

Novel Technologies for Tall Timber Buildings: Research Streams and Three Solutions

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1. Introduction

Due to the continued densification of modern cities, tall buildings between 10 and 30 stories comprises a rapid growing sector of the construction industry in Australia and worldwide. Timber is ideally placed to be the preferred material for buildings of these heights. Nevertheless, concrete and steel are the dominant materials for structural, load bearing systems. As a structural material, timber has a long history yet its applications in structural systems of tall buildings remain largely unexposed, specifically in Australia. Perceived technical limitations and regulatory constraints have and continue to restrict the application of timber beyond low-rise constructions [1]. However, significant technological developments, advanced manufacturing processes [2], and growing sustainability drivers are shifting the balance in favour of timber [3,4].

With the objective of transforming future tall timber buildings in the Pacific region, academics, government and industry have come together to form a research consortium called the "Future Timber Hub" [5]. The Future Timber Hub aims to deliver the knowledge necessary to overcome the constraints that limit the development of tall timber buildings in Australia. The aim of the Hub is to transform the timber construction industry in Australia by generating the skills, knowledge and resources that will serve to overcome current technological and social barriers limiting the application of timber to tall structures.

The Future Timber Hub was founded as an interdisciplinary partnership between: The University of Queensland, the Queensland State Government Department of Agriculture and Fisheries, Arup, Hyne Timber, Lendlease, the Queensland Fire and Emergency Services (QFES), Scion NZ, Griffith University, the University of British Columbia and the University of Canterbury.

The Future Timber Hub covers novel methodologies (and practices) for the manufacturing, design and construction of tall timber buildings. Practices that incorporate in a comprehensive manner, architectural, engineering and sustainability drivers while meeting the intent of regulatory constraints. In order to develop successful methodologies, The Future Timber Hub brings together an interdisciplinary team that includes product manufacturers, construction managers, fire safety engineers, architects, and structural engineers.

Current projects of the Future Timber Hub includes:

- (1) Alternative uses for under-valued sawmill products in innovative timber structures: investigations into the design of innovative and alternative structural timber systems and technologies that adopt "low value" timber products such as sawmill offcuts.,
- (2) Prefabrication and digital fabrication strategies for large-scale timber construction: this project will seek to combine Hub partners' expertise in digital fabrication, prefabrication, and manufacturing automation to develop new, beneficial structural components and systems suited for large-scale or modularised timber structures.,
- (3) The optimization of wood-based mass-panels for Australian building systems: this project aims to deliver technical tools, training and demonstration that will support local industry to supply the building sector with a versatile palette of high performance products from which to design and construct innovative timber buildings.,
- (4) Delivery of long-term performance sustainability of massive panel production in tall timber construction: this project will identify the key issues and concerns relating to the impact of continuous drying on key performance and production criteria of engineered wood structural elements for tall timber construction.,

- (5) Non-destructive evaluation of elastic material properties and acoustic characterization of wood based massive panels: this project aims to develop and optimise a protocol to determine the global stiffness properties of full-scale mass timber panels directly in the production line and to access their acoustic performance.,
- (6) Superior sound isolation of cross laminated timber (CLT) using junction detailing: this project explores junction detailing for CLT construction, in order to improve sound transmission performance of built systems and allow designers more freedom to work with exposed CLT surfaces.,
- (7) Pathways to net zero energy for engineered wood multi-storey buildings in Australian Tropical and Sub-Tropical Climates: this research project aims to demonstrate the superior holistic performance, economic advantages, and reduced environmental impact of net zero energy buildings that employ optimized CLT solutions.,
- (8) Progressive collapse resistance of tall timber frame buildings with CLT floors: progressive collapse is characterised by a disproportionate and severe collapse of a structure due to local failure, which is usually caused by accidental or abnormal loadings. This project will investigate the progressive collapse of timber frame buildings with CLT floors.,
- (9) The behaviour of critical connection and core wall systems in tall timber buildings: this project will evaluate the performance of timber core-walls and provide technical information to guide core-wall design in tall timber buildings, with and without the incorporation of low-damage seismic design technology.,
- (10) Exploring the self-extinguishment mechanism of engineered timber in full-scale compartment fires: this project investigates the self-extinguishment mechanism of CLT at full-scale in order to establish design criteria for the fire-safe use of CLT in tall-timber buildings.,
- (11) Long-span floor timber systems and the potential for improved fire performance: this project investigates the fire performance and structural integrity of floor timber systems. The development of a floor timber system incorporating fibre reinforced polymer (FRP) products will be used as integral part of the work herein, aiming at a composite system with structural stability during and after fire., and
- (12) Resilient design of structural timber beam-to-column connections in fire condition: this research will investigate the performance of structural timber connections exposed to fire in order to grow understanding of mass timber structures under fire conditions.

Use of above technologies in tall timber buildings will be demonstrated through a series of exemplar projects. The hub has already delivered its first exemplar through the analysis and peer review of the Lend Lease K-5 building where state of the art knowledge was used to restructure the approval of the tallest fully exposed timber office building. Currently the hub is developing the Maryborough Fire Station where state of the art structural systems developed and analysed by the hub are being introduced in an optimal manner to the design of the fire station.

Preliminary findings of three key projects are presented in this paper. Three projects discussed in detail include (a) pre-fabrication and digital fabrication strategies for large-scale timber construction, (b) Long-span floor timber systems and the potential for improved fire performance, and (c) Exploring the self-extinguishment mechanism of engineered timber in full-scale compartment fires.

2. Project: Prefabrication and digital fabrication strategies for large-scale timber construction

2.1. Introduction

The Future Timber Hub at the University of Queensland is currently developing a suite of digital fabrication, prefabrication and manufacturing automation technologies that are designed to achieve material optimisation in the design of timber frame and truss structures. This paper presents two of these technologies: (a) a parametric translation of the Australian Standard for Timber Structures to optimise timber section sizes; and (b) an inventory based design tool to optimise truss geometry from low grade or discarded short length timber.

2.2. Parametric Translation of the Australian Standard

A first optimisation strategy is being pursued through the Future Timber Hub Project: "Prefabrication and digital fabrication strategies for large-scale timber construction". This project proposes to use integrated digital design and fabrication processes to look for efficiencies in delivery of typical prefabricated mass timber structures, including for example glulam trusses and post and beam frames. The first phase of this project has been completed to develop a Glulam truss digital workflow (Figure 1) that includes scripted modules for geometry generation, structural analysis and member design to both structural and fire loads. The script also includes connection design, 3D model and BIM IFC file generation for building documentation deliverables.

A key benefit of this workflow is it enables a designer to more easily move between the different design ecosystems for standard and proprietary building products. Standard products are specified with typical performance-based methods to Australian Standards, but proprietary products are being implemented in the market far faster than Australian Standards can adapt. Designers typically therefore rely on manufacturer-specified information or European design standards. For either case, the integrated workflow can swap geometric information and design calculations quickly and as needed. Of greater interest however is how these design processes can also be adapted to absorb atypical connection design or member design procedures, as described for example in the next project.

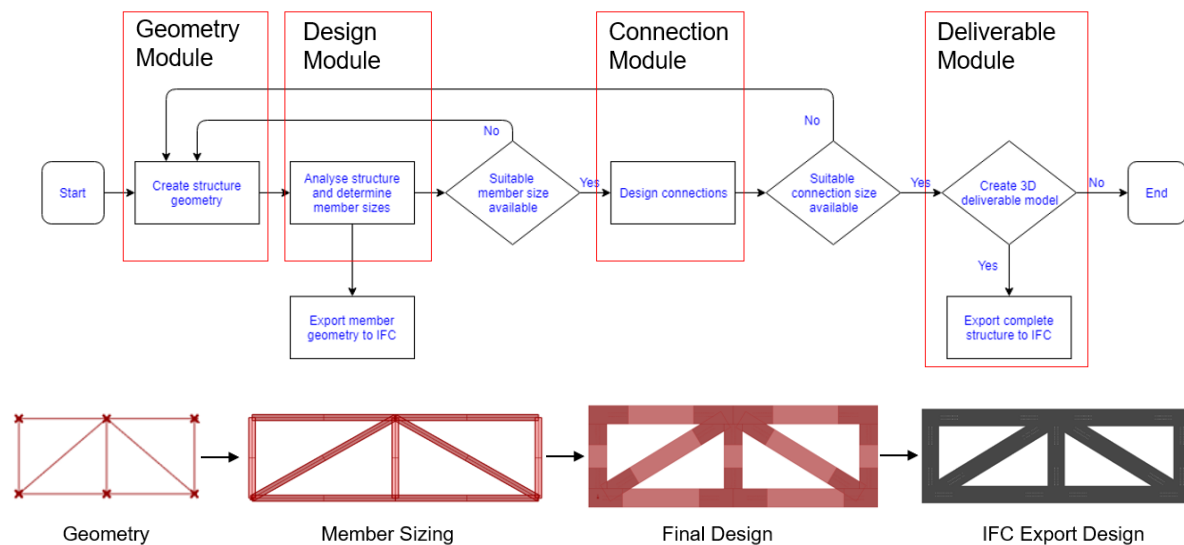


Figure 1: Glulam truss digital workflow

2.3. Inventory Based Truss Optimisation Tool

A second optimisation strategy is being pursued through the Future Timber Hub Project: "Alternative uses for under-valued sawmill products in innovative timber structures". This optimisation tool was developed to increase the yield of structural grade timber from otherwise undervalued or low grade members with frequent 'defects' or 'features'. Medium to long length framing members containing multiple knots, checks and wane are scanned at the saw mill. Scan data for each member in a pack of undervalued framing timber is analysed automatically through a Mat Lab script, generating a digital inventory of usable lengths after defects are cut out (Figure 2). In the digital design software, truss chord and web members are selected through a solver-based optimisation routine selecting 'best fit' permutations from the given inventory (Figure 3). Timber joints are modelled automatically in three dimensions and provide toolpath geometries to be mass-customised via cnc machining.

Via this automated optimisation process, translated into a mass customised fabrication process, the time penalty typically associated with adapting a truss pattern to bespoke web lengths has been significantly reduced, allowing virtually all of the structural grade timber to be recovered from a given member.

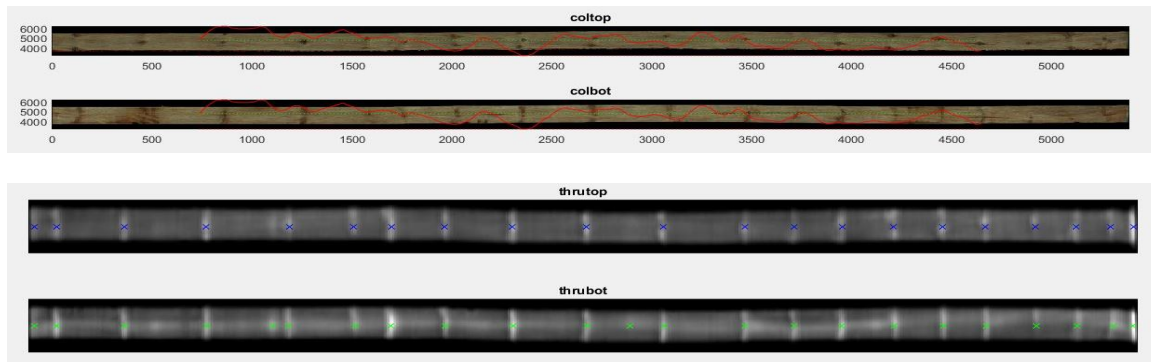


Figure 2: Scan data from Saw Mill identifying 'defects' or 'features'

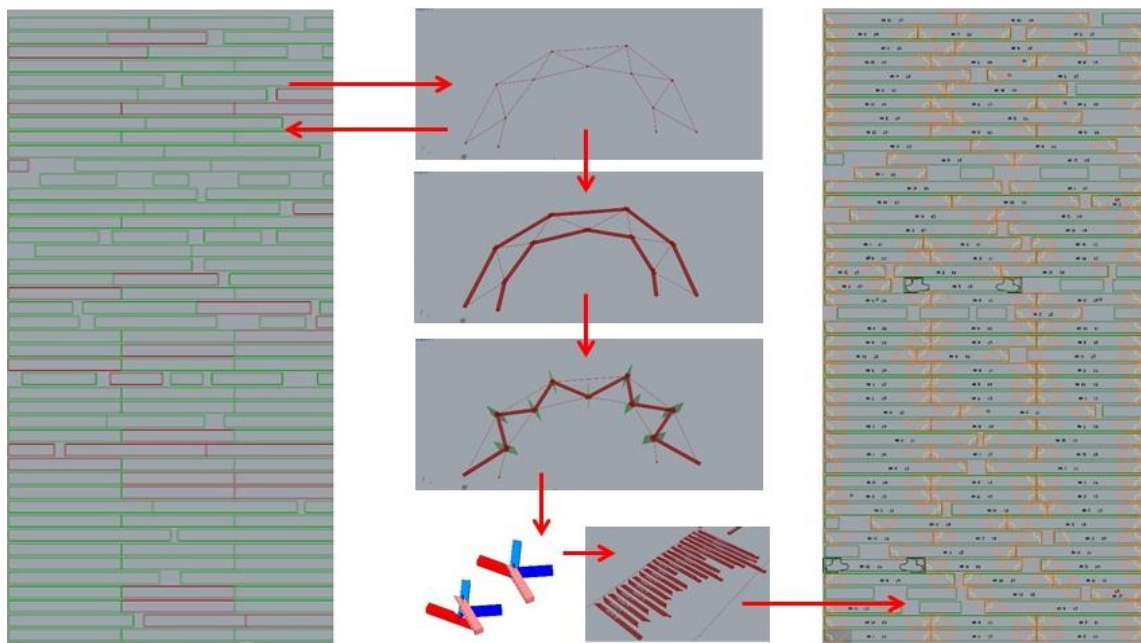


Figure 3: Resultant short length Inventory, applied to truss web geometry to derive optimal permutation, then cnc machined

2.4. Future Directions

As demonstrated in these two projects, the technologies being researched at the hub are investigating opportunities for optimisation at both the sawmill, and through the interpretation of the Structural Design Standard. By demonstrating that short, random length members can be utilized rationally and economically, and that section sizes can be optimised within a greater range of increments, ultimately, this research may justify changing the structural grading system and the accepted industry norm of cutting to standard lengths and section sizes, resulting in a more efficient use of the resource.

3. Project: Long-span floor timber systems and the potential for improved fire performance

3.1. Introduction

Conventional load-bearing floor systems including glued laminated timber (Glulam) that span between shear walls or columns can have restricted span capacities influenced by fire safety considerations (among other considerations, e.g. serviceability). The principles of floor timber systems replicate those of a traditional steel or concrete structures.

In terms of structural fire performance, there are critical gaps on the behaviour of load-bearing floor timber systems during or after fire. Fire-induced failure mechanisms of Glulam beams are induced by reduction of the members' cross section (charring and/or delamination) or weakening of the connecting conditions during fire.

Enhanced fire performance of timber floor systems may be achieved through the introduction of a mechanism that provides improved hybrid action to the load-bearing system. E.g. additional anchoring to improve connection performance during fire, material layers with higher fire performance to compensate strength loss due to charring of timber. The aim of this work is to further generate knowledge in the fire safe design of Glulam beams and demonstrate the enhanced fire performance of a prototype Glulam-FRP hybrid floor system (Figure 4).

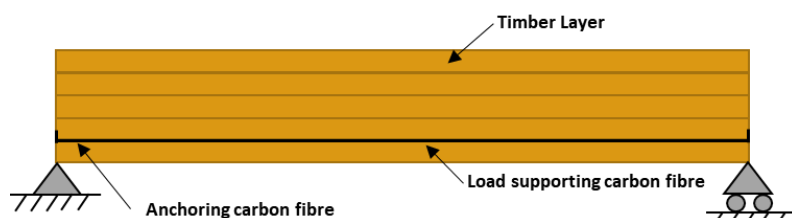


Figure 4: Sketch of a Glulam-FRP hybrid.

When exposed to fire, the surface of the wood undergoes pyrolysis and produces char. The rate of charring has been observed to be consistent for various wood types, therefore can be predicted based upon numerous available experimental studies. Due to the char's negligible structural capacity, the charring of a structural member leads to a loss in effective cross-section. As the structural capacity of a member is strongly dependent upon the cross-section, the charring of a structural member directly results in a loss of structural capacity. Furthermore, the in-depth heating of the timber results in further loss of mechanical capacity and elasticity.

3.2. Experimental Campaign

A numerical model to predict the structural behaviour of the reinforced Glulam beam and non-reinforced Glulam beam at ambient and fire conditions was formulated to investigate the strain-stress profile in the prototype Glulam-FRP hybrid. The primary concept is that upon capacity reduction at the exposure to fire at the bottom surface, the relatively stiffer FRP element can counter for the loss of cross section (Figure 5).

Results from the numerical analysis suggested that upon failure of the bottom lamella, the neutral axis drops and the maximum strain within the system decreases; thus, indicating a significant drop in section capacity. Comparison of the theoretical moment capacity shows that the theoretical fire performance of a Glulam-FRP hybrid is 130% higher than that of a Glulam beam.

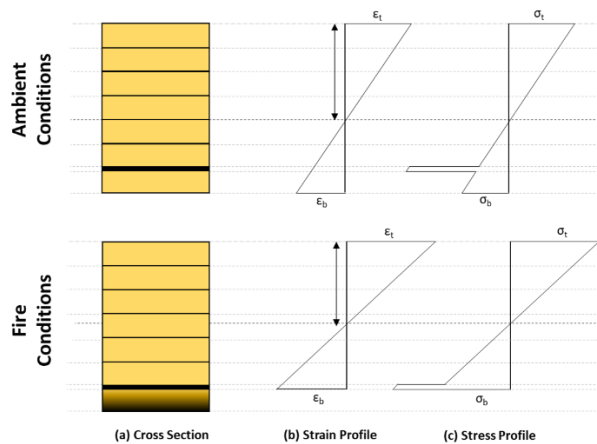


Figure 5: Theoretical strain-stress profile of a Glulam-FRP hybrid at ambient conditions and during fire.

The experimental investigation included testing at ambient temperature and testing of samples under sustained load during a heating regime. Beams with and without FRP were tested for ultimate capacity on a four-point bending configuration. Strain was measured at various key positions to monitor the stress-strain distribution within the tested elements.

Similar to ambient tests, beams with and without FRP were tested for on a four-point bending test; load to a target sustained strain-stress condition. Load was then kept constant during heating. Heating was applied at the bottom, mid-span section of the beams. A mid-span length of 500 mm was heated during testing. All tests were conducted using a custom-built testing rigged. The test setup allows for four-point bending loading to be sustained during heating; hence, replicating stress-temperature scenario during potential fire conditions (Figure 6).



Figure 6: Fire test setup and loading apparatus.

3.3. Results and Discussion

At ambient temperature, comparison of the Glulam and Glulam-FRP hybrid shows no difference in the deflection at which compressive yielding occurs; however, fire tests show a significant increased time-to-failure (heating time at which compressive yielding occurs).

The outcomes of the fire tests indicated that when exposed to fire conditions, the Glulam-FRP hybrid maintained 80% ambient capacity before charring of the second lamella from the bottom. In comparison, the unreinforced Glulam beams fail during charring of the first lamella from the bottom, when load was sustained at 80% of the capacity at ambient temperature.

4. Project: Exploring the self-extinguishment mechanism of engineered timber in full-scale compartment fires

4.1. Introduction

In the last decade, raising mass timber buildings has become a challenging aspiration from the building industry, essentially due to the potential benefits of using timber, a sustainable and durable structural material. Prescriptive code solutions implemented by regulations, however, restrict the use of mass timber structures such as CLT in mid- and high-rise buildings due to the latent fire risks. This is, for instance, the case of the National Construction Code in Australia [6], which prescriptively allows mass timber structures in buildings of up to 25 metres in effective height if the timber is fire-protected. These constraints are fundamentally related to unquantifiable fire safety risks included by the extended use of a combustible structural material such as timber. The use of exposed mass timber structures in buildings is thus among one of the major challenges faced by the building industry at present.

Especially in mid- and high-rise buildings, fire safety of building occupants relies on the engineering principles of compartmentation and maintaining structural integrity until burn-out [7,8]. Compartmentation allows controlling the horizontal and vertical spread of the fire within the building, so that egress of building occupants and fire service intervention can occur safely. Burn-out, which relates to the consumption of all the compartment floor fuel load, is crucial for the design of all structural components. Due to the combustible nature of timber, the use of mass timber may result in the structural timber participating actively in the fire and thus prevent the attainment of burnout. Consequently, fully challenging the fire safety strategy of the building. Fundamental knowledge of the fire dynamics of timber and tools for the adequate fire-safe design and use of timber buildings are then urgently needed.

4.2. self-extinguishment mechanism of engineered timber

Previous research has demonstrated that the charring nature of timber may allow the cease of flaming combustion of timber, generally denoted as self-extinction [9]. Generally, it can be considered that flaming of a combustible material can cease when reaching a critical mass loss rate (burning rate) [10]. Recent research efforts using bench-scale flammability testing have focused on the quantification of this phenomenon so that engineers can analyse the extent of exposed timber structures within building enclosures that would enable self-extinction. For instance, Emberley et al. [11] observed that for Radiata Pine CLT the critical mass loss rate of extinction is $3.65 \text{ gm}^{-2}\text{s}^{-1}$, whereas Bartlett et al. [12] assessed a critical mass loss rate of $3.48 \text{ gm}^{-2}\text{s}^{-1}$. The critical mass loss rate can conservatively be linked to a critical rate of energy flux at the surface of the timber received from external sources. Bartlett et al. and Emberley et al. report values of 31 and 44 kWm^{-2} , respectively.

The assessment of self-extinction beyond the sample scale has also been carried out using medium- and full-scale compartments by several authors. Recent work by Gorska et al. [13] using compartments with internal dimensions 0.48 m x 0.48 m x 0.37 m indicates that the area of exposed CLT and its configuration plays a major role in the compartment fire dynamics and the achievement of self-extinction. Emberley et al. [14] developed a full-scale demonstration of a compartment with internal dimensions 3.5 m (width) x 3.5 m (deep) x 2.7 m (tall). The outcomes from this test showed that CLT self-extinction can be achieved for a limited floor fuel load and if the ceiling and the lateral wall are exposed. Further full-scale experiments by Hadden et al. [15] and Bartlett et al. [16] showed that extinction was achieved once the exposed CLT surfaces reached a critical mass loss rate, consistent with the outcomes at a bench-scale. However, as emphasised by [15] for several of the other compartments tested, the heat transfer from a large area of exposed timber dominated and prevented the self-extinction. Fall-off of charred lamella due to the failure of the adhesive and encapsulation failure due to dehydration of the plasterboard

can prevent self-extinction. Therefore, design aiming at self-extinction of mass timber construction requires a comprehensive analysis of the plasterboard and char fall-off failures along the determination of critical exposure of timber.

4.3. Current project

Research led by the Future Timber Hub aims at further developing a design framework to enable the use of exposed mass timber structures such as CLT. The ongoing research focuses on a methodology based on the identification of characteristic failure times represented by the char fall-off and encapsulation failure, which must be strictly lower than the duration of the fire (burnout of floor fuel load). In order to facilitate the development of the design methodology, a series of medium-scale and full-scale CLT compartment fires, replicas from Gorska et al. and Emberley et al., are being developed. The objective of the medium-scale compartment fires is to assess the fire regimes observed when increasing exposed timber surfaces are used. Additionally, these experiments aim at identifying the heat feedback on compartment boundaries for a variety of design fire scenarios and the associated burnout times for variable fuel loads and materials (cellulosic or plastic). The outcomes from this work are providing an understanding of the role that the design fire plays on self-extinction, and potentially suitable design fires for studying self-extinction. Based on the outcomes of this work, the full-scale tests are designed to allow a parametrisation of the fire duration so that char fall-off and encapsulation failure can be analysed independently reducing the uncertainty of the design fire. Full-scale experiments will then investigate the conditions that induce these failures and the critical surface area of exposed CLT for self-extinction if those failures can be prevented.

5. Summary

The Future Timber Hub aims to drive the future development of tall timber buildings in the Australian built environment. The aim of the Hub is to transform the timber construction industry in Australia by generating the skills, knowledge and resources that will overcome current technological and social barriers limiting the application of timber to tall structures. The Future Timber Hub as an interdisciplinary partnership between: The University of Queensland, the Queensland State Government Department of Agriculture and Fisheries, Arup, Hyne Timber, Lendlease, the Queensland Fire and Emergency Services (QFES), Scion NZ, Griffith University, the University of British Columbia and the University of Canterbury.

Current activities of the Future Timber Hub involves 12 projects looking at developing methodologies (and practices) under the key themes (1) manufacturing and digital design, (2) material anisotropy, heterogeneity and variability, (3) acoustics, (4) sustainability and durability, (5) structural performance, and (6) fire safety. The use of methodologies developed under each key theme will on tall-timber buildings will be demonstrated through a series of exemplar projects.

This paper summarizes current progress and findings of three key projects, (a) pre-fabrication and digital fabrication strategies for large-scale timber construction, (b) Long-span floor timber systems and the potential for improved fire performance, and (c) Exploring the self-extinguishment mechanism of engineered timber in full-scale compartment fires.

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