THE CHALLENGES FOR DESIGNERS OF TALL TIMBER BUILDINGS

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ABSTRACT

This paper describes several major challenges facing the designers of tall timber buildings. "Tall" in this context generally means 10 storeys or more, although many of the challenges also apply to timber buildings over 4 or 6 storeys, becoming more severe as the buildings get taller. Structural design starts with the selection of structural form and structural materials, the major objective being to control lateral displacements under wind or earthquake loading. The challenges then include the structural engineering difficulties of wind and earthquake design, followed by design for fire safety. Briefer reference is made to other design challenges in the areas of longevity, construction and connections. While solutions to all these challenges do exist, they can be difficult to find or implement. Top quality advice and engineering judgement is always required.

KEYWORDS

Tall timber buildings, Fire, Wind, Earthquake, Moisture, Design, Challenges, Structural

1 INTRODUCTION

Tall timber buildings are becoming a desirable reality in many countries, and some governments are offering incentives for construction of such buildings. This promotes the use of local renewable resources, mitigates carbon dioxide emissions, and stimulates regional growth.

Some structural engineers who have designed tall concrete or steel buildings may believe that it is a simple matter to convert a concrete or steel design philosophy to timber, but this is not as easy as it may appear.

There are many challenges facing designers of tall timber buildings and, while solutions to all these issue do exist, they can be difficult to find or implement. This paper looks at structural engineering challenges for wind and earthquake design, followed by design for fire safety, and the construction process. Briefer reference is made to other design challenges in the areas of longevity, construction and connections.

2 TALL TIMBER BUILDINGS

"Tall" in this context generally means 10 storeys or more, although many of the challenges described in this paper also apply to timber buildings over 4 or 6 storeys. Most of these design challenges become more severe as the timber buildings get taller.

2.1 Scope

This paper only includes those special issues which become important for design of tall or very tall timber buildings. It does not include the issues applying to all other timber buildings such as durability, noise control, and floor vibration.

This paper refers to design of multi-storey timber buildings where all vertical and lateral loads are resisted by timber structure. Buildings with reinforced concrete cores for lateral load resistance are not included.

2.2 Structural Materials

The most traditional type of timber building is light timber framing used for houses and some taller buildings, with studs and joists of sawn timber, and plywood, strand board, or plasterboard bracing. This type of timber construction can be used for buildings up to six or ten storeys, optimised with prefabrication for rapid erection. Multi-storey light timber frame construction is popular in areas of the world which rely on light timber frame housing, especially in the USA and Canada.

A range of recent and planned tall timber buildings are shown in Figures 1 to 6.

A rapidly emerging new form of engineered timber construction is “massive timber” or “solid wood” construction which uses large prefabricated timber panels enabling rapid erection [1]. The prefabricated timber elements can be manufactured from Glulam (glue laminated timber), LVL (laminated veneer lumber) or CLT (cross laminated timber). These are manufactured under factory conditions at large production facilities. Although the most common examples of massive timber construction are in Europe, they are now spreading to North America, Japan, Australasia and elsewhere.

Figure 1: *Forte Building, Melbourne [www.woodskyscrapers.com]*

Figure 2: *Treet Building, Bergen, Norway [www.woodskyscrapers.com]*

Figure 3: *Possible 30-storey building, Canada [12]*

Figure 4: *University of Northern British Columbia, Prince George, Canada [www.unbc.ca]*

Figure 5: *Proposed 15-storey building, Ottawa, Canada [Douglas Consultants, Quebec City]*

Figure 6: *Possible 42-storey building, Chicago [15]*

2.3 Structural Form

Later, this paper will talk about designing tall timber buildings for wind or earthquakes. However, regardless of location (seismic or non-seismic, high wind or low wind), recent designs have shown that the need for lateral stiffness will dictate the structural form of tall timber buildings.

Designing for stiffness rather than strength creates a situation where it is necessary to use walls to limit deflections. Moment-resisting structural frames become too flexible even for 3 or 4 storey buildings, and are unable to provide economical section sizes that are sufficiently stiff for taller buildings. In order to increase the feasibility of structural frames for tall timber buildings, diagonal bracing elements must be added to increase the stiffness of the whole structure, following the example of many structural steel frame designs.

As shown in Figure 7, stiffness can be significantly increased using box, C or I section walls around the stairwell and lift cores. Converting a single wall into an I-shaped core group will increase the area of timber required by 2 while increasing flexural stiffness by 3.9 times. In the design of these walls, however, the tube stiffness could be significantly reduced by connections between panels which should be considered as part of the system design and not be left for last-minute verification during detailing. Post-tensioning can be used to connect solid wood panels to each other and to the foundations [2].

In structures without sufficient walls to carry all of the gravity loading, floors are supported on timber beams and columns. Prefabricated timber floors and

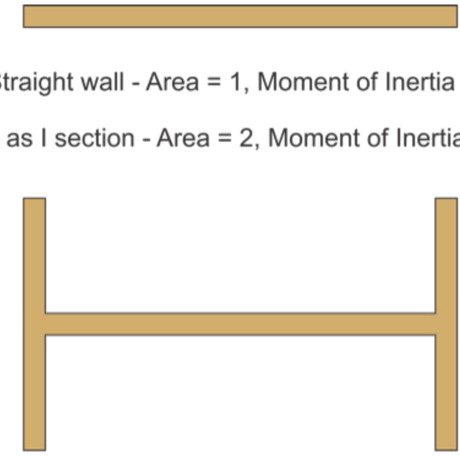

Figure 7: *Relative dimensions and area-stiffness ratio for a single wall compared with an I-profile wall*

timber-concrete composite floors represent some of the timber based flooring systems available. These can be post-tensioned if long spans and low floor-to-floor heights are necessary.

2.4 Public Perceptions

Public perceptions are very important. Because there are so few tall timber buildings, many perceptions have to be overcome before tall timber becomes widely accepted.

For tall timber buildings to gain and retain a place in the market, it is essential that the first generation of buildings be designed and constructed to a very high standard. A few poor designs could gain a lot of bad publicity and undo a lot of the great work being done by innovators around the world. This is especially true for any failure connected to already negative perception, such as a devastating fire or an expensive durability problem.

Reduced erection time is already widely accepted as a big advantages of timber construction, contributing to significant cost savings. Early discussion with the builder on the preferred installation procedure should be undertaken, to ensure rapid erection on site.

2.5 Structural Design Issues

2.5.1 Lateral displacements

The structural form of a tall timber building will most likely be governed by the desire to limit lateral movement. The need to limit lateral displacements may also govern connection design [3].

The physical size of possible timber element production, transportation limits, or limits on what can be placed onsite, all lead to many connections being required for a tall timber structure. Each of these connections acts as a 'soft' area reducing stiffness in the wall system. Early in the design process, the impact of connections on total building stiffness must be accounted for, even if this is simply by applying an estimated reduction to the total stiffness of solid walls. If this stiffness reduction is not considered early on, more walls and expensive fasteners may be needed during the detailed design, leading to unforeseen structural costs.

Because the lateral load design of tall timber structures is often governed by the displacement of the lateral load resisting system, is it necessary to know the stiffness of all the timber members and their connections. Unfortunately the stiffness of fasteners is often neglected in design, with only limited guidance given in design codes, and values often affected by large scatter. Manufacturers of proprietary products like brackets or hold-downs normally provide strength values, but little information about stiffness. This represents one significant area of improvement needed to enable tall timber structural design.

2.5.2 Displacement limits

In New Zealand, for both wind and seismic loading, lateral displacement limits in the serviceability limit state range from H/600 (0.17% drift, or ~5mm) for unreinforced masonry to H/200 (0.5% drift, or ~15mm) for paper-finished gypsum board walls. Further, more or less stringent, limits may be imposed by the designers of non-structural elements, which requires clear and honest dialogue between the structural engineer and the product provider.

3 DESIGN FOR WIND

Due to the high flexibility of a tall timber building the natural period of the structure is long, meaning that design base shear from wind loading is usually higher than that from possible earthquake loading, even in high seismic areas.

Design for wind is generally a matter of assessing the strength of the lateral load resisting system at the ultimate limit state (ULS), and checking the lateral deflections at the serviceability limit state (SLS).

3.1 Wind-induced vibrations

The problem of wind-induced vibrations applies to all very tall buildings, and may be more of a problem for timber buildings than steel or concrete because of the low mass of the building and the low stiffness of the wood materials. Possible solutions include vibration control such as tuned mass dampers or increased understand and modification of the building profile through wind tunnel testing.

4 DESIGN FOR EARTHQUAKE

4.1 Wind vs earthquake

The sections above have discussed how structural form is often governed by a search for stiffness to ensure limited deflections under frequently occurring wind loading.

Even if wind loads are greater than design-level seismic loads, seismic design cannot be ignored in earthquake-prone regions, for several reasons:

1. Seismic design codes provide maximum expected values that are sometimes greatly exceeded (as experienced in Christchurch in 2011).
2. Traditional timber buildings in seismic areas have been small dwellings with low consequences of collapse. A tall timber office structure or residential building has much higher consequences of collapse.
3. Timber is a brittle material with connections which can occasionally have brittle failures if not well designed.

Given these three points, all tall timber buildings should be designed to maintain life safety objectives under maximum credible seismic loading [4].

Several key objectives in ensuring good seismic performance are considered in the following paragraphs.

4.2 Ductility

4.2.1 Yielding of connections

Because timber is a brittle material, ductile connections are required to maintain adequate strength and avoid collapse beyond design level loading. Ductility is normally provided by the design of yielding steel connections [5].

Ductility is obtained by the formation of plastic hinges in metallic dowel type fasteners like nails, but also staples, screws, dowels or bolts. Connectors in timber elements often show a typical pinching behaviour in their hysteresis loops because of timber embedment failure. If a connection fails only through embedment of wood, it has zero strength under cyclic loading until it reaches its previous point of maximum load. To ensure some residual strength, it is important to ensure that failure modes are governed by the formation of plastic hinges in the steel fasteners, rather than by crushing in the timber. This normally occurs for small diameter fasteners like nails, but can be more difficult to achieve for larger dowels or high strength connections, typical of tall timber buildings.

It is also necessary to avoid any brittle failure modes in the connections, such as row shear, block shear, splitting etc. Recent research is addressing these failure modes, but their general applicability is not yet fully determined, and the over-strength margin between yielding and brittle failure modes of many connections is still unknown. Therefore conservative treatment of this issue is recommended.

4.2.2 Connection of special yielding devices

One way to ensure stable ductile behaviour is to design for yielding of specifically designed ductile elements made from mild steel. The connections of these elements to the main structure becomes critical because these connections must be both stiff and inexpensive,

Development is underway into increasingly intelligent ways of ensuring controlled ductility without excessive additional cost [6, 7]. Such as the mini buckling restrained brace ("plug and play" device) shown in Figure 8(a) or U-Shaped Flexural Plates (UFP) as shown in Figure 8.

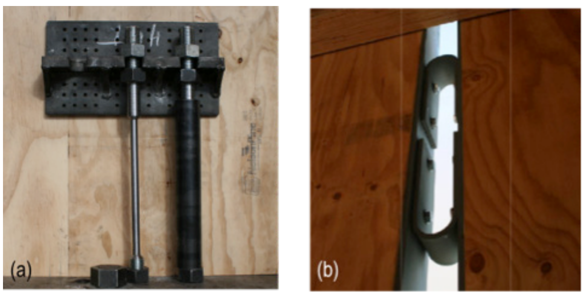

Figure 8: *(a) "Plug and play" and (b) UFP dissipation devices*

4.2.3 Capacity design

Capacity design is the generally accepted way to ensure that seismic loading beyond a building's elastic strength leads only to ductile failure and sudden brittle failures are prevented. To do this, all brittle elements and possible brittle connection failure modes need to be capacity protected, i.e. they need to be designed to resist loads from the over-strength of the ductile yielding zone. Capacity design principles are well established in the seismic design of concrete and steel structures, but still raise questions in design of timber buildings, especially because of the lack of generally accepted definitions and codified values.

The over-strength in timber structures normally considers the statistical scatter of material properties, the discrepancy between codified strength values and real values, material safety factors, hidden reserves from friction etc. [5]. Designers of tall timber buildings need to use good engineering judgement to decide where the highest risk of over-strength lies, and to establish clearly defined, capacity protected, load paths protecting against collapse.

4.3 Higher mode effects

A code-based Equivalent Static Analysis will not give accurate seismic design actions for walls, frames and floor diaphragms in tall timber buildings. This very simple method assumes the dynamic response of the structure will be governed by its first natural period and accordingly distributes the base shear up the structure in a linear fashion. Because of the flexible nature of timber lateral load resisting systems, timber structures with more than 4 storeys are significantly affected by higher mode effects. Dynamic amplification on top of over-strength values should therefore be considered when designing the lateral load resisting system [8]. In a tall timber building where an essentially elastic response is expected, linear methods of dynamic analysis become more acceptable. Response Spectrum Analysis for example will provide a useful indication of higher mode demand on the vertical lateral load resisting system. Care must still be taken in the definition of diaphragm demand.

5 DIAPHRAGM DESIGN

Timber diaphragms tend to be more flexible than their concrete counterparts, with increasing floor spans further reducing stiffness.

In seismic design, although the presence of flexible diaphragms causes closely spaced modes (i.e. a number of modes with almost the same period of vibration, corresponding to the diaphragm frequency) and elongates the fundamental period of the structures, this can normally be neglected in the design of the vertical lateral load resisting system.

Because of the higher modes of the lateral load resisting system and the diaphragms, the force demand on the diaphragms cannot be estimated with a simple equivalent static analysis. Preliminary research by Moroder et al. [9] has shown that diaphragm forces are almost constant up the height of the structure and can be 2 to 5 times the forces determined by an equivalent static analysis. Care also needs to be taken when assessing the in-plane displacements of flexible diaphragms in relatively rigid wall structures.

When designing for wind loads, the role of the diaphragm in tying lateral load resisting elements together is crucial to good performance. The load path from the façade elements to the vertical load resisting elements needs to be guaranteed. Wind loads normally create line loads along the diaphragm boundary, so it is necessary to transfer these forces into the remaining part of the diaphragm to fully activate it. Wind suction on the leeward face of the building is a special case requiring tension connections to the adjacent diaphragm panels and between all components of the diaphragm, whether they be massive timber panels or light timber framing.

6 STRUCTURAL ANALYSIS

As for any other structure and construction material, numerical computer models should be kept as simple as possible, so that the load paths can be followed and the behaviour of the structure be understood. Unfortunately the use of complex finite element models is becoming more and more popular. Without adequate understanding of the building's behaviour there is an increased risk that timber elements and connections are represented incorrectly as full panels with rigid connections. A computer model will only represent what a designer tells it to.

There is often a temptation to increase the complexity of a model in order to 'better represent' structural behaviour. Increasing complexity does not necessarily mean increasing accuracy. Advanced computing cannot prevent inadequate design of moment connections or tension perpendicular to grain failures which are then overlooked in the detailed design phase.

Computer models can be kept simple by modelling sub-assemblies (i.e. prefabricated timber elements or segmented CLT walls) instead of modelling each individual member and fastener. Although specialized timber analysis software is becoming available, hand calculations are often needed to ensure that the members can withstand the required force or displacement demand, considering the anisotropic and flexible behaviour of timber.

7 CONNECTION DESIGN

Tall timber buildings will have very large structural members which must be designed to resist very large structural forces. As mentioned earlier, because wood is a brittle material, ductility in timber structures generally comes from ductility in the steel connections, which have to be carefully designed to ensure appropriate behaviour [3]. Most connection testing has been performed on small fastener groups of up to 100kN due to the difficulty in testing higher strength connections. Care must therefore be taken when extrapolating the expected performance of large high-strength connections such as those likely in a tall timber building.

A large number of connectors can add significantly to the cost of tall timber buildings. The use of proprietary products is one way to limit this cost, however early consideration is necessary to assess how they will interact with other aspects of design and consenting.. This warrants early discussion with the complete design team (i.e. architect, fire engineer, builder, and acoustic engineer).

Post-tensioning of timber structures has been developed as an option for wall and frame connections in timber buildings [2]. Although the original applications of post-tensioning focused on the use of rocking to reduce earthquake damage, this is not likely to be a design focus for tall timber buildings which will remain elastic. Nonetheless, post-tensioning is still a very economical way of providing high strength and high stiffness connections between timber elements, also between timber elements and the foundations.

8 DESIGN FOR CONSTRUCTION

A big challenge for designers of tall timber buildings is to design and detail structural elements which can be economically produced under factory conditions, then be erected rapidly and be connected together with suitable connections which will serve the life of the structure.

Big cost advantages of timber structures are the cost savings in preliminaries, i.e. the on-site costs. Accurate dimensioning through CNC machining leads to rapid construction. Reduced erection time, lighter members and therefore less craneage, improved handling, and accurate tolerances of the pre-fabricated timber members can provide large savings, in addition to those from early occupation of the building. Cost savings can be further increased by partial or full pre-fabrication of subassemblies like wall or floor panels and by pre-installing all steel hardware on the timber elements.

Bad weather conditions during construction can impair the constructability and aesthetics of timber structures due to swelling and staining of the timber. To prevent this, proper erection planning is necessary and timber members should be protected temporarily by wrapping them individually, or by the use of temporary cover of the whole structure. Contrary to common belief, timber will not deteriorate if exposed to the weather for a short period of time, but care should be taken to keep this time to a minimum.

9 DESIGN FOR LONGEVITY

Long term performance and durability of tall timber buildings is similar to regular timber buildings, however, the cost of failure is significantly greater due to the increased cost of the structure.

Long term deflections can be controlled and designed for using widely accepted creep coefficients. Care must be taken where a combination of materials is used, for example the attachment of non-flexible facades or around steel lift shafts, to ensure that movement can be accommodated.

Internal and external moisture control always requires careful attention in a timber building. Moisture and temperature change will cause timber to shrink and swell, however under normal, climate controlled, conditions this is not a significant factor even in a tall timber building. None the less, this should be checked throughout the design phase to make sure there is no real issue.

10 DESIGN FOR FIRE SAFETY

As tall timber buildings become more popular, it will be necessary for code writers in different countries to adopt requirements which reflect these ideas in a rational way. More research including quantitative risk assessment will help to further define the options. However early adopters should not be discouraged, designers simply must carefully consider a number of influencing factors.

10.1 Structural timber fire resistance

Heavy timber has excellent fire resistance, which is well documented in the literature [10]. This excellent behaviour is a result of the slow and predictable rate of surface charring in severe fires, leading to simple calculation of fire resistance by subtracting the charred area and a thin layer of heat-affected wood from the original cross-section. As a result of this charring behaviour, unprotected heavy timber structural elements have excellent fire resistance, much better than unprotected structural steel, for example.

10.2 Fire challenges

Fire safety is a major concern in all tall buildings, regardless of materials. The special challenges for tall timber buildings are all related to the consequences of sprinkler failure [10]. The taller the building, the more attention has to be given to:

1. Prevention of vertical fire spread
2. Fire resistance to avoid structural collapse.
3. Encapsulation of structural timber.
4. Design for burnout.

10.3 Recent reports

There are several recent major reports on fire safety in tall timber buildings, which can assist designers in discussion with consenting authorities :

- Technical Guideline for Europe [11]
- The Case for Tall Wood Buildings [12]
- Fire Safety Challenges of Tall Wood Buildings [13]
- Tall Wood Buildings in Canada [14]
- The Timber Tower Research Project [15]
- Use of Timber in Multi-Storey Buildings [16]

All of these reports confirm that well-designed timber buildings have very good fire safety. Careful design is needed to ensure that safety is ensured in every phase of construction and use, throughout all possible fire scenarios. The reports all recommend automatic sprinkler systems, and some protection of wood by partial or full encapsulation to avoid rapid fire spread and to increase the fire resistance of protected structural timber elements.

10.3.1 Sprinkler systems

Most of these reports do not consider the possible failure of the automatic fire sprinkler system. Even though this may be a very low probability, it raises serious challenges. Automatic fire sprinkler systems provide by far the best fire safety for tall buildings (active fire protection). However they are not 100% reliable. Possible failure can occur as a result of maintenance problems, too many sprinkler heads being activated due to an explosion, or no water supply due to a major earthquake or terrorist event. If the sprinklers work as intended, zero structural fire resistance is required, but everything changes if the sprinklers do not work for any reason, and a small fire grows through flashover to a fully developed fire.

Sprinkler reliability is essential for fire safety in tall timber buildings. Strategies to reduce the risk of sprinkler failure include on-site water supplies, reliable pumps, enhanced maintenance systems, and frequent security checks. One recent example is a 15-storey timber office building in Ottawa which was planned with a supplementary water tank at the roof level to ensure a water supply in the sprinkler system regardless of any damage to the water supply in the street.

Sprinklers are the essential lifeline system in a tall timber building. As a fallback position some reliance must be placed on fire fighter intervention, but this becomes limited as the height of the building increases. The principal design option then requires that all reasonable measures be taken to enhance the effectiveness and reliability of the automatic sprinkler system.

10.4 Design for burnout

The design strategy for steel and concrete buildings is based on the concept of burnout, as a last resort, so that after all the fuel in the fire compartment has been consumed and the fire goes out, there has been no serious fire spread and the building remains standing, even with no intervention by fire fighters. Design for burnout requires prevention of vertical fire spread from floor to floor, regardless of structural materials [17].

The only certain way to design for burnout in a timber building is to apply full encapsulation, so that none of the structural timber ever begins to char, throughout the full process of fire growth, development and decay. The required encapsulation will depend on several factors:

- The fire severity, and duration of the burning period
- The rate of temperature drop due to ventilation in the decay phase of the fire
- The effectiveness of partial encapsulation
- Intervention after the fire is out

There is some uncertainty about the self-extinguishing properties of wood and wood-based materials after severe fire exposure, which can be overcome by providing full encapsulation.

10.4.1 Encapsulation

Encapsulation refers to covering wood surfaces with non-combustible materials (passive fire protection). Encapsulation can improve fire safety, but it does not immediately solve all fire problems in timber buildings.

Figures 9 to 13 show a range of interior views with different amounts of structural timber exposed to view (and exposed to fire). Figure 14 shows a multi-storey timber building during the process of encapsulating all the exposed wood with fire resistant board.

Full encapsulation will require that the wood be encapsulated with enough layers of protective material to prevent any ignition or charring of the wood in a complete burnout of the fire compartment, giving the same fire resistance as any non-combustible material.

Partial encapsulation will prevent any rapid fire spread on wood surfaces, but the smaller number of layers may fall off before burnout, exposing structural timber to the later stages of a severe fire. In both cases there is an aesthetic dilemma because building owners, users and architects often specify timber due to its aesthetics, whereas the fire engineers may need to cover it from view. The cost of encapsulation is also a major factor.

10.4.2 Vertical fire spread

If a fully developed fire occurs, the first design challenge is to contain the fire on the floor where it

Figure 9: *Wood walls and ceiling exposed.*

Figure 10: *Columns, beams and part ceiling exposed.*

Figure 11: *Wood ceiling and furniture exposed.*

Figure 12: *Wood columns exposed.*

Figure 13: *Wood columns and beams exposed, also post-tensioning anchorages and dissipation devices.*

Figure 14: *Wood ceiling, beams and columns during process of encapsulation with fire-resistant board.*

starts. This requires adequate fire resistance of the floor-ceiling system and all walls enclosing vertical stairs, shafts or services. It is also essential to design the exterior façade, spandrels, and windows to prevent vertical fire spread via the outside of the building.

10.5 Performance based design

Design for fire safety is rapidly moving from prescriptive codes into performance-based design, where designers ensure that a minimum level of performance is achieved, as required by performance-based (or objective-based) national fire codes. The fire safety design must consider all phases of fire development from the pre-flashover fire through flashover to the fully developed fire, and eventual decay.

For performance-based fire design, it is essential that the performance requirements be clearly established. The target objectives can be summarised as:

- The same level of fire safety as in other buildings
- Design to meet code-specified performance levels
- Occupant safety in all fires

- Very tall buildings should remain standing after the fire, even if no fire-fighting services are available

10.5.1 Risk assessment

These challenges for fire design of tall timber buildings are all risk-related, referring to possible very severe consequences of an extremely unlikely event; that is an out-of-control fire in a sprinkler protected building. To assess the risk in a qualitative way we have to consider a number of parameters:

- Height of the building
- Occupancy
- Fire fighter intervention
- Encapsulation

10.5.2 Height of the building

The height of the building is a critical parameter. A building less than about 5 storeys in height, where there is easy escape and easy access by fire fighters presents a low risk. Challenges surrounding access and escape mean that the risk grows as the building height increases to 10 or 20 storeys or more.

10.5.3 Fire service response

Response by fire fighters is critical if the sprinklers fail to control the fire for any reason. Different scenarios include rapid response which requires good access routes and the fire starting on a lower floor. A slower response will be due to poor street access, or fire on upper floors of the building, and the worst case scenario will be no response at all due to a major disaster such as a massive earthquake or terrorist attack.

10.5.4 Encapsulation design

There is a wide range of options for encapsulation, as shown in Figures 9 to 14:

1. All timber walls and ceilings exposed to view.
2. All walls exposed to view, ceilings protected.
3. Beams and columns exposed to view, walls and ceilings protected.
4. All wood protected with one layer of plaster board (partial encapsulation).
5. Full encapsulation of all wood with several layers of plaster board.

For control of early fire spread, partial encapsulation of the ceiling using option 2 is preferred over option 1 because exposed ceilings can result in rapid fire spread and ineffective sprinkler operation. As an extension to option 3, the number of exposed timber walls will depend on a balance between architectural wishes and the fire design strategy.

From a structural engineering viewpoint, critical structural elements such as isolated columns must be well protected to prevent any chance of disproportionate collapse. This can be by extra sacrificial wood or full encapsulation.

For burnout control, in the unlikely event of sprinkler failure, full encapsulation of all wood surfaces solves the possible residual charring problem, but it is expensive, and may be unacceptable to the architect and the building owner who want to see the exposed wood linings and structure.

11 CONCLUSIONS

This paper has shown that there are many significant challenges facing designers of tall timber buildings, including design for wind and earthquake, design for longevity, and design for fire safety. This should not discourage the construction of these types of structures but should ensure every member of the project team uses top quality engineering and good judgement in design. The main conclusions are:

General:

- Tall timber buildings can achieve the same level of performance as concrete or steel buildings, with careful design and attention to detailing.

Wind and seismic design:

- Displacements govern the lateral load design of tall timber structures because of the low modulus of elasticity of wood.
- Selection of structural form and materials will be dictated by design to control displacements.
- Higher mode effects must be considered because they can produce unexpected loadings on structural elements and diaphragms.
- Capacity design of connections is essential to provide ductility in the case of seismic or wind overload.

Fire safety:

- All tall timber buildings must have an automatic sprinkler system, with as many enhancements as possible to increase reliability and effectiveness.
- Large areas of exposed wood ceilings should be avoided, to control rapid fire growth in the early stages of a fire.
- Some encapsulation of the wood structure should be provided, depending on the height of the building and the location of critical wood elements.

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