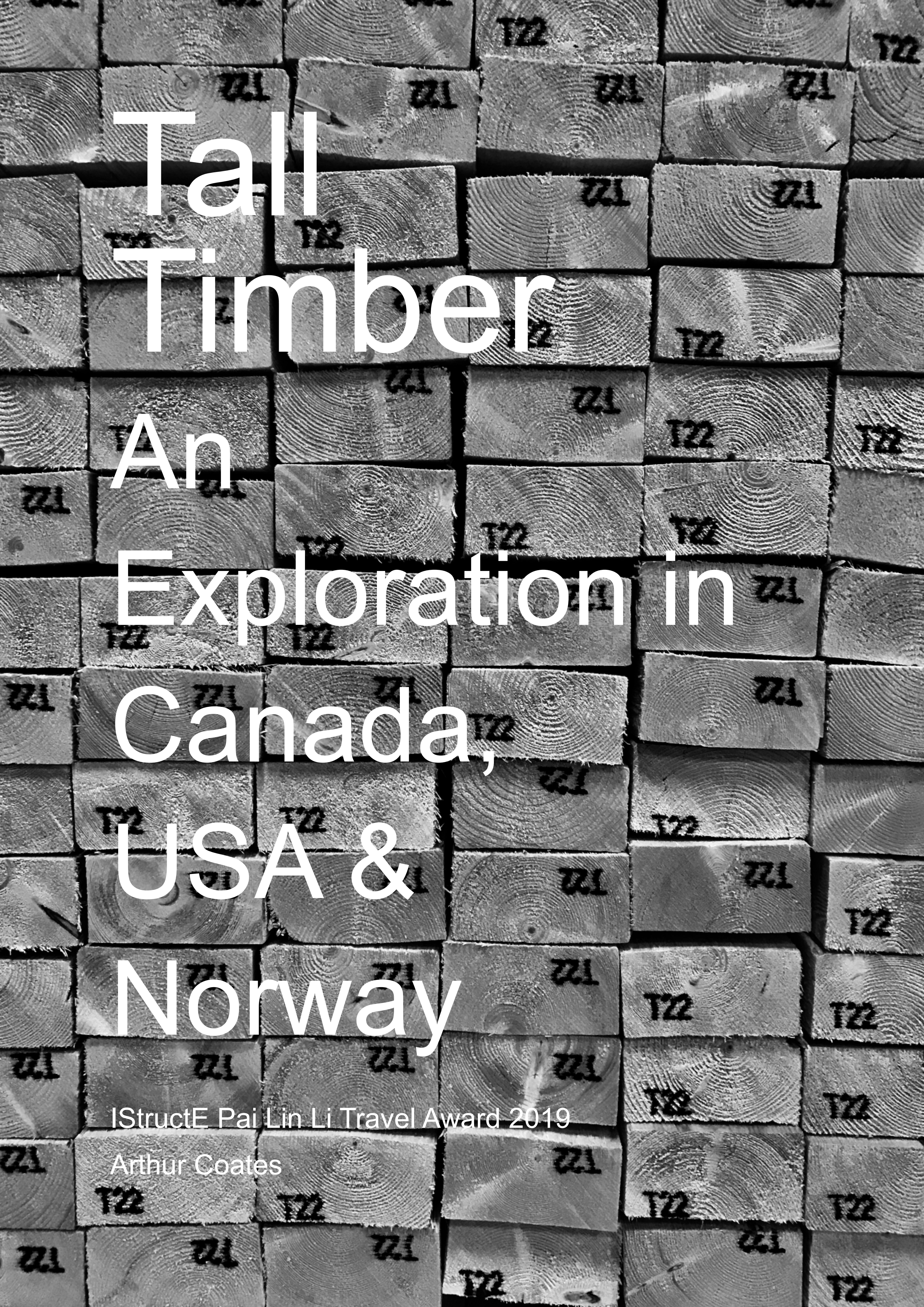


Tall Timber

An Exploration in Canada, USA & Norway

IStructE Pai Lin Li Travel Award 2019

Arthur Coates

Foreword

A timber building is widely acknowledged, although not yet formally, as 'tall' when it is above 12 storeys and has its main vertical and lateral structural systems constructed from timber. Timber is an uncommon material to use at this scale, with only a handful of examples globally.

The aim of the 2019 Pai Lin Li research trip was to discover the drivers for the development of tall timber buildings, to address the preconceptions about the use of timber, and to learn about the technical challenges facing the future of tall timber structural design. In light of the rapidly changing conditions that frame the use of timber in construction, there has not been a more important time to study this subject. The following factors underpin the context around this study:

1. In 2019, the world understood without doubt that there is a 'climate emergency', not least due to the increasing pressure on the ever-depleting stock of natural resources. Engineering institutions globally have now recognised their collective responsibility in tackling carbon emissions. As a result, radical targets to mitigate climate change are now legislated in many developed and developing nations. Trees have the ability to store up to 1.6 tonnes of carbon dioxide per cubic metre of wood[1]. This could assist in reducing the global greenhouse gas content by sequestering carbon within mass timber products.

2. Cities are densifying: the UN predicts that 70% of the global population will be resident in urban areas by 2050[2], whilst in the UK the government has pledged to build 300,000 new homes annually[3] to tackle the rising unaffordability of housing. Meeting this demand will require large building solutions with rapid construction periods.

3. A shift towards the use of timber in high-rise buildings is already happening across many western developed nations. In December 2018, the International Code Council (ICC) introduced changes to the 2021 International Building Code (IBC) allowing the prescriptive design of mass timber buildings up to 18 stories without acquiring special permission from the underlying authority. This has already been adopted in parts of North America.

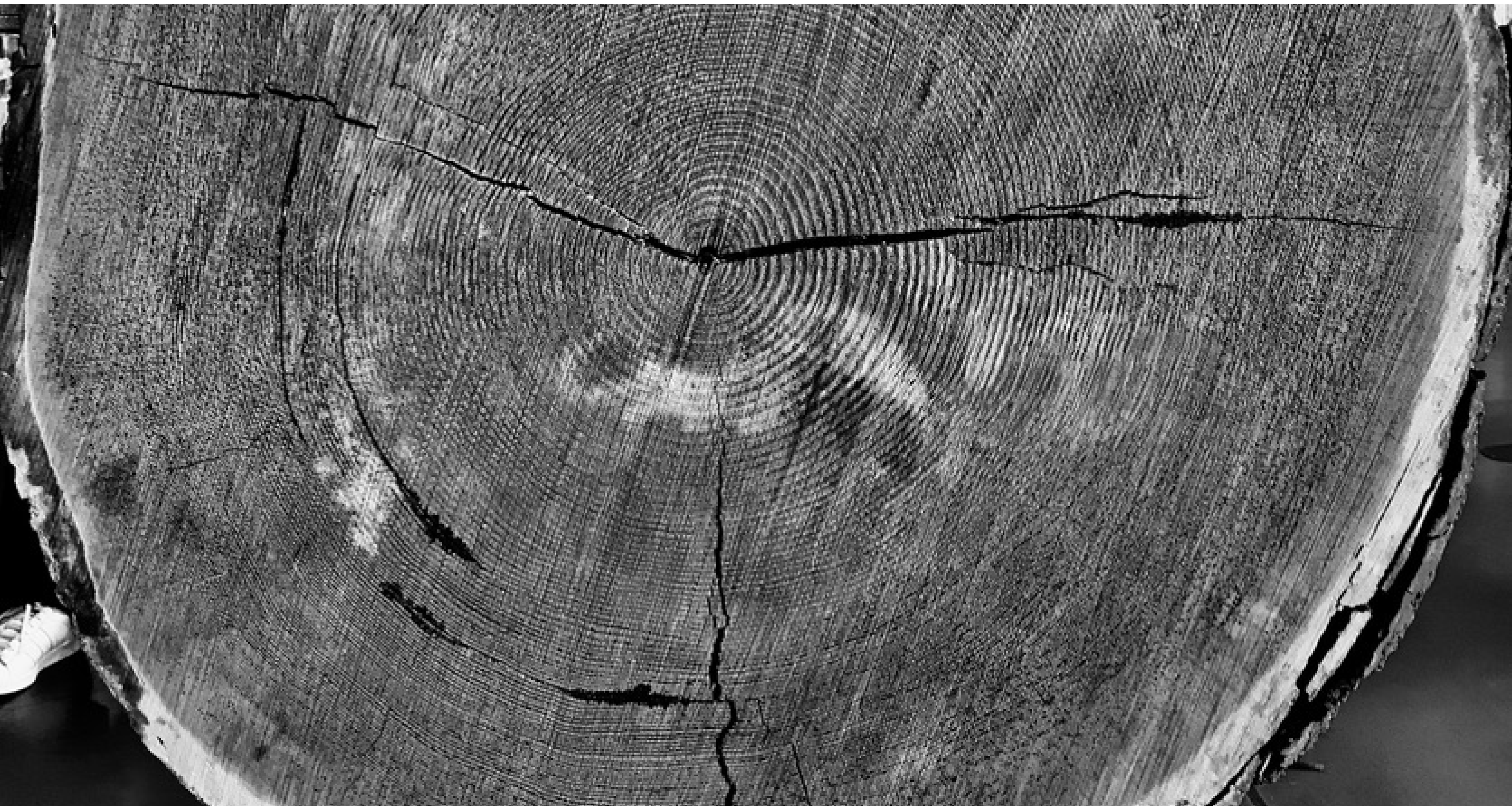
4. In the same month, the UK introduced changes to the fire safety section of the Building Regulations, effectively disinclining the use of timber in buildings above 18m tall.

5. The Council on Tall Buildings and Urban Habitat (CTBUH) found that there will be 21 timber buildings above 50m tall by the end of 2019[4], with the changes to international codes expected to drive an exponential growth in tall timber structures across North America and parts of western Europe.

It is clear that a fundamental cultural shift is required in the construction industry to limit greenhouse gas emissions, meet the demands of urban development and ensure construction quality. Most importantly, the creation of innovative material systems must ensure public safety; tall timber is testing precedence and as a result boundaries of engineering practice will need to be recast. This report can provide an insight into these tensions and offer recommendations for a potential way to progress.

Scope of Research

The first part of the research was undertaken in August and September 2019 at the global epicentre of tall timber design and construction: Vancouver, Canada. Research then continued in Portland, Oregon, and along the west coast of America to San Francisco, California. The author met with engineers, architects, researchers and contractors who have been crucial in developing



the tall timber market within North America. Their viewpoints were sought and specific building case studies were discussed.

The second stage of research involved a shorter, comparative study in Norway in October 2019. The purpose of this was to understand the differences between the European and North American mass timber industries. The trip also included a visit to the tallest timber building in the world, Mjøstårnet, and a meeting with the collaborators behind its design and construction.

The scope of the research included many different areas of study including: technical studies of buildings, research into codes of practice and how they are evolving in relation to developments in timber design, the potential impact on forestry and manufacturing, the role of technology in understanding tall timber performance and the changing economics of timber in construction. It forms a holistic overview of the current and future tall timber market. These areas are discussed in detail in individual sections of the report.

Many of the buildings studied during the trip are currently in design, with some subject to agreements that impact the level of disclosure possible in this report. In these cases, the principles of design are highlighted along with pertinent points in order to stimulate discussion. An extensive literature review has also informed the study.

Acknowledgements

The author passes on a special thanks to the IStructE and Price & Myers for their support and assistance in producing this report. This publication would also have not been possible without the help of the following companies and individuals during the research trip:

Equilibrium Consulting
Robert Jackson and Fast & Epp
Aspect Engineering
StructureCraft
David Harvey and Associated Engineering
Katerra
KLH USA
Swinerton
Thomas Robinson and Lever Architecture
TallWood Design Institute
Rune Abrahamsen and Moelven
Magne Bjertnæs and Sweco

Content

Foreword

References

1 Introduction

The Pai Lin Li travel award offers grants to study the innovative use of construction materials and techniques in countries outside of the UK. Timber is not a new construction material: it is known to have been used in the UK for building for over ten thousand years. However, it is only in recent years that timber has been utilised in tall, large-scale buildings. The 19-storey Mjøstårnet (Mjosa Tower) was completed in Norway in 2018 and is currently the tallest 'all-timber' building in the world as ratified by the CTBUH at 85 metres high[5].

The development in the use of timber is just one part of a rapidly-changing landscape in construction globally. Meeting urban growth needs will require engineers to explore new ways to design and construct buildings, in an environment where they must reduce carbon emissions and maintain biodiversity.

When compared with competitor materials, timber always seems to evoke a more emotive response in designers and end users; often cited are issues with fire safety, robustness and durability. However, bias can often form an obstacle to change. Objective research is needed to further the understanding of timber, and inform codes of practice trying to keep up with the potential systemic switching of material for taller buildings. Very recently, momentum appears to be shifting towards mass timber, specifically in Canada, USA and Norway, and away from the historic reliance on concrete and steel.

The aim of the 2019 Pai Lin Li travel award is to investigate the drivers and innovations that are allowing timber to compete with steel and concrete and the potential barriers to taller timber structures. The core objective is to establish an answer to the following question:

Is timber a viable alternative to concrete and steel framed buildings at scale?

The following areas of enquiry help frame the basis for the study:

- What are the different technical, economic and cultural forces that are affecting the facilitation of mass timber buildings?

- What are the obstacles to tall timber and how can these be overcome?

- What role can timber play in achieving a zero-carbon society whilst maintaining sustainable forestry?
- What is the potential impact on the future of structural engineering practice?

2 Introduction to Mass Timber

‘Mass timber’ is the collective term for engineered timber products such as Cross-Laminated Timber (CLT), Glulam, Dowel Laminated Timber (DLT) etc. These are solid elements comprised of sawn timber that are glued or mechanically fixed together to create a stronger, stiffer product.

2.1 Manufacture

Mass timber products are typically formed from ‘lamstock’, which is kiln-dried from fast-growing species such as Douglas fir or spruce, and sometimes larch and pine, to a moisture content of 10-14%. The specific type depends on the region and how the stock can be sourced efficiently.

CLT is manufactured from this stock (otherwise known as lumber boards) and are glued and pressed crosswise in layers to form the solid timber panels using a hydraulic or vacuum press (refer to figure 1). The adhesive typically accounts for less than 1% of the volume. The panels are then CNC cut to size within tolerances of

Figure 1: Small-scale CLT press at the TallWood Design Insitute, Oregon

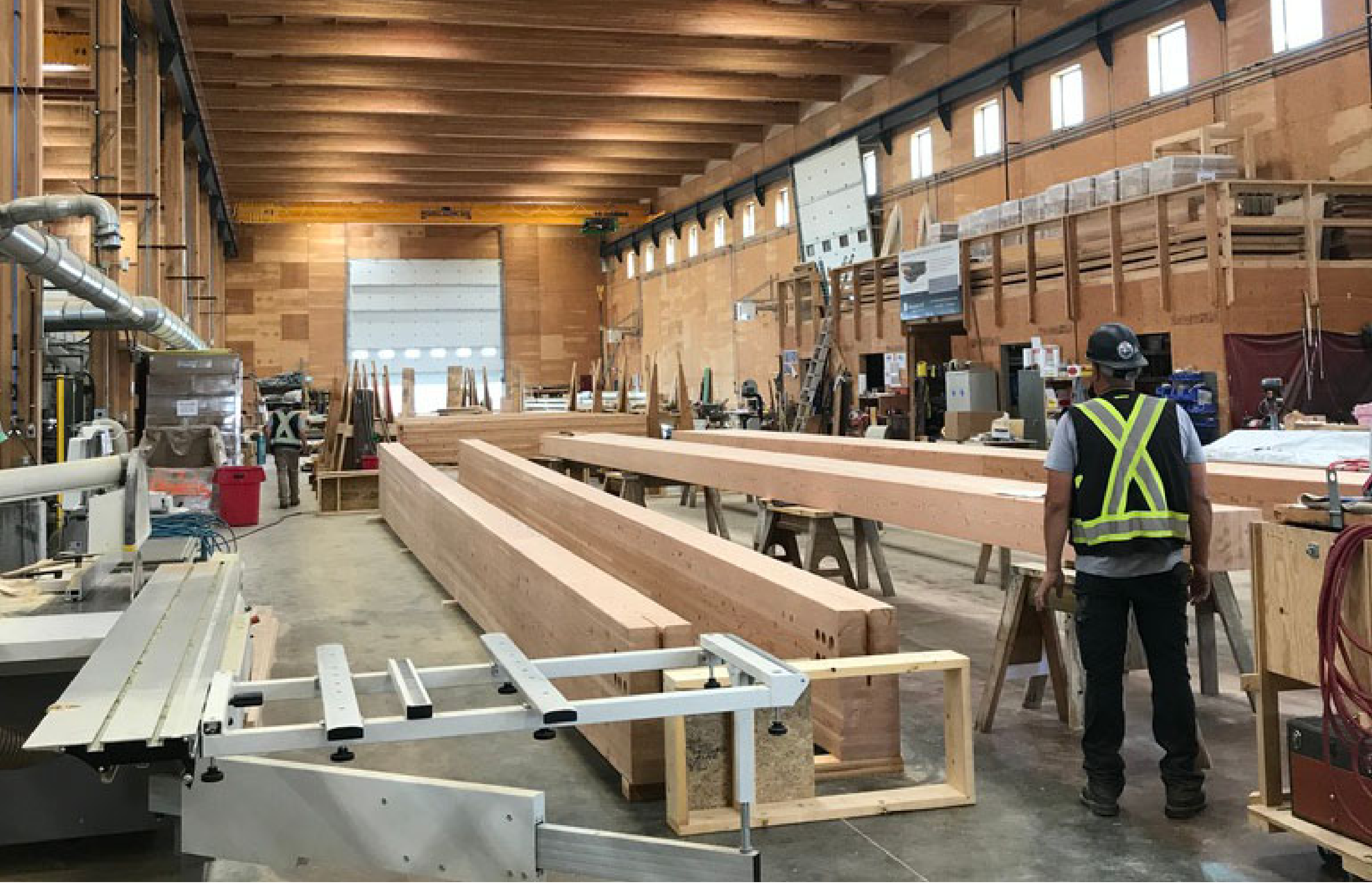


Figure 2: StructureCraft DLT and glulam factory in British Columbia

+/-1mm if required[6].

Glulam is formed in a similar way but without cross-laminations. DLT does not use adhesives with the connection formed by dowels with a lower moisture content, which expand as the moisture equalises with the sawn timber. These dowels are hydraulically driven into the cross-section to provide the integral capacity required (figure 4).

In Europe, the adhesive for Glulam and CLT is usually Polyurethane-based (PUR) which is solvent and formaldehyde-free. However, the production of this adhesive results in Volatile Organic Compounds (VOCs), which limits the end-of-life uses of the product. The formulation of the adhesive has changed rapidly in the past couple of years due to the fire requirements of mass timber products (refer to section 4 for more details).

The techniques to form mass timber products are generally derived from central Europe during the 1990s but have only recently taken a foothold within the North American market. A qualitative comparison of manufacturing techniques and an overview of the current market trends is provided in section 7.

2.2 Material Properties

To objectively compare materials and framing options, the fundamental mechanical properties must be considered. A summary of this is provided below to enhance the understanding of the capability of mass timber compared to steel and concrete.

In the table below, floors and walls are presented on a volumetric basis, whereas framing elements (beams/columns) are presented on a mass basis. Presently within Europe, material properties for CLT are not consistently reported, so an assessment from numerous manufacturers is proposed.

	Floors / Walls		**Beams/Columns**	
	CLT (CL24)	**Insitu RC (C30/37)**	**Glulam (GL24)**	**Steel (S355)**
Density (kg/m^3)	350	2400	385	7850
Strength				
Bending strength (N/mm^2)	24	4	24	355
Tensile (parallel) (N/mm^2)	16	2.9	19.2	470
Compressive (parallel) (N/mm^2)	24	30	24	*
Shear (parallel) (N/mm^2)	2.5	4	3.5	205
Stiffness				
Elastic Modulus (kN/mm^2)	11	32	11.5	210
Shear Modulus (kN/mm^2)	0.65	21	0.65	81
Embodied Carbon (kgCO$_2$e/m^3)	155	340	*	*
Embodied Carbon (kgCO$_2$e/kg)	0.44	0.14	0.51	1.55
General Comparative Metrics				
Bending/Density	69	2	62	45
Compression/Density	69	13	62	*
Stiffness/Density	31	13	30	27
Bending/CO$_2$e	54	28	47	229

Figure 3: Material properties comparison

To summarise a few key points from this comparison:

- The bending strength of mass timber is significantly poorer than steel when considered on a volumetric basis.
- The stiffness of mass timber is significantly poorer than steel and concrete, especially with regards to shear deformation. This is significant for long span elements.
- When calibrated for density, mass timber outperforms steel and concrete.
- When calibrated for embodied carbon, mass timber is significantly better than concrete, but is significantly worse in bending scenarios compared to steel.

Figure 4: DLT panel during production at StructureCraft

Using the compressive capacities listed above, conducting a basic structural assessment for a theoretical 9-storey building on a 5.0m by 5.0m grid with residential loading would result in the vertical elements requiring similar sizes for concrete and mass timber. In practice, however, this is not the case: this assessment assumes that the lateral forces and the structural fire design is covered by other means.

This example exposes the two fundamental challenges in designing tall timber buildings: firstly, that timber requires a unique approach to fire design and secondly, that it cannot compete with other materials when used for lateral stability elements. These challenges will be explored in sections 3 and 4 of the study.

Notes:

- The data on material properties are from a range of sources from the UK. The assessment is not to be taken as rigidly accurate but as a high-level comparison.

- The embodied carbon data are from the Inventory of Carbon and Energy database[7], with figures for sequestration ignored.

- The assessment for vertical element sizes is based on floor-to-floor heights of 3.1m with residential loading of 2.50kN/m^2. No lateral load is included, apart from consideration of Equivalent Horizontal Forces (EHFs).

3 Tall Timber Typologies

This section of the report will explore how mass timber is being used in new typologies to suit the growth into different sectors, followed by the design challenges that face taller and longer-spanning timber structures.

3.1 Mass Timber Framing

The growth in the number of mass timber buildings within North America and Norway isn’t just synonymous with taller structures but is part of a wider drive towards framed solutions using timber products. New typologies focused on the flexibility and adaptability of space are developing. This is particularly prevalent within the office and commercial sectors within North America where longer spans are targeted (up to around 30 feet/9.0m). To summarise the different typologies used in mass timber buildings:

1. Slabs and walls (panellised)

2. Post and beam (downstand)
   a. One-way spanning floor (refer to figure 5)
   b. Two-way spanning CLT

3. Post and slab (flat slab soffit)
   a. Two-way spanning CLT (refer to figure 9)
   b. Beam and column strips with two-way spanning CLT

One notable example of a timber-framed office building is 2150 Keith Drive in Vancouver, currently in design by Fast & Epp[8]. The ten-storey building will use CLT panels which span one-way onto steel beams around the atrium which are located within the panel depth. This creates a flat soffit for services flexibility from the core.

Figure 5: The District Office in Portland, Oregon

Figure 6: The flat soffit in the corridor of The District Office

Figure 7: The double-shear connection at the new Adidas HQ in Portland

Another example is the District Office in Portland, in construction at the time of visit (refer to figures 5 and 6). This building uses a one-way glulam ‘post and beam’ frame to create 40 foot spans (12.2m) either side of a central corridor from the core. Within this corridor, horizontal services can be freely distributed by using the two-way spanning capability of CLT between glulam columns.

Given CLT is typically manufactured and transported in panels just below 3.0m wide, the application of two-way spanning panels is limited. However, this width lends itself suitably to single-unit residential buildings such as student or hotel uses. The use of CLT in this way has been effectively utilised on the Brock Commons building in Vancouver (refer to figure 9). The CLT panels are point-supported using glulam and parallel-strand lumber (PSL) columns[9], creating a flat-slab analogous typology. This is regarded as the first practical use of this kind at scale.

Figure 8: The Adidas HQ typology using two layers of beams for flexibility in internal space and façade arrangement

Figure 9: Brock Commons, Vancouver. Source: Naturally Wood

Figure 10: Terrace House, Vancouver, in design at the time of visit. Source: Shigeru Ban Architects

3.2 Composite Systems

The typologies described above are often enhanced through the use of composite systems. Typically these are timber-concrete (refer to figure 11) where the timber is utilised in panellised flooring, with the advantage of speed of construction, and the concrete cast on top. Composite hybrid systems using timber-timber and timber-steel are also possible. In most cases using a composite system provides a more materially-efficient use of timber.

Timber composite systems are nonetheless still limited by the tensile strength of timber and there are numerous disadvantages

Figure 11: HSK timber-concrete composite connection

in using timber-concrete systems during construction. These include temporary propping (unless the timber can be justified as permanent formwork); an increase in the number of different trades required sequentially to complete the structure, negating the programme benefits of using mass timber; and potential acoustic issues in the permanent design. Normally an acoustic mat is needed for the longer spans (above 6m) for shock-based footfall in residential and office applications.

In spite of these issues, many forms of timber-concrete systems are being utilised in mass timber structures within North America. One of these is the 19-storey Terrace House project in Vancouver (figure 10) designed by Shigeru Ban Architects and Equilibrium Consulting. This project uses HSK/HBV shear connection plates[10] (figure 11) which are the most widely used products to create composite action within Europe and North America. However, relying on the adhesive to set within the timber element whilst working on site introduces complexity and risk and is only recommended to be used within controlled environments.

3.3 Considerations for Tall Timber Design

Although using framed solutions for mass timber buildings creates many advantages, such as the adaptability of space, there are design issues that need to be carefully considered if utilised at scale. Timber structures face many of the same design challenges as tall buildings using traditional materials (concrete and steel) such as lateral stiffness and vertical differential movement between elements; however, for timber structures these are exasperated at lower heights.

The following sections provide examples of the challenges encountered during the design of tall timber buildings. These are split into vertical and lateral systems and contain a list of the key considerations for both, followed by a qualitative discussion. These lists were collated through interviews with designers and an assessment of the technical literature currently available.

Figure 12: Glulam column on Mjøstårnet. Columns were CNC milled to +/- 1mm tolerance and a flitched steel connection used above floor level to ensure verticality during construction

3.4 Vertical Systems

The design challenges in using mass timber vertical systems include:

- Low biaxial strength (refer to section 2 for a comparison of materials)

- Axial shortening effects:
  - Short-term elastic shortening
  - Shrinkage parallel to grain (variations in moisture content)
  - Long-term creep

- Differential shrinkage between timber elements and differing material systems

- Connections including joint settlement

- Fabrication tolerances and movement mitigation during construction

- Accidental actions and disproportionate collapse due to the low

Figure 13: Façade on Brock Commons during construction. Source: Naturally Wood

tensile capacity

- Fire design (refer to section 4)

The effects of differential movement is a significant challenge in the design and coordination of the vertical structure of tall timber buildings. Short- and long-term analyses must be carried out to assess the impact on the support of adjoining systems, such as cladding, including sensitivity checks using a range of moisture content variations. Typically, moisture content variations would be at least +/-5% and up to +/-10% depending on the regional climactic conditions, resulting in various shrinking and swelling scenarios.

Comparing the vertical movement of mass timber to concrete elements is not a straightforward task as the creep value depends on many different factors. However, the value of combined shrinkage and creep is likely to be similar for equally-stressed elements. It is the elastic shortening effects of mass timber that need to be thoroughly considered for tall buildings given the elastic modulus is much lower (refer to section 2).

Overall axial shortening and shrinkage should not affect the construction or permanent performance of a tall timber building if

Figure 14: Glulam diagrid on Mjøstårnet during construction. Source: Moelven

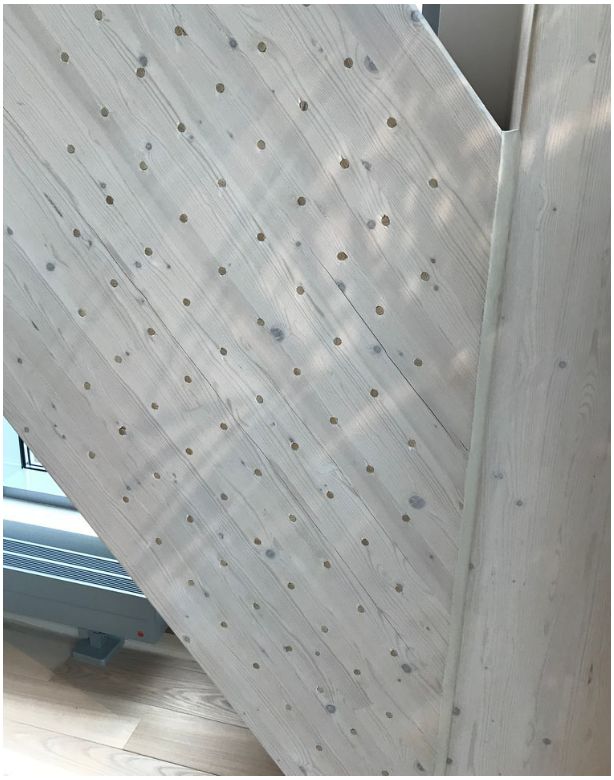


Figure 15: Base connection of diagrid on Mjøstårnet with four flitch plates and 100 steel pins

appropriately designed and detailed for predicted movement.

On Brock Commons, steel shim plates were utilised to mitigate the effects of shortening on the façade and internal fittings at three strategic levels, where up to 50mm of vertical settlement was predicted at the highest level[11]. Vertical shrinkage within the glulam columns is monitored at Brock Commons on an ongoing basis to understand the impact of moisture content and gather more data on the elastic moduli of mass timber elements. This is discussed in more detail in section 8.

3.5 Lateral Systems

Arguably the most challenging aspect to the design of a tall timber building is with lateral stability, especially if an ‘all-timber’ solution is chosen.

Lateral systems can be achieved with concrete or steel braced core(s) in combination with a timber vertical system, however it is noted that many of the ‘showcase’ buildings in the countries visited have prided themselves on creating an ‘all-timber’ structural system. Vertical stability in ‘all-timber’ buildings can be achieved through mass timber panellised cores, glulam bracing or a glulam diagrid structure. Horizontal stability can be provided by timber plates like plywood or laminated veneer lumber (LVL) acting as diaphragms, depending on the span arrangements. Shear forces across panel joints usually require the use of steel splice plates.

The design challenges posed through using an ‘all-timber’ lateral system include:

- Stiffness
- Shear deformation
- Lateral acceleration
- Holding-down (HD) system
- Fatigue in connections from load-reversal
- Connection stiffnesses and slip within joints

In addition to the list above, a crucial consideration for lateral stability is seismic loading. All buildings along the west coast of North America are designed for varying seismic scenarios. The challenge faced by designers is to achieve the required ductility within the lateral system to dissipate the applied seismic energy, whilst minimising the number of elements that need replacing post-seismic event.

Examples of timber lateral systems that can combat seismic loads in practice are:

- CLT walls with rocking type (post-tensioned, PT) systems
- CLT walls with HD systems
- CLT walls with resilient slip friction joints (RSFJ)

A significant amount of research is being carried out at institutions along the west coast of America. The timber rocking wall system has been developed by Oregon State University for the Framework building in Portland, a 12-storey office development[12] (refer to figure 16). This system allows the CLT panels to rotate and move laterally,

Figure 16: A model of the rocking-wall system on the Framework Building in Portland. Source: Framework Portland

Figure 17: Timber rocking-wall model on the Oregon State University campus

whilst the PT rods re-centre them with the energy dissipated at the sides and base with ductile plates.

Additional research has led to the use of a novel form of HD system using perforated plates and smaller diameter pins for use on Keith Drive. This system transmits lateral forces whilst allowing the walls to move and dissipate energy hysteretically[13]. Moreover a 10-storey mass timber building will be constructed and analysed on a shake table and monitored for seismic performance at the University of San Diego in 2020[14].

In addition to CLT core walls, timber diagrids can also provide lateral stability to ‘all-timber’ structures, with notable examples including Mjøstårnet and the 35-storey PMX building in Toronto, in design at the time of writing[15]. The challenge with utilising a diagrid system is the combined axial and bending forces which result in very large members and base detail connections (refer to figure 15).

3.6 Lateral Acceleration

With Mjøstårnet having an ‘all-timber’ lateral system, element sizes are governed by the combined lateral stiffness of the vertical elements. In order to combat the high lateral acceleration, the top seven floors were constructed using a precast concrete flooring solution to increase the predicted comfort level under dynamic forces[16].

An ‘all-timber’ floor structure can be 20% lighter per storey compared to an equivalent concrete frame[17]. However with such low relative weight of ‘all-timber’ to traditional concrete and steel framed buildings, the lateral acceleration and excitation effects are largely unknown in practice.

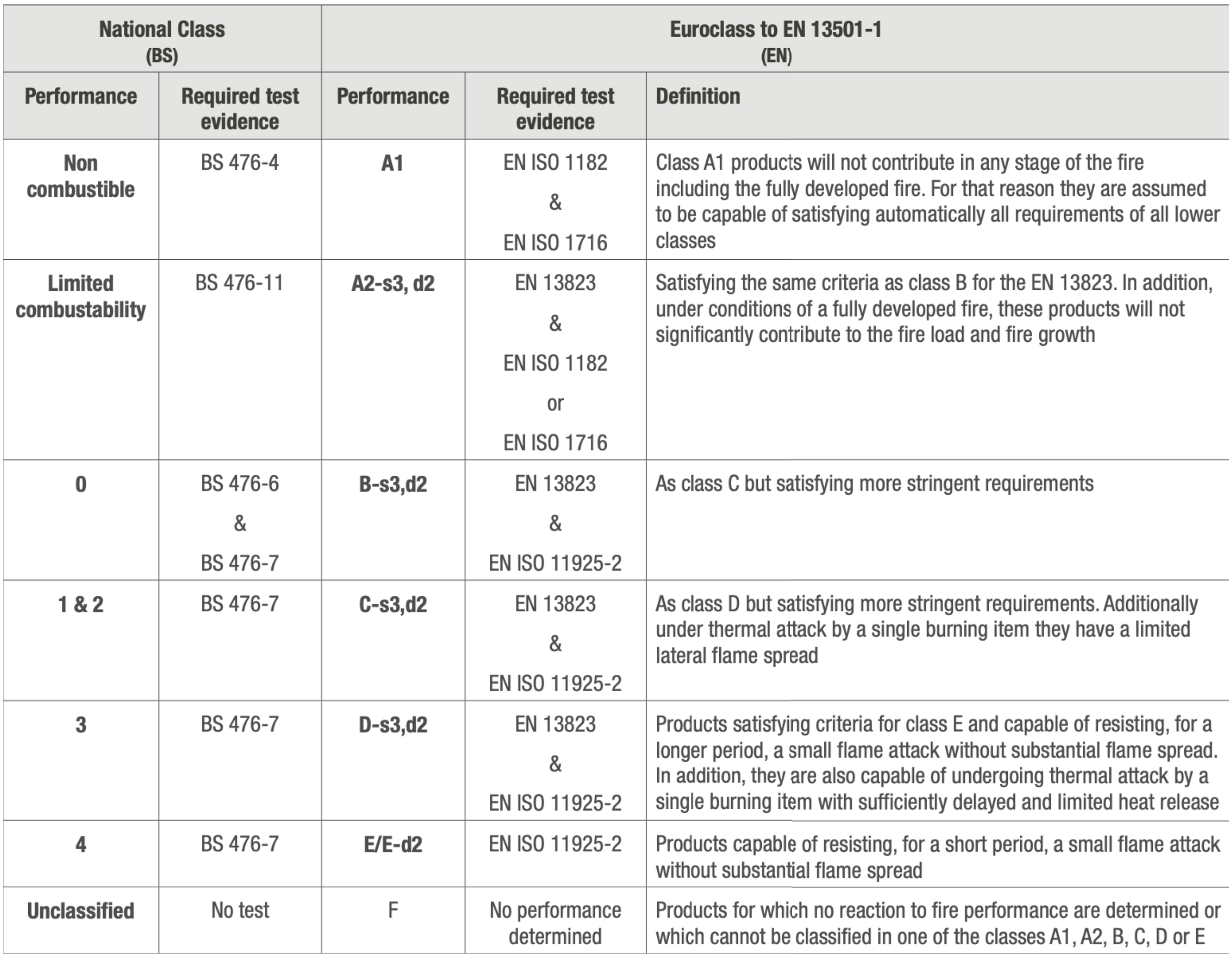
Research into damping ratios is being explored on completed projects, the effect of which is believed to be significant. On Mjøstårnet, damping solutions such as a tuned mass damper could have theoretically been used in lieu of concrete flooring. For the PMX building in Toronto, research is ongoing to determine the effect that the self-weight of a tuned-mass damper can actually have on its dynamic performance. This phenomenon is understood to be unique to ‘all-timber’ tall structures.

Although dependent on the slenderness ratio and core requirements, overall ‘all-timber’ lateral systems tend to struggle above 12 stories due to stiffness and connection considerations.

4. Fire Safety Design

4.1 Introduction

Fire safety is the most significant obstacle to the proliferation of tall timber buildings. Timber is a combustible material and therefore it must be treated differently from a structural fire design perspective when compared to concrete and steel elements. Simply due to precedence, these two materials form the basis of most guidance documents on fire safety design. Comparing attributes to EN 13051-1, timber is Euroclass D in terms of combustibility, whereas concrete is class A1 (refer to figure 18)[18]. Recently, many fire engineers have argued that the traditional fire resistance tables (such as table B4 from Approved Document B in the UK[19]) cannot apply to timber, given the derivation of these tables is from testing carried out on non-combustible materials[20].

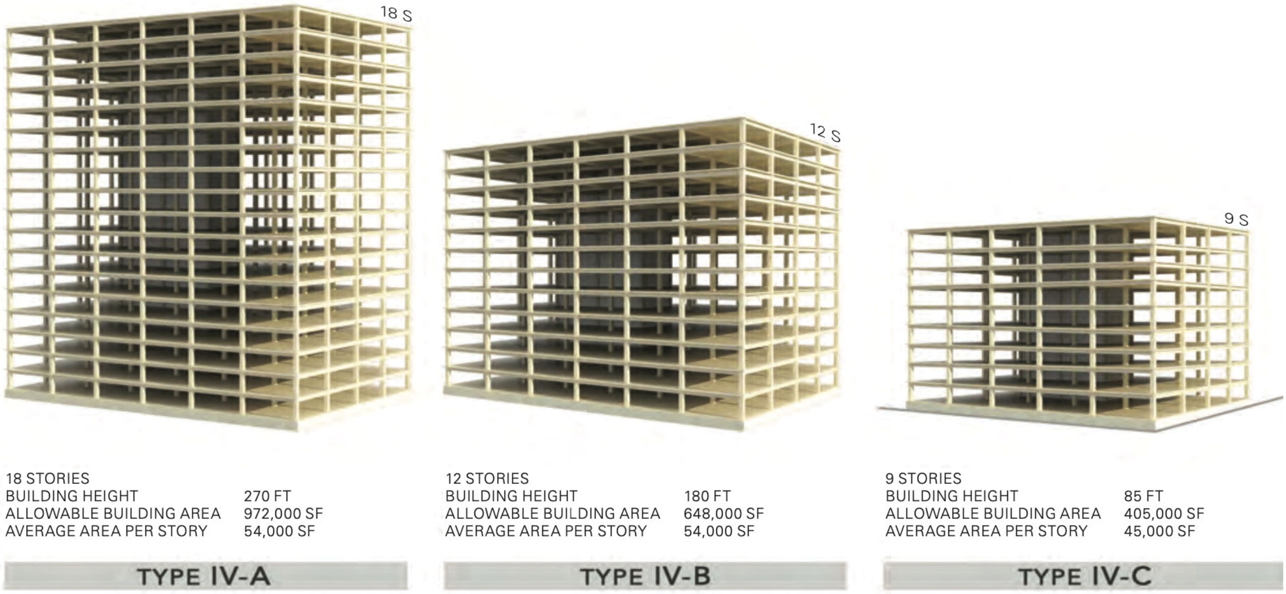


National Class (BS)		**Euroclass to EN 13501-1 (EN)**		
Performance	**Required test evidence**	**Performance**	**Required test evidence**	**Definition**
Non combustible	BS 476-4	**A1**	EN ISO 1182 & EN ISO 1716	Class A1 products will not contribute in any stage of the fire including the fully developed fire. For that reason they are assumed to be capable of satisfying automatically all requirements of all lower classes
Limited combustability	BS 476-11	**A2-s3, d2**	EN 13823 & EN ISO 1182 or EN ISO 1716	Satisfying the same criteria as class B for the EN 13823. In addition, under conditions of a fully developed fire, these products will not significantly contribute to the fire load and fire growth
0	BS 476-6 & BS 476-7	**B-s3,d2**	EN 13823 & EN ISO 11925-2	As class C but satisfying more stringent requirements
1 & 2	BS 476-7	**C-s3,d2**	EN 13823 & EN ISO 11925-2	As class D but satisfying more stringent requirements. Additionally under thermal attack by a single burning item they have a limited lateral flame spread
3	BS 476-7	**D-s3,d2**	EN 13823 & EN ISO 11925-2	Products satisfying criteria for class E and capable of resisting, for a longer period, a small flame attack without substantial flame spread. In addition, they are also capable of undergoing thermal attack by a single burning item with sufficiently delayed and limited heat release
4	BS 476-7	**E/E-d2**	EN ISO 11925-2	Products capable of resisting, for a short period, a small flame attack without substantial flame spread
Unclassified	No test	F	No performance determined	Products for which no reaction to fire performance are determined or which cannot be classified in one of the classes A1, A2, B, C, D or E

Figure 18: Combustibility requirements from fire tests. Table from WIS 2/3-3 by Trada

In the UK, structural fire design is a performance-based task: a building must ensure ‘stability for a reasonable period of time’[18]. However, in December 2018 a prescriptive element was introduced - regulation 7 of Part B - which disallows the use of combustible material, including timber, in the external wall build-up of all buildings used for residential purposes above 18 metres. This change was a result of the Hackitt report[20] following the Grenfell Tower tragedy. As the UK construction industry enters an environment of heightened scrutiny of fire safety regulations, the spotlight is on designers to demonstrate competency in fire safety design.

Contrastingly in the same month, the International Code Council (ICC) introduced changes to the International Building Code (IBC) 2021 allowing ‘all-timber’ buildings up to 18 stories, without



	IV-A	**IV-B**	**IV-C**	**IV-HT**
Interior Surface of Building Elements	Always required. 2/3 of FRR, 80 minutes minimum	Required with exceptions. 2/3 of FRR, 80 minutes minimum	Not required*	Not required*
Exterior Side of Exterior Walls	40 minutes	40 minutes	40 minutes	15/32" FRT sheathing or 1/2" gypsum board or noncombustible material
Top of Floor (above Mass Timber)	1" minimum	1" minimum	Not required*	Not required*
Shafts	2/3 of FRR, 80 minutes minimum, inside and outside	2/3 of FRR, 80 minutes minimum, inside and outside	40 minutes minimum, inside and outside	Not required*

**Not required by construction type. Other code requirements may apply.*
5/8" Type X gypsum = 40 minutes.

Figure 19: Mass timber building categories from the IBC 2021 code. Source: Think Wood

acquiring special permission (refer to figure 19)[22]. At the time of writing, these standards had already been adopted in Canada, and the north-western states of USA.

This section of the report is approached from a structural engineering perspective and further investigation is required with input from a 'fire engineer' to evaluate the suitability of UK and North American fire safety regulations. However, a high-level reflection on two contrasting approaches to structural fire design of high-risk timber structures in two differing regulatory frameworks is offered. This is based on research and discussions with designers.

The IBC changes appear to offer a codified way to design tall timber buildings in comparison to the structural fire design methods in the UK. These contrasts appear not just limited to building height but pose questions about the fundamental approach to the design of mass timber structures in fire scenarios. The difference in ambition is also stark: there are two parts of the world with varying confidence in the use of timber with height.

4.2 Current Structural Fire Design Processes within UK

Given that the majority of membership of the IStructE practise within the UK, this section will compare North American guidance to the UK. The following is a brief summary of the fire design processes for timber usually carried out within UK practices:

1. The Engineer takes the minimum structural fire resistance period from table 4 of ADB.

2. The Engineer must satisfy themselves that the building is 'common', that 'stability is maintained for a reasonable amount of time' and have complied with accidental load criteria from Part A3[23].

3. The Engineer designs elements using Eurocode EC5-2[24] which assumes a zero-strength layer (ZSL) and a resultant reduced cross-section method (RCSM) using updated strength and stiffness parameters.

Both the regulatory framework (Building Regulations Act) and the design procedure recommended within it (EC5) reveal shortcomings. For instance, what should a designer do if the building is not 'common', as is the case for 'tall' timber buildings?

It has also been shown that the RCSM data is sometimes inappropriate and varies depending on whether the element is in tension or compression, and in combination with shear. There is also currently no defined code of practice for the structural fire design of CLT[25].

Overall it is widely acknowledged[20] that there are issues with both the performance-based criteria for timber buildings and the prescriptive fire design methods in the UK.

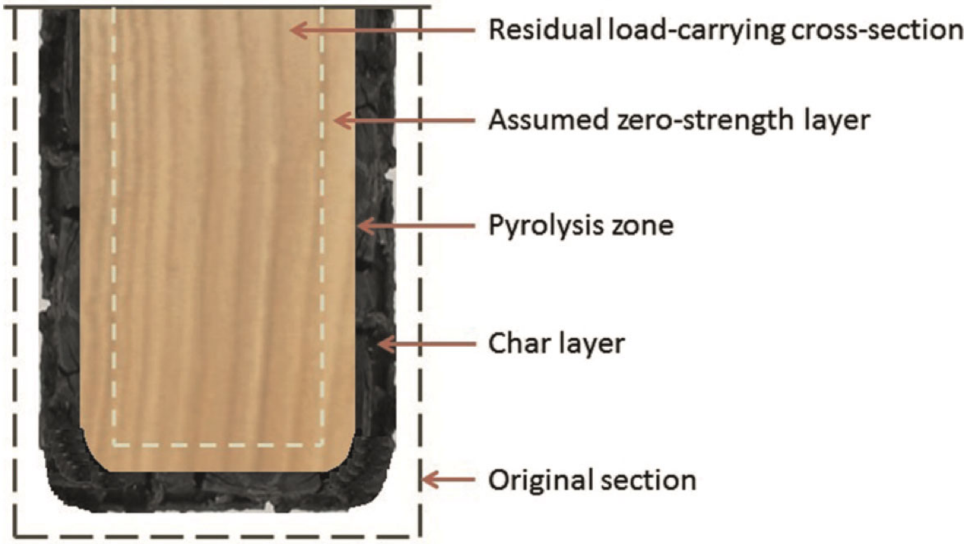


Figure 20: Outline RCSM for fire design of timber elements. Source: USDA Forest Products Laboratory

4.3 Comparison to North American Timber Codes

The fire design process of mass timber elements within North America follows a similar approach to the UK. However, there are differences in the research and basis for structural fire design methods within the codes of practice. Four significant areas of difference in the structural fire design of mass timber are identified. A qualitative comparison of these is described below:

1. Adhesives

UK

Mass timber products within the UK, most notably CLT, are designed in fire scenarios using product specific European Technical Approvals (ETAs) as these are deemed to be ‘innovative’ products outside the scope of technical standards. Many of the charring rates used in the RCSM vary across suppliers[26] and depend on the size of the laminations and adhesive behaviour, whereby different formulations are used.

North America

The introduction of ANSI/APA PRG320 (2018) – Standard for Performance-Rated CLT[27] attempts to create a harmonised product standard for adhesives. The aim of the standard is to unify the adhesive behaviour by dictating its minimum heat resistance, which delays the process of delamination. Annex B dictates that unprotected CLT must sustain fire exposure for a minimum of four hours without char layer fall-off, whilst sustaining load.

Comparison

PRG 320 helps to identify and exclude heat-delaminating adhesives. This has subsequently caused fresh research into adhesive technology with improved formulations for PUR-based and melamine formaldehyde (MUF) resin. However, it is noted that delamination cannot be fully removed as it will always occur at sufficiently high temperatures within adhesive-based mass timber products[28].

2. Temperature Effects

UK

The RCSM approach accounts for char depth and heat-affected timber beyond the char line, taken as 7mm in the UK. The maximum testing temperature is 90°C for the adhesive line of CLT[25].

North America

A similar RCSM approach and char depth as the UK is used in North America. In addition PRG320 states that temperatures must not exceed 510°C during the decay phase of the fire after 150 minutes. Further specific guidance is given in the NDS for Wood Construction[29] and the CSA 086[30] to determine the fire resistance based on a reduced cross-section.

Comparison

The North American codes appear to offer more guidance on this subject. The temperature effects, especially during the decay phase of a fire is a major area for ongoing research and has been identified as a serious issue with large compression members and a ‘stay-put’ fire safety strategy[31].

3. Compartment Fire Tests

UK

There have been a limited number of small compartment fire tests carried out within the UK, the most notable being those carried out by Arup and the University of Edinburgh in 2016[32]. Issues encountered included delamination resulting in cyclic burning as well as an inconsistency in results for repeat tests.

North America

A series of fire tests have been carried out on a compartment basis over two storeys with varying amounts of timber exposed to aid the IBC 2021 changes[33,34]. The compartment fire test is also a requirement of PRG320 in Annex B.

Comparison

The number of compartment fire tests is very limited in both areas, although North American technical guidance has extrapolated more information from the tests carried out to date. The basis for the changes to IBC is to ensure that the highest risk buildings (type A and B) can ensure burnout within a partially-encapsulated compartment without the use of sprinklers or other intervention. The improved heat resistance of adhesives has minimised issues with compartment burnout in tests. It is understood that further tests are being proposed to maximise the use of exposed timber within compartments.

4. Approval Process

UK

Refer to section above. The onus is on the designer to demonstrate efficacy of the engineering solution as part of the performance-based criteria of the Building Regulations.

North America

The approval process can vary depending on the region in North America. Within British Columbia, the appointment of a code consultant is mandatory. Their role is to review and advise the design team in terms of fire requirements within the regulatory environment. Moreover, the limitations of the local building codes are usually clear. For example, the British Columbia Building Code (BCBC) 2020 allows encapsulated mass timber buildings up to 12 stories, with other specific caveats, such as around stair cores. If the proposed building does not conform to these rules, then the building is subjected to an alternative approval process defined within the code. For many of the tall timber buildings referred to in section 3, this alternative process has involved rigorous review from expert, independent engineers at numerous stages of the design.

Comparison

A comparison is difficult due to the variety in local, state and federal codes within North America. Within British Columbia the regulations appear more prescriptive of what is allowed within mass timber buildings compared to the UK. Moreover, there is a clear path for alternative approval if required. This can reduce uncertainty regarding the approval of fire safety design for engineers.

4.4 What can the UK learn from North America?

There is an implied Hippocratic duty for all structural engineers to assure public safety in the design of all buildings. Yet design can often take engineering outside the scope of current models of practice. It is therefore imperative that design based on objective, evidence-based research and historic performance is used. This is certainly the case with regards to the design of tall timber structures. Unfortunately, there are not enough precedents to give certainty around fire performance and the more research that is done, the more complex this issue reveals itself to be.

A clearer risk-based performance approach is required within the UK. To paraphrase a conclusion reached by the University of Edinburgh fire engineering team; ultimately the design of ‘all-timber’ buildings must ensure self-extinction following the consumption of all of the fuel load, including all combustible structural elements, without the reliance on external fire-suppression systems[35].

Whilst the North American codes allow a greater use of timber compared to the UK, these do not form the ‘endgame’ for the fire design of mass timber structures. Further research and code development is essential. Several high-level suggestions based on the travel research are:

- Changes to the specification of adhesives to ensure a minimum fire resistance.

- More compartment fire tests to better understand the fire dynamics of exposed timber surfaces. These must ensure burnout without intervention.

- More research into the decay phase of a fire, accounting for the thermally-affected timber beyond the char line. The next edition of EC5-2, to be released in 2023, intends to address this with a greater scope of reduction factors using the RCSM for exposed timber structure.

- Greater education of structural engineers through increasing the scope of university courses to include timber and structural fire design.

- In the UK a ‘fire engineer’ should be a mandated role within a design team with the responsibility of mitigating design risk in fire scenarios.

- Guidance on alternative fire-engineered solutions must be provided.

5. Tall Timber and the Impact on Forestry

The recommendations of this study should hopefully result in greater clarity with national building regulations and the structural fire design of timber.

This section of the study will explore the different cultural and economic forces driving tall timber projects and what the potential implications are on the forestry reserves of Canada, the USA and Norway. Equally importantly, the study includes how future ventures could enhance the forestry cycles and thereby the future mass timber output in these regions to meet this flourishing demand.

5.1 A Culture of Timber

Within Canada, 94% of forest is publicly owned and managed by local provincial, territorial and federal jurisdictions under Natural Resources of Canada (NRCAN)[36]. A forest can only be harvested once an agreed Forest Management (FM) plan is in place. These practices are monitored on a regular basis by the Canadian Forest Service, who ensure sustainable forestry practices and operations across the supply chain. As a result, Canada has maintained over 90% of its original forest coverage and the rate of deforestation has been virtually zero over the past 30 years[37].

In contrast only 40% of the forest coverage in the US is publicly owned[38] and there is no universal standard to ensure sustainable sourcing. In practice, the Forest Stewardship Council (FSC) and the Sustainable Forestry Initiative (SFI) operate sustainable certification schemes in many forests. In spite of this the deforestation rate within the USA remains higher than Canada at around 14% between 2001 and 2018[39].

In contrast, 40% of Norway is covered in forest and around 80% of this is privately owned[40], typically through the use of cooperatives. However the management of Norwegian forest is mandated through the Forest Act which ensures sustainable harvesting of timber. In 2000, Norway became one of the first countries to wholly join the Programme for Endorsement of Forest Certification (PEFC).

Within Canada and particularly the north-western states of US, there is a ‘culture of timber’, predominantly stemming from the large lumber industry. Over 35% of all Canadian forestry operations occur in British Columbia with 30% of forestry exports being sawn softwood[41]. Similarly, roughly half of Oregon’s 62 million acres of landmass (similar size to the UK) is covered with forest, much of which is Douglas Fir and Penderosa Pine. These species are the most commercially viable stock for the production of mass timber due to the wider coverage and faster growth cycle.

Figure 21: Pine forest near Portland. Oregon’s forestry coverage is roughly 50%, compared to 10% in the UK

5.2 Drivers of Tall Timber Projects

The culture of timber has been supported in legislation in British Columbia since 2009, with the introduction of the Wood First Act. The aim of the Act is to encourage designers to specify wood as the primary construction material for new publicly-funded buildings. Although the Act has only been loosely followed since introduction, it has been a catalyst for movements promoting the wider use of timber such as WoodWorks BC and the Forestry Innovation Investment (FII). A similar form of legislation has been recently announced in France, mandating all public buildings to be constructed from at least 50% mass timber by 2022[42].

There is also a substantial federal push within Canada to financially support pioneering tall timber projects. NRCAN partners with upcoming projects to contribute the funding required to research and prove the viability of engineering concepts. In 2017, seven projects were awarded funding for the next four years totalling $40m[43]. This programme has built on the success of the TallWood Building Demonstration Initiative (TWBDI) with Brock Commons in Vancouver and Origine in Quebec[44], both thought of as the first tall timber projects. The Keith Drive and The Arbour projects, both in design by Fast & Epp (refer to section 3), are also benefiting from this NRCAN funding.

It is too early to know whether the NRCAN funding programme has been successful in encouraging the adoption of timber in tall buildings. However, it has brought mass timber to the forefront of the public's attention through the production of many showcase buildings like Brock Commons. What the programme emphasises so far is that innovation needs two key drivers: forward-thinking designers willing to challenge the norm, underpinned by a public body reinforcing this with commitment, either through funding or other acts of support such as legislation.

5.3 New Ventures and the Impact on Forestry

Alongside development in design and legislation, the economics of forestry cycles must improve to allow timber to compete with steel and concrete in tall buildings. The average Spruce tree is 80 years old before harvested for CLT[17] meaning the supply of timber may not meet an increase in short-term demand. New ventures involving younger, faster growing trees are developing to increase the financial viability of mass timber production[45].

PRG 320 states that any softwood species recognised by the American Lumber Standards Committee (ALSC) with a minimum specific gravity of 0.35 as published in the National Design Specification for Wood Construction can be used for CLT production. This includes Fir, Spruce, Larch, Cedar and Redwood which are all common species along the western region of America, which have not yet been utilised at scale. In essence, research has shown there is an opportunity to expand the capability of existing forest stock to support a growing demand for mass timber.

Although mass timber can be recycled into low grade products, like OSB, research is undergoing at Oregon State University into the re-use of timber from deconstructed stud-framed buildings in new mass timber products[46]. An early evaluation study has found that wood from deconstructed houses in Portland would meet sufficient stiffness parameters for effective CLT production to PRG 320. Although this circular procurement route is yet to be established at scale and requires further development, this could relieve the burden on existing forests whilst opening up new wood waste markets.

6. Sustainability Considerations of Mass Timber

Many countries around the world have brought in legislation to tackle the production of greenhouse gases (GHG) by targeting net zero carbon emissions by 2050 in line with the Paris Agreement[47]. Norway leads the way with a deadline of 2030. Notably absent from the list of countries taking legislative action is the USA, however the cities of Portland and San Francisco have made declarations aligned with the 2050 goal.

The predicted path to limiting global warming temperatures requires the net removal of CO_2 from the atmosphere[48]. The two main methods of Carbon Dioxide Removal (CDR) are either through a program of restoration of forests or development of bio-energy with carbon capture and storage (BECCS) technology. The current BECCS operational capacity is negligible and as such reforestation offers the only viable solution to remove CO_2 from the atmosphere. A surge in mass timber usage linked with global reforestation appears to be a potential way of achieving carbon emission targets. However, the carbon impact of mass timber is nuanced and its complexities will be explored in the following section.

6.1 Life-Cycle of Mass Timber

The production of mass timber enables the conversion of CO_2 into valuable products. Up to 50% of the dry weight of wood is carbon and there is up to 1.6 tonnes of carbon dioxide per cubic metre of wood depending on the species[49]. The British Columbia annual harvest is around 67 million m^3 of wood, equivalent to around 1 MT CO_2[50]. For context, this is equivalent to the emissions from the energy use of 8 million homes for the same year, which is nearly four times the number of private houses in British Columbia[51].

However the life-cycle of mass timber, and ultimately the total embodied carbon, depends on a number of factors such as:

- How much carbon the species of tree can absorb over its lifetime.
- How much carbon is emitted when it is turned into a mass timber product. This is addressed through modules A1-A3 of the Life

Cycle Assessment (LCA).

- How much carbon is emitted in the transportation and construction of the building. This is addressed through modules A4-A5.

- How the forest cut is managed and the long-term effect on the forest yield.

- The design life of the building.

- The end of life scenario of the building. This is covered by module C.

The embodied carbon output can vary significantly from positive to negative depending on how the sequestration potential of timber is treated. In order to utilise the sequestered value within embodied carbon calculations, designers must be able to justify:

1. The specification of timber is from a sustainable source such that the yield of timber is maintained or enhanced on an annual basis.

2. Design for the end-of-life scenario of the building, ensuring storage of the carbon in perpetuity.

To aid the first assumption, sustainable certification could be brought into legislation, potentially through existing schemes like the FSC or PEFC. Designers have a good level of control over the specification of sustainably-sourced timber.

Designing for reversibility of connections and re-use of components within current building structures would go some way to justifying the second assumption. This could be achieved by standardising sections and details, as has been done by the steel industry to the benefit of their procurement and accreditation processes. That said, although 90% of steel is recycled in the UK, only 6% is re-used[52]. More research must be carried out to ensure glued timber products like CLT can be used for biomass applications at end-of-life. For instance, the adhesives prescribed under PRG320 in North America cannot be incinerated without significant atmospheric VOC production. Designers have little control over what happens to the designed mass timber at end-of-life. As such this could be ignored in sequestration values for embodied carbon.

Overall in the author’s opinion, calculated embodied carbon figures should be presented in a binary form: with sequestration and ignoring sequestration, in order to present the assumptions of using timber in structural elements.

6.2 Changing Legislation and Tall Timber

Although national measures do exist, much of the change towards low-carbon policy is being driven by smaller bodies. Within British Columbia, changes have been made to the Energy STEP code which states that all new buildings should be net-zero by 2032[53], with many utilising Passivhaus principles of design.

Cities are also driving change through carbon reduction targets and policies, such as Vancouver which has called for a 40% reduction in embodied carbon by 2030 compared to 2018[54]. The intention is to monitor and regulate this through the mandatory reporting of embodied carbon figures as part of the building approval process. Other measures come in the form of the pilot schemes aiding the adoption of new design standards. An example of this is Canada's

Figure 22: CGI of Canada's Earth Tower, Vancouver.
Source: Courtesy Perkins and Will

Earth Tower, a new 40-storey Passivhaus mass timber building in design at the time of writing (refer to figure 22). The building is striving to meet the Canada Green Building Council (CaGBC) Net Zero Carbon Standard[55].

Material switching could have a large impact on achieving industry-led carbon targets, through removing the reliance on carbon-intensive materials like concrete and steel. The C40 report[56] suggests that a progressive target in stemming global warming temperatures to below 1.5°C by 2030 requires 75% of all residential and 50% of commercial buildings to be constructed from timber in order to successfully reduce consumption-based emissions. These figures would require a dramatic rebalancing of structural materials. The research is based on buildings up to 6 stories, when in theory this study suggests these proportions could be higher. On the other hand, it is proving difficult due to current fire safety regulations in the UK.

The majority of buildings designed today will be around in 2050[57] when net zero legislation is meant to have been achieved. It is therefore important to balance the needs for adaptability, to enable future changes of use and servicing, with the need to design in

Figure 23: CGI of the flat soffit of Keith Drive, allowing the flexibility of services distribution. Source: Fast & Epp

a more carbon neutral way now. This can be achieved by using design solutions such as flat soffits which do not overly compromise the lower embodied carbon solution, but which might enable future services adaptability. This is already being implemented in some mass timber projects such as Keith Drive and The Arbour buildings (figure 23).

Building tall inherently implies a densification of urban population but this must be weighed up against the potential social disadvantages of denser environments. For instance, does the creation of bespoke, high-value tall timber structures benefit the mass population? With growing calls for Environment Social Governance (ESG) development, engineers must ensure construction is carried out sustainably in tandem with the upgrading of infrastructure, and the increased accessibility to public institutions like education, healthcare, and affordable housing. The IStructE's commitment to the UN's Sustainable Development Goals are an important path for addressing this[58], as well as achieving future carbon targets.

7. Manufacturing and Procurement

This section will explore the current state and emerging trends in North America for the manufacturing of mass timber; it will also highlight how business and procurement models are evolving to support the industry.

7.1 Manufacturing

The use of mass timber is still in its infancy within North America. As well as a general lack of experience in how to contract and construct a mass timber building, there are also significant inefficiencies in the manufacturing of mass timber elements. An example of this is the production of lamstock: the lumber industry in the USA generally produces timber at 19% moisture content which

Figure 24: Finger-jointing machinery at Moelven glulam factory, Moelv, Norway

Figure 25: Glulam press at Moelven glulam factory, Norway

means that additional kiln-drying is required to take it to 12% for use within CLT[59]. Factories are currently not set up for this. In addition, lamstock is solely produced in two-inch multiples to suit the stud frame housing sector. This means that the US-produced CLT panel is deeper compared to European equivalents. In Europe, panel sections are optimised using different lamella thicknesses. Given mass timber production currently represents such a small proportion of timber produce for construction, efficiency is unlikely to improve in the near future.

7.2 Evolving Procurement Models and Market Disruption

In the USA, where most of the forest land is privately-owned, many large forestry companies are looking to disrupt the traditional models of building procurement. Their aim is to vertically integrate their processes: grow the wood needed, manufacture their own mass timber components and construct the buildings directly. This has created an oligopolistic market for mass timber supply within certain regions of North America where these companies have effective control of lamstock production and price.

Sensing this opportunity, there has recently been major investment in mass timber production within North America, which is seen as an emerging market. For instance there are only seven factories in North America at the time of writing producing CLT certified under PRG-320[59]. However, companies who traditionally focus on lumber production have begun constructing CLT factories (Kalesnikof, Element 5, Nordic as examples), with more in the pipeline. Major corporations are also partnering directly with these CLT producers to de-risk their upcoming developments. Recent news that Walmart has invested directly in a new CLT plant with Canadian-based Structurlam is an example of this[60].

Mass timber is also attracting interest from tech giants, traditionally based in Silicon Valley, California, who believe the construction and property sectors are ripe for disruption. One example of this is the Toronto Quayside development by Sidewalk Labs, a start-up formed under the Alphabet umbrella. In January 2020 they released plans for a proof-of-concept building designed from a ‘kit-of-parts’ assembly of mass timber components[15]. As referenced in section 3 the PMX building is 35 stories and uses a modular timber cassette floor system. Sidewalk Labs’ aspiration is to build their own factory and manufacture all timber systems needed to construct the development within Ontario[61].

Another example is Katerra, whose goal is to construct modular building components off-site using mass timber, enabled through advanced digital technology. Katerra were valued at $4bn in 2019 and recently constructed an $80m CLT factory in Washington[62].

Both Sidewalk Labs’ and Katerra’s predominant aim is to use design for manufacture and assembly (DfMA) techniques to meet the ambitious housing targets set in the major American and Canadian cities, whilst also hoping to increase affordability. Using mass timber within a systems-based procurement model can increase construction speeds, reduce waste and ultimately drive down project costs in the long-term by increasing efficiency.

Although this increased investment and innovation is welcome, there are some concerns with this shift for the North American construction sector. An ‘innovate or die’ culture could emerge, with mass timber acting as an agent for the wider disruption of construction and housing, potentially piggy-backing on the low carbon credentials of locally-sourced lumber. Large obstacles still remain within the market. These include a general deficiency in design and construction expertise of mass timber. Existing manufacturing infrastructure also requires significant adaptation to produce mass timber at a significant scale to meet demand.

8. Post-Monitoring of Tall Timber

To understand the true performance of tall timber buildings, post-monitoring measures are being implemented in ongoing research projects. The most notable example of this is on Brock Commons, where measures are being carried out in three ways: moisture content monitoring through the service life of the building; string-pot sensors to understand the axial shortening effects of the columns, and accelerometers to help verify the lateral acceleration performance from wind and seismic forces[11]. A similar approach is being undertaken on Mjøstårnet to understand the building's lateral performance, adding to data gathered from the Treet project, a 14-storey all-timber building in Bergen from the same team[16].

Initial results suggest that the flexural modulus of glulam elements is higher than predicted for both Brock Commons and Mjøstårnet. This is understandable given Eurocode 5 prescribes minimum moduli for design purposes. It is understood that the research by the University of British Columbia on in-service performance is to be published shortly.

The most prescient forms of post-monitoring include:

- Lateral acceleration data, especially concerning seismic scenarios, gained through the use of accelerometers. There is also a need to understand the long-term fatigue effects with height which can be measured through the use of strain gauges in connections.

- Moisture and relative humidity testing, especially due to seasonal changes, and the implications on shrinkage calculations. To this end, research is undergoing to embed sensors within the lamella of CLT panels on the newly constructed Peavy Hall at Oregon State University, with research funded by the TallWood Design Institute[63].

- Strain gauges to measure elastic moduli values and understand the effects of axial shortening.

The post-monitoring of buildings will help to define and refine current beliefs about the performance of tall timber structures as well as lead to better decisions on mass timber systems from construction to service life. This research is important to help codes evolve by 'closing the design loop' thereby allowing designers to verify material usage through in-service data.

8.1 The Effect on Insurance

The post-monitoring of mass timber structures is essential in developing designers' understanding of higher risk issues like durability and fire safety, whilst also mitigating common defects.

Recently the insurance industry has played a key role in unlocking major mass timber developments, as well as preventing them, especially within the UK where fire regulations appear much stricter in terms of use of timber compared to North America. Insurance companies typically price risk on the maximum expected loss and across the countries studied, mass timber projects are priced with a significant premium[64], mainly due to the enhanced fire risk. Data, procured through post-monitoring measures, on basic structural performance and durability is needed to test the belief that tall timber structures are safe and robust. With more precedence comes greater confidence. However, without this precedence, the long-term expectation remains uncertain and therefore risk remains high.

There is also a need to fully document testing and research analysis, and present findings to the insurance market. This is an important hurdle for the tall timber market to overcome in order to take a foothold in the construction industry. The recent Structural Timber Association guide, produced in collaboration with The Construction Insurance Risk Engineers Group, is useful in outlining the process towards compliance for timber buildings in the UK[65]. In comparison, the prescriptive nature of local building codes in North America (as described in section 4) has streamlined the regulatory approval process, and therefore reduced design risk of timber structures in those areas. In turn this should reduce insurance costs for mass timber projects in the near future.

9. Conclusions and Recommendations

The following conclusions and recommendations for using mass timber in tall buildings in the future can be drawn from this report:

- Current and future projects are proving that timber buildings can be built higher than engineers have historically designed. There is a gradual loosening of height limits in regulatory codes within North America and across parts of western Europe.

- Mass timber can be used in framed typologies. This is not just restricted to residential but there are now opportunities for office, commercial and industrial projects.

- Although ‘all-timber’ tall buildings can be designed, stiffness is an issue. The best use of mass timber is in combination with other materials and overall engineers need to use the right material in the right way based on structural properties.

- There are still concerns about tall timber that need to be addressed through further research. These include structural fire design, durability, seismic performance and effectiveness under lateral loading conditions.

- A greater engagement with contractors from Europe is needed to refine the manufacturing and construction aspects in developing markets such as the USA and Canada.

- Additional testing of compartmentalised mass timber in fire scenarios is required to better understand the risks of exposing timber.

- Mass timber can be utilised in collaboration with DfMA techniques and Passivhaus principles using advanced manufacturing capabilities. High-profile companies in North America are rapidly exploring this.

- From a carbon point of view, there needs to be a gradual switching of material from steel/concrete to timber. Research shows that there is enough timber to supply future projects but more must be done to make sustainable certification mandatory. In turn this would help combat climate change by enhancing forest stocks.

- Engineers must consider the future adaptability of spaces and services provision of mass timber buildings in order to aid the drive towards a low carbon society.

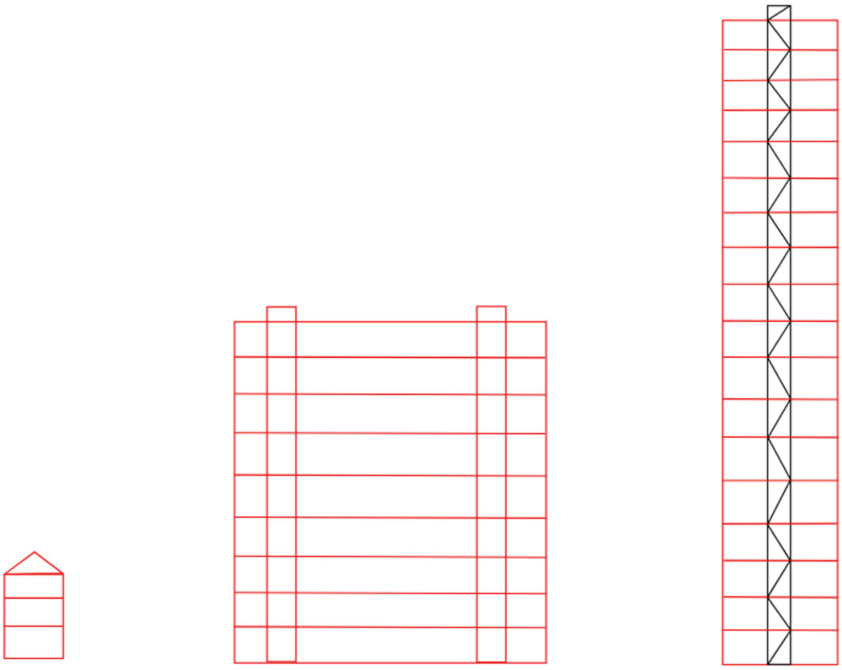
- The post-monitoring of mass timber structures is essential in understanding the real-time performance of buildings and help guide design parameters in the future.

- Public funding and regulatory support for tall timber buildings is catalysing change within North America and with precedence comes confidence. The emergence of these buildings should help the insurance industry adjust to new mass timber systems in time.

Returning to the original question posed in the introduction:

Is timber a viable alternative to concrete and steel framed buildings at scale?

In the author’s opinion, tall timber is likely to be a phenomenon that is short-lived. The recent projects, especially those of an ‘all-timber’ construction, can be viewed more as demonstrations of the capability of mass timber. There will always be limitations on its effectiveness at height and adequacy of its performance in fire



Small - 1-6 stories
Timber frame

Medium - 6-12 stories
Mass timber frame

Tall - >12 stories
Steel/concrete core in combination with mass timber elements

Figure 26: Recommendations for the pragmatic use of timber based on scale of building

scenarios of high-risk buildings. However, this does not denigrate the work of tall timber concepts in championing the wider use of wood in construction. In this regard, these tall timber projects have been very successful.

The greatest opportunity for mass timber should be in buildings of between 6-12 storeys (medium height – refer to figure 26) where it could take a greater share of the construction market traditionally dominated by concrete-framed buildings. Below six stories, softwood stud framing can be efficiently utilised; over 90% of housing in the USA is stud framing[66] and there are obvious reasons for this. Traditional timber framing offers the lowest embodied carbon, and usually cost, option compared to mass timber alternatives. Engineers must make the most of its capacity.

References

1. FPInnovations (2019). CLT handbook: cross-laminated timber
2. Population Division of the UN Department of Economic and Social Affairs (UN DESA) (2018). 2018 Revision of World Urbanization Prospects. Available at: www.population.un.org/wup/Publications/Files/WUP2018-Report.pdf. (Accessed: June 2020)
3. Gov.UK (2018). Available at: www.gov.uk/government/news/government-announces-new-housing-measures. (Accessed: June 2020)
4. Council of Tall Buildings and Urban Habitat (2018). Tall Timber: A Global Audit
5. Council of Tall Buildings and Urban Habitat (2019). Available at: www.ctbuh.org/news/mjostarnet-tallest-timber-building/. (Accessed: June 2020)
6. Discussions with KLH during research trip
7. Circular Ecology (2020). Available at: www.circularecology.com/embodied-carbon-footprint-database.html. (Accessed: June 2020)
8. Fast & Epp. Available at: www.fastepp.com/portfolio/2102-keith-drive. (Accessed: June 2020)
9. Fast P., Jackson R. (2018). The TallWood House at Brock Commons, Vancouver. The Structural Engineer
10. Timber Composite Technology. Available at: www.ticomtec.de/en/company/firmenprofil. (Accessed: June 2020)
11. WoodWorks (2018). Brock Commons Tall Wood House, A Case Study
12. Zimmerman R.B., McDonnell E. (2017). Framework - A tall re-centering mass timber building in the United States. Available at: www.db.nzsee.org.nz/2017/O5C.3_Zimmerman_&_McDonnell.pdf. (Accessed: June 2020)
13. Zhang X. et al (2018). High-capacity hold down for mass-timber buildings
14. Design Safe-CI (2018). Available at: www.designsafe-ci.org/community/news/2018/july/tall-wood-buildings/. (Accessed: June 2020)
15. Eckholm C. (2020). Available at: www.medium.com/sidewalk-talk/exploration-1-how-to-design-a-timber-building-that-can-reach-35-stories-1c68de983390. (Accessed: June 2020)
16. Ambrahamsen R. (2017). Mjøstårnet – Construction of an 81 m tall timber building
17. Waugh Thistleton Architects (2018). 100 Projects UK CLT
18. Trada (2013). WIS2/3-3 Flame-retardant treatments for timber

products.
19. HM Government (2019). The Building Regulations 2010: Approved Document B – Volume 1: Dwellings [Online]. (Accessed: June 2020)
20. Law A., Hadden R (2020). We need to talk about timber: fire safety design in tall buildings. The Structural Engineer
21. Hackitt J. (2018). Building a Safer Future: Independent Review of Building Regulations and Fire Safety: Final Report [Online]. (Accessed: June 2020)
22. Think Wood (2019). Mass timber stands tall
23. HM Government (2019). The Building Regulations 2010: Approved Document A –Structure [Online]. (Accessed: June 2020)
24. British Standards Institution (2004). BS EN 1995-2:2004. Eurocode 5: Design of timber structures - Part 1-2: General - Structural fire design
25. Wiesner et al. (2018). Requirements for engineered wood products and their influence on the structural fire performance
26. Structural Timber Association (2015): Timber engineering notebook series. No. 13: Cross-laminated timber construction – structural design
27. ANSI/APA (2018). PRG320 – Standard for Performance-Rated CLT
28. Deeny et al. (2018). Fire safety design in modern timber buildings. The Structural Engineer
29. American Wood Council (2016). National Design Specification for Wood Construction.
30. Canadian Standards Association (2014). O86-14 Engineering design in wood.
31. Wiesner F., Bisby L (2018). The Structural Capacity of Laminated Timber Compression Elements in Fire: A Meta-Analysis
32. Wiesner et al (2019). Structural capacity in fire of laminated timber elements in compartments with exposed timber surfaces
33. Woodworks (2019). Tall Wood Buildings in the 2021 IBC Up to 18 Stories of Mass Timber
34. National Fire Protection Association (2018). Fire Safety Challenges of Tall Wood Buildings – Phase 2: Task 5 – Experimental Study of Delamination of Cross Laminated Timber (CLT) in Fire
35. Law A., Hadden R., Bisby L (2019). Comment & reply – The Tall Wood House at Brock Commons, Vancouver. The Structural Engineer
36. Natural Resources of Canada. Available at: www.nrcan.gc.ca/our-natural-resources/forests-forestry/sustainable-forest-management/forest-land-ownership/17495. (Accessed: June 2020)

37. Forest Products Association of Canada. Available at: www.fpac.ca/canadas-forests-near-zero-deforestation/. (Accessed: June 2020)
38. US Endowment for Forestry and Communities. Available at: www.arcgis.com/apps/Cascade/index.html?appid=d80a4ffed7e044219bbd973a77bea8e6. (Accessed: June 2020)
39. Global Forest Watch. Available at: www.globalforestwatch.org/dashboards/country/USA. (Accessed: June 2020)
40. International Family Forestry Alliance. Available at: www.familyforestry.net/article.cfm?id=6222. (Accessed: June 2020)
41. Natural Resources of Canada. Available at: www.nrcan.gc.ca/our-natural-resources/forests-forestry/state-canadas-forests-report/forest-industry-contribute/16517. (Accessed: June 2020)
42. Dezeen (2020). Available at: www.dezeen.com/2020/02/12/france-public-buildings-sustainability-law-50-per-cent-wood/. (Accessed: June 2020)
43. Natural Resources of Canada. Available at: www.nrcan.gc.ca/science-data/funding-partnerships/funding-opportunities/forest-sector-funding-programs/green-construction-through-wood-gcwood-program/20046. (Accessed: June 2020)
44. Natural Resources of Canada. Available at: www.nrcan.gc.ca/our-natural-resources/forests-forestry/forest-industry-trade/forest-products-applications/greening-our-built-environments-wood/16834. (Accessed: June 2020)
45. TallWood Design Institute. Available at: www.tallwoodinstitute.org/performance-clt-modular-building-utilizing-low-value-pine-lumber-logs-harvested-pacific-nw-forest. (Accessed: June 2020)
46. Arbaleaz et al. (2019). Salvaged lumber for structural mass timber panels: manufacturing and testing
47. United Nations Framework Convention on Climate Change. Available at: www.unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement. (Accessed: June 2020)
48. Intergovernmental Panel on Climate Change (2018). Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development
49. Woodworks. Available at: www.woodworks.org/why-wood/carbon-footprint/. (Accessed: June 2020)
50. Natural Resources of Canada. Available at: www.nrcan.gc.ca/statsprofile. (Accessed: June 2020)
51. United States Environmental Protection Agency. Available at: www.epa.gov/energy/greenhouse-gas-equivalencies-calculator. (Accessed: June 2020)
52. Steel Construction Institute (SCI). www.steelconstruction.info/The_recycling_and_reuse_survey. (Accessed: June 2020)
53. Energy Step Code. www.energystepcode.ca. (Accessed: June 2020)

54. City of Vancouver. Available at: www.vancouver.ca/green-vancouver/climate-emergency-response.aspx. (Accessed: June 2020)
55. Perkins & Will. Available at: www.perkinswill.com/project/canadas-earth-tower/. (Accessed: June 2020)
56. C40 Cities, Arup, University of Leeds (2019). The future of urban consumption in a 1.5°C world
57. World Green Building Council (2019). Annual Report 2018/2019
58. Arnold W (2019). A Targeted Approach to the UN Sustainable Development Goals
59. The Beck Group (2018). Mass Timber Market Analysis
60. Woodworking Network. Available at: www.woodworkingnetwork.com/news/woodworking-industry-news/walmart-invests-mass-timber-maker-structurlam-paves-way-90-million. (Accessed: June 2020)
61. Jaffe E (2019). Available at: www.medium.com/sidewalk-talk/5-minute-explainer-how-factory-construction-can-help-housing-affordability-f16d0b5cbe03. (Accessed: June 2020)
62. Construction Dive. Available at: www.constructiondive.com/news/katerras-valuation-could-hit-4b-following-a-rumored-700m-softbank-fundin/546274/. (Accessed: June 2020)
63. Tall Wood Institute. Available at: www.tallwoodinstitute.org/living-lab-peavy-hall-structural-health-performance-mass-timber-buildings. (Accessed: June 2020)
64. Fast & Epp (2017). Mass Timber – a developer’s guide
65. Structural Timber Association (2017). 16 Steps to Fire Safety
66. United States Census Bureau. Available at: www.census.gov/construction/chars/highlights.html. (Accessed: June 2020)