Large-Scale Experiments. Fuel load and instrumentation choices were based on those used in the laboratory-based study, albeit adjusted for the increased size of these compartments. Compartment mass loss, fuel consumption rate, gas phase temperatures, solid phase temperatures, and flow velocity were measured, with an additional analysis of sample gases conducted.

Full details of the instrumentation can be found in the full report, along with details on compartment mass loss rates, movable fuel mass loss rates, compartment thermocouple temperatures, and selected solid phase temperatures for each compartment.

c. Experiment Results

The initial stages of all three large-scale fires was reasonably consistent; however, the onset and duration of external flaming varied across the three compartments. For the NLT compartment, an additional period of flaming combustion was observed along with the fall-off of substantial sections of the NLT ceiling. This was accompanied by the presence of a secondary temperature spike in the gas phase compartment temperatures in the NLT ceiling compartment. For the CLT compartment flashover occurred significantly earlier (5 minutes).

Variations in behaviour following the cessation of external flaming were also observed particularly concerning the smouldering/char oxidation of the exposed timber surfaces after burnout of the movable fuel load. Due to little sustained smouldering/char oxidation in the Glulam ceiling, there was limited further consumption of its timber. This had important consequences for the subsequent structural performance and auto-extinction of the compartments.

All three compartments – which were allowed to burn without any intervention or firefighting – eventually collapsed completely; this was attributed to smouldering which was localised in the CLT and Glulam compartments, but extensive in the NLT compartment. The collapse mechanisms appeared to vary due to these observed variations in fire behaviour and product performance. In the Glulam compartment, the ceiling was still largely intact while the CLT back wall was consumed, so the structure collapsed under the weight of the ceiling. In the NLT ceiling compartment, fall-off of large sections of ceiling was observed coinciding with an additional extensive flaming period.

CONCLUSION

This summary, and the three reports it is based on, seeks to highlight many challenges and associated research gaps relevant to areas in which current regulatory approaches may require reconsideration to account for the additional, novel hazards presented by structural engineered timber products. In short, by acknowledging the inherent limitations of a fire resistance framework based upon ‘survival until burnout’ for combustible timber elements, existing and ongoing research efforts can be harnessed to define a credible design philosophy which – from its conception – explicitly considers the inclusion of combustible mass timber elements.

Many unique challenges remain for the use of modern engineered timber products and combustible compartment boundaries, and the wholesale extension of existing correlations and design methods from earlier research is difficult to defend. However, insights can be gained, and significant encouragement should be taken from the fact that there already exists a framework via which well-considered design approaches can be developed. This can support the detailed research required to meet pressing fire safety and construction challenges presented by modern timber buildings. Given the wide range of stakeholders keen to advance the use of timber construction elements, these challenges need not remain insurmountable if attention is directed towards supporting and performing this required research.

Transforming
Timber

Supported by:

UK RI
Innovate
UK

Project partners::

Built
Environment
—
Smarter
Transformation

ECOSYSTEMS
TECHNOLOGIES

Edinburgh Napier
UNIVERSITY

SNRG
EMPOWERED BY CENTRICA

THE UNIVERSITY of EDINBURGH
School of Engineering

BSW Timber Group