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RIBA President's Awards for Research 2016: Winner, Design and Technical Category

Super Tall Timber: design research for the next generation of natural structure

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This research project aspires to make truly tall timber buildings a reality. Through a combination of theoretical design and physical testing this research demonstrates the viability of timber buildings at much greater heights than has previously been possible. By pushing the limits of theoretical designs into the realms of the supertall, sometimes beyond that which is feasible using current materials and construction technologies, this research also sets out the requirements for the next generation of engineered plant-based materials.

The research is a collaboration between academics, practising architects and practising structural engineers. The approach is research through design, and design through research. Timber towers are designed well beyond existing heights, and analysed to understand how they stand up and which areas are most critical for further research. By bringing highly regarded architectural and structural designers together with the research capabilities of a leading university, this project creates a precedent-setting model for interdisciplinary engagement within and between the design and research communities. By coupling exemplary design in timber with a university's research capacity, the project represents a real opportunity for transformational change in the design of tall timber buildings. Essential details and connections are determined and 'unknowns' with respect to material and structural performance are identified. A programme of testing to investigate these unknowns and validate the design approaches is carried out at the university. Outcomes of the test programme and new insights are fed back into the design process.

The results show that tall timber towers are feasible, with substantial but surmountable questions outstanding. By providing thought provoking yet credible solutions for the design of tall timber buildings and exceeding current limits, the project can inspire the design community to think beyond the status quo and embrace the possibilities offered by timber construction.

Super Tall Timber

The tallest tree in the world is "Hyperion", a 115 m coastal redwood. The tallest modern wooden building in the world reaches less than half this height. Why should this be?

This research project, and the resulting design for Oakwood Tower (Fig. 1), is in part a response to this simple question. Conceived of as an opportunity to bring researchers and designers together in order to reimagine what is possible with wood as a structural material, the project was able to overcome many of the traditional barriers to innovation in timber building design. In achieving the 300 m height required for classification as 'supertall', the concept design has set a new standard for structural timber and demonstrates that there is nothing about timber as a material that prevents its use in a tower that would truly place Hyperion in the shade.

The tallest timber building in the world is Treet, a 14 storey, 48 m high residential building in Bergen, Norway¹ (Fig. 2). Completed in 2015, it follows a trend in increasing heights in timber buildings from Murray Grove (9 storeys, 30 m) in London,² arguably the first modern "tall" timber building, and Forté (10 storeys, 32 m), in Melbourne. Buildings in excess of five storeys in timber are no longer unusual. Buildings up to 10 storeys tend to use cross-laminated timber (CLT) as the primary structure; above this height, platform construction techniques and perpendicular-to-grain crushing are difficult to overcome. Treet on the other hand uses large-scale glued-laminated timber trusses.³ Further incremental advances in timber buildings will continue, as evidenced by both proposed buildings and those under construction.⁴ While some conceptual designs for taller timber

buildings have been proposed,^{5,6} the current crop of tall timber buildings are of the same scale as the world's first modern skyscraper, William Le Baron Jenney's Home Insurance Building, built in 1884 in Chicago to an original height of 42m⁷. Less than 50 years later, the 102 storey Empire State Building was completed in New York, reaching a height of 381m.⁸ Research suggests that we may be due for a similar step-change in the scale of timber construction,⁹ based on architectural, engineering, and research expertise in contemporary wood construction.

Research-led design and design-led research

In order to address the challenge of designing the world's first supertall (300m+) timber building, a new approach was required. While engineered timber products have become increasingly common in low-rise construction, their use in tall and supertall building is not yet well understood. Furthermore, it was not clear that there were any practicing designers with experience of tall timber building design at anything approaching 300 m tall. For this reason, the Super Tall Timber research programme was established; bringing teams of leading designers together with the research capabilities of a leading university, in order to explore the possibilities afforded by engineered timber for the construction of tall and supertall buildings. As part of this research programme PLP Architecture and Smith and Wallwork engineers joined the Centre for Natural Material Innovation at the University of Cambridge to collaborate on the first of these projects: the Oakwood Tower.



Figure 1. Oakwood tower in context. Reproduced with permission, image copyright PLP Architecture.

Design considerations

At the first charrette, location, height, form and programme were all debated. London was an obvious choice as a dynamic and growing city, and an ambitious 300 m height to warrant the supertall designation was agreed. By avoiding overly prescriptive building regulations and encouraging performance based design, the UK provides a benign regulatory environment for exploring the potential of new building materials, and London in particular is home to a number of the tallest and largest modern

timber buildings in the world.¹⁰ The team chose to site the building, somewhat provocatively, within London's iconic Barbican complex (Fig. 3).

The Barbican was designed in the middle of the last century to bring residential living into the city of London. The proposed tower sits within the Barbican as a way to imagine what the future of construction could look like in the 21st century. The position is compliant with London's protected viewing corridors and the site, owned by the City of London, provided an ideal opportunity to generate

Figure 2. The 14 storey Treet building in Bergen, Norway.



discussion with the authorities (Fig. 4). Set within the brutalist concrete development the Oakwood Tower proposal represents an opportunity to explore new avenues for design, construction and living.

Following the initial phase of design, the Oakwood Tower proposal was presented to then Mayor of London, Boris Johnson. The reaction to the proposal from the Mayor, the public and developers alike, was overwhelmingly positive; indicating that there is a very real appetite for tall timber buildings in an urban context. This provides further support for the

contention that it is only a matter of time until the first truly tall timber skyscraper is built.

Timber as an architectural material for supertall buildings

A strong driver for the increasing use of timber in the built environment is its potential to moderate the relationship between people and their urban surroundings. The world's urban population is growing, and one of the drivers of the Oakwood Tower was an aspiration by the designers to improve wellbeing in an urban context. Timber buildings are thought to have the potential architecturally to create a more pleasing, relaxed, sociable and creative urban experience. Oakwood Tower is, in part, an exploration of this idea and an opportunity to consider the potential of timber and other natural materials as a medium for transforming the city.

While some of the most iconic tall buildings are expressive of the structural material from which they are constructed – the Eiffel Tower in Paris, the John Hancock Center in Chicago, the brutalist Barbican towers in London – this is generally not the case. There appears to be a particular reluctance to expose structure in the building interior, where the architecture, more often than not, seeks to conceal rather than reveal the structural materiality.

Regardless of the rights and wrongs of this trend with respect to steel and concrete buildings, it is clear that in the case of timber there is both an opportunity and a benefit to revealing the structural material. It is well recognised anecdotally that people respond in a positive way to exposed wood. While there is no direct evidence that



Figures 3, 4. The notional site for the Oakwood Tower - London's Barbican. Reproduced with permission, image copyright PLP Architecture.

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Table 1. Preliminary timber specification.

Element	Material	Grade	Service class	Visual grade	Fire ¹
Columns	Softwood glulam	GL24h	1	visual	120 min
Bracing	Softwood glulam	GL24h	1	visual	120 min
Wall elements	Softwood CLT	C24	1	visual	120 min

¹Assumption for initial design purposes.

people distinguish between structural and non-structural wood in this regard, it is hard not to feel that exposure to the working material is rather more interesting, and more authentic, than exposure to purely decorative timber finishes.

Timber as a structural material for supertall buildings

As a structural material, timber has excellent specific strength and stiffness. This means that when the strength and stiffness are compared to the mass of material used, timber performs similarly to steel and far better than concrete. Concrete buildings for example have a typical bulk density (an approximate measure determined by dividing a building's mass by its gross volume) of approximately 300 kg/m³, while steel buildings, which usually have concrete floors, typically have a mass of about 160 kg/m³.¹¹ In contrast, the Oakwood Tower has a mass of 125 kg/m³. While this reduction in building mass presents new challenges with regard to uplift forces and responses to wind or seismic excitation, the material savings are considerable and the opportunities to reduce foundations or reuse existing foundations are significant.

Unlike most conventional structural materials, timber is highly anisotropic. While timber's specific strength and stiffness in the parallel-to-grain direction are excellent, its strength and stiffness perpendicular-to-grain are an order of magnitude less. This means that while large timber elements may carry high axial loads, the structural systems in which these elements are arranged must be thoughtfully designed and detailed in order to transfer loads at connections. Unlike steel or concrete, it is often the strength or stiffness of connections that governs the behaviour of timber structures.¹² For a tall building, the effect of even very small movements in connections at the lower levels can lead to lateral displacements at the top of the building several times larger than those predicted by a simple elastic deflection prediction.

The primary material for the tower is C24 softwood which was chosen for its wide availability in sustainably managed forests throughout central and northern Europe. The timber is as an engineered timber in glulam and CLT form (Table 1). These engineered timber materials take advantage of homogenisation to reduce the inherent variability in the raw timber material. Counterintuitively, the more variable the raw graded timber, the greater

the homogenisation benefit.¹³ This has interesting implications for the enhanced utilisation of native UK softwood species which tend to produce weaker raw timber than other northern European countries, due to the warmer climate of the UK.

Influence of timber on supertall building form

A key objective of the Super Tall Timber research programme is to explore new design potentials with timber buildings, rather than simply copying the familiar forms of conventional construction in steel and concrete.¹⁴ The research is driven by the recognition that the transition towards the widespread use of timber and other natural materials in construction has the potential to drive positive changes in urban environments and building aesthetics, as well as innovation in building structural and environmental technologies. In particular timber is seen as a powerful medium for addressing the challenge of densifying cities in a manner that respects both the environment and the city's inhabitants. A fundamental premise of the research is that timber and other natural materials are vastly underused and their potential benefits are largely understated. However, there is no such thing as a perfect material; alongside the potential benefits, timber presented a number of challenges for the Oakwood Tower design.

Tall building design principles were reviewed and preliminary design heuristics indicated that, given the available footprint, at 300 m the structural design would be led by lateral stability systems. As such, tower form and orientation would play a key role in defining wind loads and providing opportunities for bracing systems. Bracing systems

considered included tubes, diagrid and mega-truss. These followed the general principles of structural systems, somewhat independent of material, but were undeniably influenced by more conventional construction in steel and concrete. Time was spent challenging the concept that timber should lead to a different structural solution that would embrace the nature of the material and its potential for off-site manufacture. The lightweight nature of timber focused the design effort on providing a stability system that would place the bracing on the building façade with the aim to channel as much of the weight of the tower in to the façade and bracing systems. This would help reduce the potential for load reversal in structural elements and connections under wind load. The idea of a lightweight tower proportioned to resist wind overturning purely through effective use of its own deadweight was also inviting.

As buildings get taller, the overturning moment at the base increases by a power of two, and the bending deflection at the top of the building increases by a power of four. Shear deflections can increase total displacements at the top of the building by even greater amounts. This means that supertall building design is often governed by the design of the lateral load resisting system. It is generally desirable for a building to be capable of resisting overturning under the strongest lateral loads due to its self-weight alone, and for it to be capable of resisting normal service loads without undergoing load reversal. Since supertall buildings are usually rather slender – typically having slenderness ratios greater than seven – they are geometrically disadvantaged in resisting overturning

moments. In order to mitigate this fundamental geometrical disadvantage, it is important to direct the vertical loads in the building into the lateral load resisting system and to position the lateral load resisting system as close to the perimeter of the building as possible. The reduced mass of a timber building, compared to a conventional steel or concrete building, means that the permanent vertical loads that can be relied upon to resist overturning are commensurately reduced. Directing self-weight effectively to a perimeter lateral load resisting system is particularly important. This encourages the adoption of a soft core in order to avoid diverting load from the perimeter load resisting system and means that the location of the core is no longer constrained by structural considerations. This allows flexibility in the plan arrangement and encourages the consideration of innovative vertical transportation solutions. For the Oakwood Tower the core is located 'externally', in the natural rebate that forms between two of the buttressing sub-towers (Fig. 5).

For the Oakwood Tower, the excellent parallel-to-grain properties of timber suggested that linear rather than planar elements be used as the principal vertical and lateral load paths. Similarly, the need to direct load to a perimeter lateral load resisting system naturally led to a design that sought to maximise clear spans across the main floorplate, transferring load almost entirely to the perimeter mega-truss system that characterises the building's architectural and structural expression. Providing sub-towers that act to buttress the central tower increases the building depth available to resist overturning at the critical lower levels while

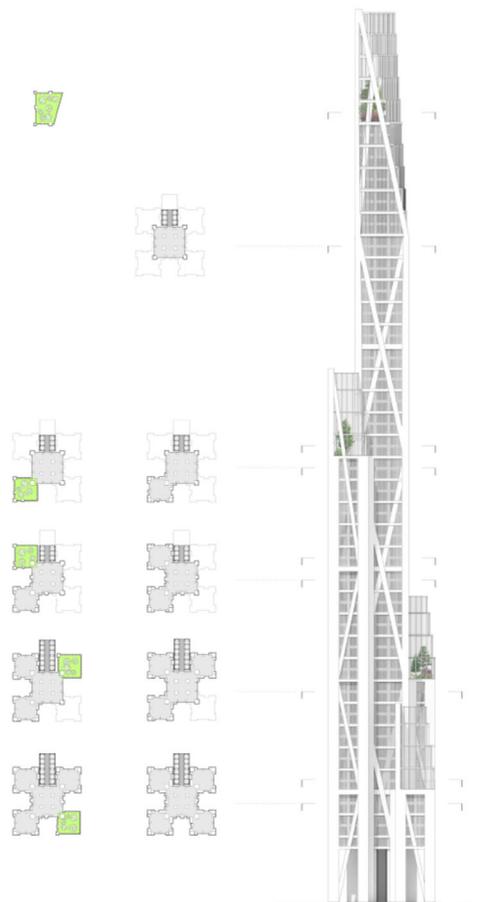
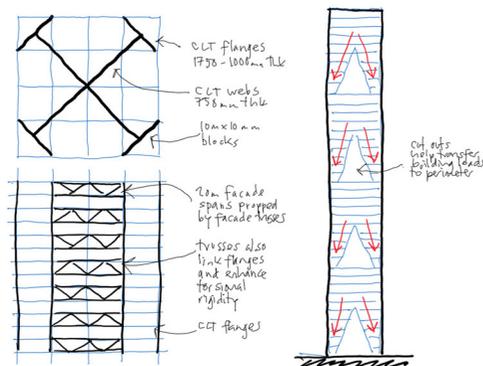


Figure 5. Floor plans at various levels highlighting sky gardens and core. Reproduced with permission, image copyright PLP Architecture.

providing a lightness of presence that belies the tower's great height. The spiral stepping of the sub-tower heights further lightens the composition architecturally, while providing a variable wind profile that is designed to improve the structural

Figure 6. Crossed mega I-beam. Reproduced with permission, image copyright Smith and Wallwork.



dynamics of the tower. The siting of the building in London means that wind is the governing lateral load case and seismic design is not required.

Building elements

The mega-columns and mega-bracing elements that make up the buttressed mega-truss structure are designed using glued-laminated timber at an extraordinary scale. Columns in excess of two metres square are required at the lower levels, although similarly sized columns would be required in concrete. Glued-laminated softwood timber was chosen for the main structural elements both because of the availability of the material – Oakwood Tower would use some 65 000 m³ of structural timber – and because of its favourable specific strength and stiffness in comparison with steel. The huge timber members are protected from the vagaries of the British weather by the building façade, allowing the structural elements to be designed to higher stresses and allowing the

occupants to interact with the working material that characterises the building's expression.

The great size and spacing of the mega-truss elements also plays a key role in the fire strategy of the building. Under fire conditions, the outer surface of thick timber elements begins to char, forming a protective layer insulating the working timber underneath. The key structural timber elements are thus expected to maintain their structural integrity in the presence of a serious and extended fire, even without other forms of protection. Active fire-suppression systems would also be required in a building of this height, regardless of structural material. While further fire engineering of the Oakwood Tower concept is ongoing, the initial indications are that the structural strategy adopted provides a sound basis for further design.

Structural Solutions Investigated

Once the approximate relative contributions of the parameters affecting the design were understood, a structural analysis was carried out. The first phase of this structural analysis was restricted to a static analysis focussing on lateral stability systems. Sway at the top of the building was limited to 600 mm (height/500). Based on experience of similarly sited tall buildings, a static wind load equivalent to 1.5kN/m² was taken for the preliminary analysis. Although the design developed in the direction of a truss solution, two structural concepts were initially investigated – a crossed mega I-beam and a buttressed mega-truss.

Crossed mega I-beam

Although ultimately difficult to reconcile with the architectural aspirations for the building, the I-beam proposal (Fig. 6) challenges past precedent and takes advantage of the panelised nature of cross laminated timber. A cruciform shear wall arrangement forms a pair of mutually orthogonal and extremely large I-beams working as vertical cantilevers. On plan, these 40 m deep I-beams create a tower footprint of approximately 40 m by 40 m. At 85 floors a 300 m extruded tower of this type provides some 100,000m² gross floor area. The flanges of the I-beams are linked on the perimeter by storey height trusses that help to support the large slab edge spans and also provide additional stiffening under whole building torsional effects. Large internal web cut-outs are provided over the height of the building to channel vertical loads to the perimeter of the building and also to help alleviate wind loading.

A 3D finite element model of the tower was developed with gravity and wind loading applied (Fig. 7). Timber thicknesses were adjusted until satisfactory wind load sway was achieved (less than 600 mm) and working stresses under gravity and wind loads were below 7N/mm². A total of 65,000m³ of timber was used in the 3D model, equivalent to a timber usage of 0.65m³/m². The 3D model did not include all structural elements so it could be expected that detailed design would see timber usage of between 0.65–0.75m³/m² for the 300 m tower. Timber elements up to 1.75 m thick (I-beam flanges) and a minimum of 0.75 m thick (I-beam webs) were used in the analysis. Such thicknesses of timber are not yet available in cross

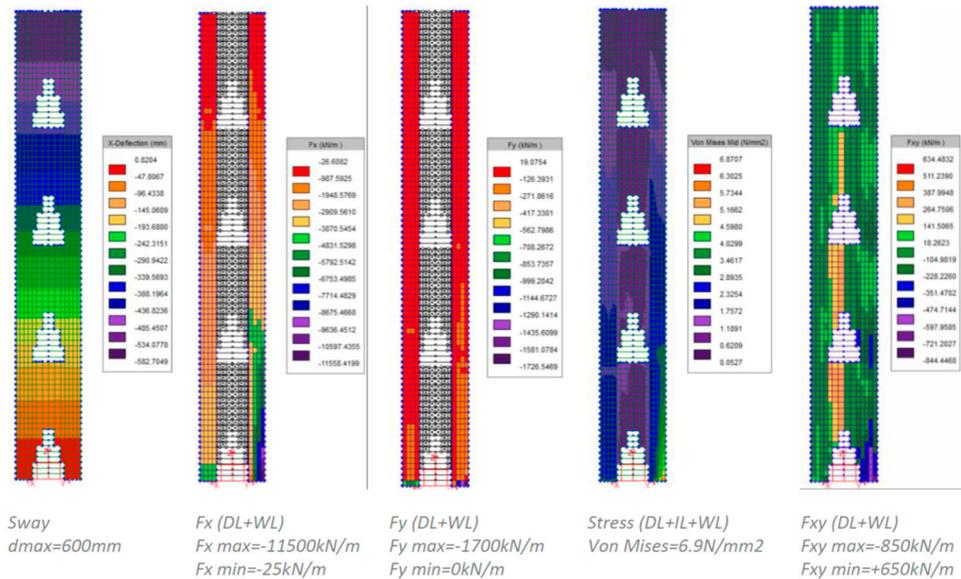
laminated timber and new methods of fabrication would need to be investigated to realise a solution of this type.

The 3D structural model highlighted that the I-beam web cut-outs performed as intended and channelled the gravity and wind loads to the perimeter of the tower and in to the I-beam flanges. The intention to eliminate load reversal from the timber under dead and wind load was successful using this approach. This would make the detailing of site connections a less onerous task and reduce joint movements in certain joint types

Buttressed mega-truss

The mega-truss proposal recognises that the orthotropic nature of timber, which means that it is very much stronger in the parallel-to-grain direction, makes it particularly well suited to the use in linear rather than planar structural elements. The mega-truss approach also takes advantage of the fact that timber has comparable specific strength and stiffness to steel, in the parallel-to-grain direction.¹⁵ This means that for a similar mass of structural material a timber mega-truss may provide similar performance to a steel mega-truss. This hypothesis was adopted previously in relation to the design of the 14 storey timber mega-truss Treet building in Norway.¹⁶ Subsequent analysis of the completed building has suggested that this may be correct.¹⁷ A 20 m by 20 m central tower rises 300 m and is buttressed by four corner towers of varying heights (65 m, 125 m, 190 m and 250 m) (Fig. 8). These 15 m by 15 m buttressing towers overlap the central tower and form a 40 m by 40 m tower

Figure 7. 3D finite element model for the crossed I-beam structural solution. Reproduced with permission, image copyright Smith and Wallwork.



footprint at ground level. At 85 floors a 300 m tower provides some 90,000m² gross floor area.

The multiple step buttressed mega-truss approach helps optimise wind loading and orientation would be informed by considerations including the predominant wind direction and wind tunnel testing. The bracing of the trusses is also arranged to channel gravity and wind loads to the perimeter of the building. This reduces the potential for load reversal in timber elements. A 3D finite element model of the tower was developed with gravity and wind loading applied (Fig. 9). Timber sizes were adjusted through successive iterations of analysis until satisfactory wind load sway was achieved (less

than 600 mm, i.e. height/500) and working stresses under gravity and wind loads were below 9 MPa. A total of 60,000m³ of timber was used in the 3d model, equivalent to a timber usage of 0.65m³/m². The 3D model did not include all structural elements so it could be expected that detailed design would see timber usage of between 0.65–0.75m³/m² for the 300 m tower. Timber CLT elements up to 1.75 m thick and glulam columns up to 2.5 m by 2.5 m were used in the analysis. As for the previously described proposal, these timber elements are larger than those used in any known buildings to date and this highlights both the fabrication challenge and the need for experimental investigations

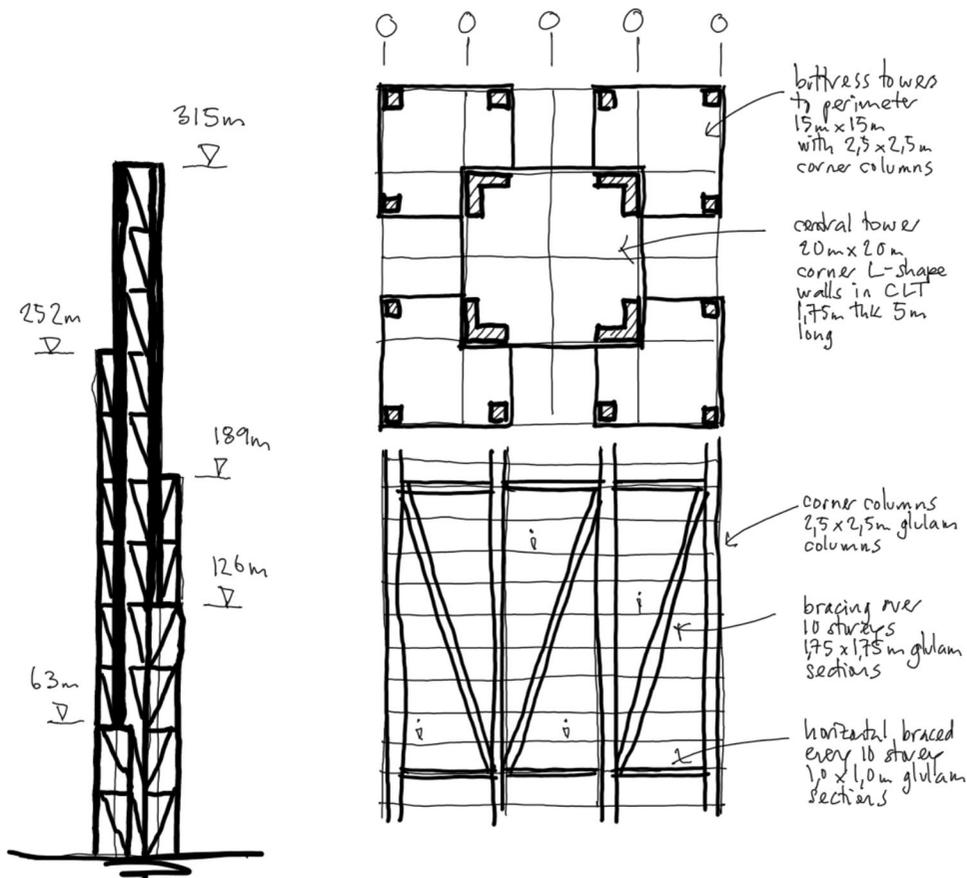


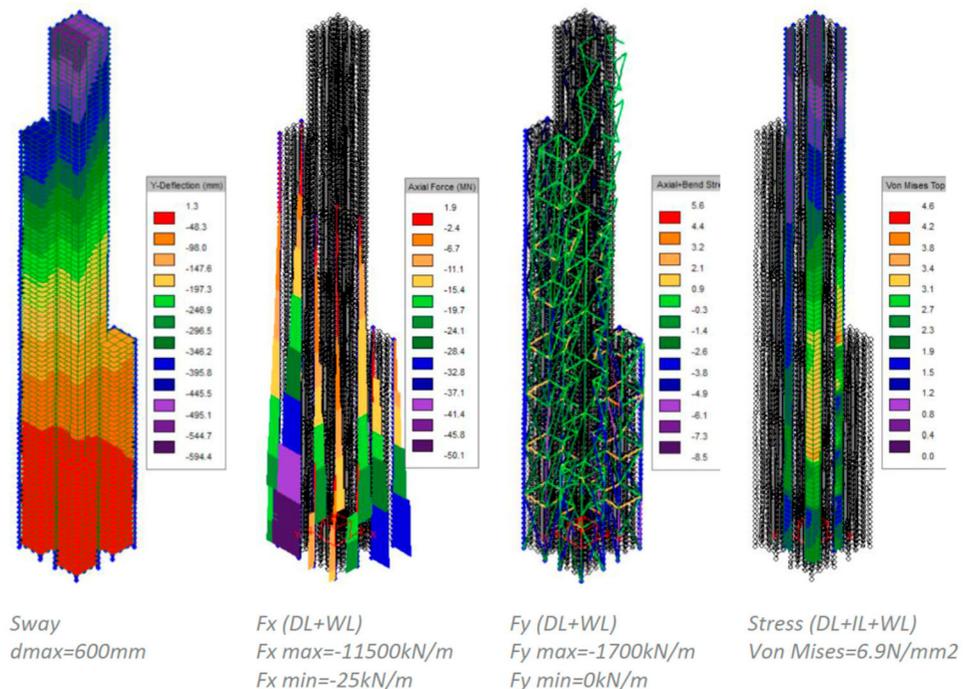
Figure 8. Butressed mega-truss. Reproduced with permission, image copyright Smith and Wallwork.

into the behaviour of elements at this mega-scale. A lab study into the effects of size on timber column behaviour is ongoing and is a direct result of this research project.

The 3D structural model highlighted that the trussing performed as intended, and effectively

channelled gravity and wind loads to the perimeter of the tower and in to the perimeter columns. The intention to eliminate load reversal from the timber under dead and wind load was successful in almost all areas of the structure using this approach. The maximum compression loads under wind load

Figure 9. 3D finite element model for the buttressed mega-truss structural solution. Reproduced with permission, image copyright Smith and Wallwork.



and dead load of 50MN compared to maximum tension loads of 2MN. It is expected that further refinement to the structural design would make it possible to completely eliminate load reversal under service loads. This would make the detailing of site connections a less critical area of design.

The connection nodes generated by the mega-truss approach present some interesting challenges given the anisotropic nature of timber. Steel node points would provide a well understood and somewhat 'conventional' solution. Alternatively a

more innovative reinforced timber node could be the subject of further development (Fig. 10). Between node points mega-truss elements are effectively unbraced. While the core of the building is designed to be 'soft' in the sense that it does not provide primary lateral stability to the building, its CLT design allows it to act locally as a vertical beam providing a stiff connection to floors between nodes.

As is the case for the preliminary design of any tall, slender building is possible that further analysis will

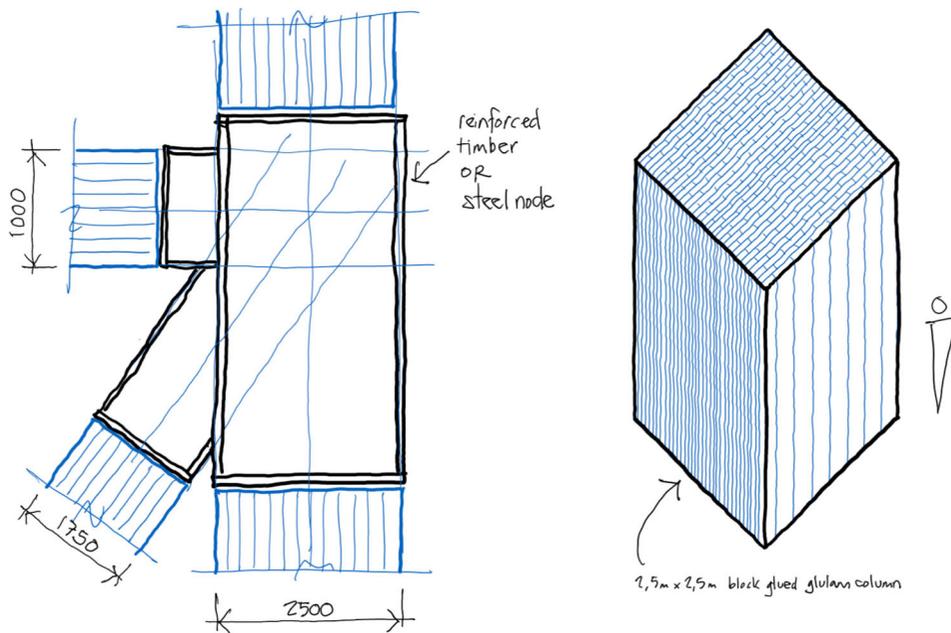


Figure 10. 'Nodes' connecting truss elements. Reproduced with permission, image copyright Smith and Wallwork.

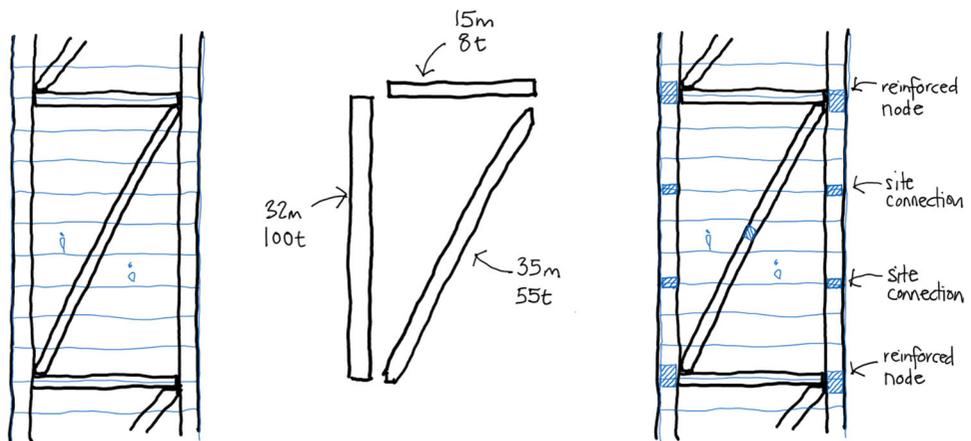
indicate that specialist damping technologies will be required to enhance the vibration performance of the tower when subject to lateral excitation from the wind. However, by achieving compliance with a relatively onerous static deflection limit for the preliminary design, there is no particular reason to believe that the building should be considerably more prone to dynamic excitation than a comparable steel design.

Timber Structural Detailing

Both tower proposals share a number of common themes in their detailing. All of the timber columns

and walls run continuously throughout the height of the building, eliminating the cross-grain floor plate crushing that limits the height of buildings using a conventional platform construction joint. Timber connections (site connections) for all vertical elements would be close tolerance butt joints that utilise non-slip glued-in rods. Glued-in rods would be required to transfer any tensile forces that develop in the structure due wind loading or for robustness in the case of an accidental design scenario. All connections would be required to maintain design for a suitable duration in the case of fire event. In order to reduce the weight of the

Figure 11. Connecting mega-elements. Reproduced with permission, image copyright Smith and Wallwork.



tower and eliminate wet trades from the build process, with the design incorporates a floating timber floor that helps provide acoustic separation between floors. All timber is contained within the building envelope and as such no preservative treatment is required. It is intended that much of the timber would form part of the internal finish of the building and as such is designed for inherent fire resistance through charring. Visually exposed timber may require a spread-of-flame treatment to the surface. As a result of this project, innovative approaches to improve the performance of timber in fire are being explored by the authors in collaboration with academic and industrial collaborators.

Construction Logistics

Building in London provides some logistics challenges that timber is well suited to help

overcome. It is possible to deliver approximately 40m³ of timber components with each delivery lorry, meaning that construction traffic is reduced. This represents a significant environmental, logistical and safety benefit in the case of a constrained urban site. It has been suggested that a concrete structure would typically require five times the number of lorry deliveries during construction that a timber structure would require.

Building with timber is quick and quiet when compared with steel and concrete construction. While the speed with which timber can be constructed on site is untested for the supertall building scenario, the rate of installation is likely to be restricted by crane hook time availability rather than speed of delivery to site. A properly developed fabrication, transport and crange strategy is thus likely to be critical if full advantage of the potential construction benefits of engineered timber construction is to be taken.

The mega-truss option uses some extremely large timber sections that will require interrogation of gluing techniques and lamella lay-up. Ideally the mega-truss elements would run as complete fabricated elements from node point to node point. However, at up to 35 m in length and weights of 100t this would not be possible. Larger elements would need to be assembled in situ, introducing additional site connections between truss nodes (Fig. 11). The possibilities of carpentry joints on a mega-scale are being explored for forming site connections in elements of this type. This mega-carpentry approach presents a number of exciting possibilities which the authors are presently exploring.

Future Work

This work represents the first phase in an ongoing research programme involving, at present, four design 'teams' in Europe and North America. The next phase of research is the physical testing of elements and connection details, the results of which will be fed back into the design process (Fig. 12).

An important development in the research programme, partly as a result of the response to the Oakwood Tower by the public and policy makers, has been the engagement of the fire engineering community. The authors are currently in discussions with both academic and practicing fire engineers, about engaging fire engineering expertise in the design team from the earliest stages. From the work carried out to date on the Oakwood Tower and other projects, a need for further research and



Figure 12. Physical testing of large timber components at the University of Cambridge

development in a number of areas has been identified:

- The structural behaviour of 'mega-' laminated timber elements that substantially exceed the sizes for which there is existing test data available. Separating the likely detrimental effect of size, from the likely beneficial effect of homogenisation in these large built-up elements will provide a particular challenge and the authors are devising a specific research programme to address this question.

- The possibility of mega-carpentry and the factors that may influence behaviour and performance of such joints. An experimental study of the capacity of carpentered joints at conventional- and, insofar as possible, mega-scale is being developed by the authors.
- While the structural performance of timber in fire conditions is relatively well understood, other considerations such as the surface spread of flame and the contribution of the structural material to the fire load, require further investigation. The potential of new and existing technologies to enhance the properties of timber in the presence of fire are similarly an area for further research and development.
- It has been identified that logistical considerations are key to exploiting many of the construction advantages of timber. As a Norwegian CLT and glulam producer and contractor explained rather bluntly to the second author, "if the hook isn't moving, I'm not making money". Proper integration of logistics and construction sequencing requires contractor input at the design stage and the authors are engaging with a leading international contractor for this purpose.
- Open floor plates maximising clear spans are beneficial in directing gravity load to the building perimeter and hence into the lateral load resisting system. This arrangement is also commercially desirable. However, the dynamic behaviour of long-span timber floor systems in response to footfall induced vibrations remains an area for further research and development. Conversely there is a considerable benefit to the use of

timber floor system; in that exposure of the timber structure may be architecturally desirable. This may obviate the requirement for suspended ceilings and provide a greater feeling of height, even where the structure may be slightly deeper than is conventional.

This research has provided a clear demonstration of the feasibility of timber buildings up into the super-tall height range. Physical testing, in conjunction with further evidence based design development, is being carried out by the authors in order to demonstrate the viability and reliability of such buildings. By contemplating the use of timber at heights far beyond those previously thought possible, this research opens up a new space for the architectural design of tall buildings, and seeks to inspire architects and engineers to develop new and innovative approaches to the use of natural materials in an urban context.

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