Structural Sustainability

sustainability and preservation as they pertain to structural engineering

Timber Tower Research Project

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The Timber Tower Research Project by Skidmore, Owings & Merrill, LLP (SOM) was publically released in June of 2013, and is available for download at SOM's website. The goal of the research project was to develop a structural system for tall buildings that uses mass timber as the main structural material and minimizes the embodied carbon footprint of the building. The structural system research was applied to a prototypical building based on an existing concrete benchmark for comparison. The concrete benchmark building is the Dewitt-Chestnut Apartments, a 395-foot tall, 42-story building in Chicago designed by SOM and built in 1966.

SOM's proposed system is the "Concrete Jointed Timber Frame". This system relies primarily on mass timber for the main structural elements, with supplementary reinforced concrete at the highly stressed locations of the structure: the connecting joints. This system plays to the strengths of both materials and allows the structural engineer to apply sound tall building engineering fundamentals. The result is believed to be an efficient structure that could compete with reinforced concrete and structural steel systems, while reducing the embodied carbon footprint of the structure by 60 to 75%.

Project Basis

The basis of the research project was rooted in sustainable urban development. Recent population projections have estimated the current world population of 7.0 billion people to increase to 11.0 billion people by the year 2050. More importantly, the number of people that will be living in cities has been estimated to double from 3.5 billion people to 7.0 billion people in the same time frame. Tall buildings will likely be needed in order to house that many additional people in growing cities. Tall buildings constructed to meet population demands need to be developed in sustainable ways to limit environmental impacts.

Tall buildings built using current technology and materials pose a challenge to sustainable city development because they offer both positive and negative environmental impacts. Positive impacts include reducing urban sprawl, promoting alternative transportation, and efficient energy use. These benefits come at the cost of emitting more carbon dioxide to produce the materials and to construct the building. These carbon emissions are referred to as the embodied carbon footprint of a building. A tall building's embodied carbon footprint is significantly higher relative to low-rise buildings on a per square foot basis. This is because the structure is usually responsible for the majority of the building's embodied carbon footprint, and tall buildings require far more structure to support their height. The structural system chosen for a tall building can have a significant impact on the overall embodied carbon footprint of the building.

Design and Sustainability Issues

Structural engineers currently have four primary materials in which to design buildings: steel, concrete, masonry, and wood. Tall buildings currently use steel or concrete almost exclusively, for two reasons. First, with some limited exceptions, non-combustible materials are required by most building codes for buildings greater than four stories tall. Second, steel and concrete have higher material strengths than masonry and wood, making them a natural choice for tall buildings which require support of very large loads. These factors have generally limited wood use to low-rise buildings. Recently, developments in mass timber technology are overcoming these challenges. Mass timber products such as cross-laminated timber (CLT) can be built up using small pieces of dimensional lumber and structural adhesives to achieve panels as large as 1foot thick and 40 feet long. These panels can be used as floors and shear walls with structural sizes necessary to support a tall wooden building. Wood members of this size have an equally important characteristic; they behave like heavy timbers in a fire and form an insulating char layer which protects underlying material. The charring behavior is predictable and preserves a portion of the member's structural strength, making performance based fire design of mass timber structures possible. Mass timber has made wood a viable choice for multi-story buildings as evidenced by completed projects in Europe and Australia, and many other proposed projects around the globe.

The structural and fire engineering advancements of mass timber have made recent multi-story wood buildings possible. However, the sustainability of wood seems to be an equally important consideration in the resurgence of multi-story timber buildings. Wood has been shown to be more sustainable than other materials because it generally requires less energy to produce compared to structural steel and reinforced concrete. More importantly, wood is approximately 50% carbon by weight, a carbon sink that is the natural result of photosynthesis. These sustainable aspects of wood make mass timber an attractive material from which to construct the sustainable cities of the future. The intersection of increasing urban populations, need for tall buildings, and the sustainability of wood has led to the increasingly popular concept of tall wood buildings. SOM has committed decades of tall building

Architectural detail of the wood structure proposed in the Timber Tower Research Report.

design expertise to furthering this concept, through the Timber Tower Research Project, by identifying key design and construction issues related to tall wood buildings and proposing the "Concrete Jointed Timber Frame" structural system. This system is optimized for tall buildings and could be competitive with existing tall building structural systems. The proposed system balances the requirements of building marketability, economy, and sustainability.

Material Optimization

The primary goal of any structural system is to provide a marketable and valuable building to the owner and occupants. A marketable building must have adequate and flexible floor area to layout useful space for the occupants. The most marketable building layout is an open floor plan which allows a variety of room layouts and maximum flexibility for future changes. An open floor layout requires that the floor structure span the entire distance of the leasable area. This distance in the Benchmark Dewitt-Chestnut building was 28 feet 6 inches, with a clear span of 26 feet 3 inches. The most advantageous system to span this distance is a flat mass timber panel which minimizes floor-to-floor height of the building. The required panel thickness to span the required distance was determined to be 13½ inches. This thickness was thought to be too great compared to the material required for the Reinforced Concrete Benchmark to be economically viable. Therefore, alternative methods to span the required distance were investigated in order to reduce the amount of structural materials used.

The controlling design consideration for the mass timber floors was determined to be vibration due to occupant activity. The floors were analyzed according to American Institute of Steel Construction *Design Guide 11*, utilizing the velocity-based methodology, which was found to be more useful for flat slab-type floors. Evaluation of the criteria shows that increasing floor stiffness is the most effective way to control vibrations. The floor stiffening effect of end rotation restraint (fixed end condition) was quickly realized as an efficient way to reduce vibrations. It was determined that an 8-inch-thick mass timber floor panel could be used if end restraint was provided. This requires moment connections at the intersection of mass timber floor panels with vertical elements such as mass timber shear walls and structural glued laminated timber perimeter columns. Several connection schemes were investigated to provide the required moment connections. Steel reinforcing epoxy connected to the mass timber and cast-in reinforced concrete joints were determined to be the most reasonable solutions due to the ability of reinforced concrete to resist complex load paths. These reinforced concrete joints are able to resist floor-to-floor compression, shear, bending moments, and torsion, thus creating an efficient composite-timber system.

The reinforced concrete joints also proved to be useful in other tall building aspects. The concrete jointing between timber floors and timber shear walls provides a link beam between individual wall panels. This creates a stiff lateral load resisting system which is required for a tall building. It was also determined that the demands on the link beams were beyond the capacity of a structural glued laminated wooden link beam, requiring the use of a material other than wood. The concrete joints and link beams were also useful in the design of the lateral system to resist net uplift due to lateral loads. The Prototypical Building has approximately 40% of the dead load of the Benchmark Building. This led to net uplift forces at the extremities of the lateral load resisting system. This net uplift would have been exacerbated without the concrete joints which account for over 50% of the entire structure dead load, yet only 20% of the structural material volume for a typical floor.

SOM's Timber Tower Research Project proposes a "Concrete Jointed Timber Frame" system that relies primarily on mass timber for the main structural elements, with supplementary reinforced concrete at the connecting points.

A comparison of the structural materials required to construct the Benchmark and Prototypical building shows that the proposed system is very efficient in material consumption and could be competitive with reinforced concrete. The goal of minimizing the structural materials used, namely mass timber, will help reduce costs and minimize new demands on forest resources which may become strained due to increasing populations and demands.

The non-structural effects of the proposed system were evaluated and the most notable effect was the acoustic treatment required on top of the mass timber floors in order to achieve a marketable acoustic rating. The most effective treatment was determined to be a 2-inch-thick gypsum concrete topping. This treatment thickness, in addition to potential ceiling finishes, required 3 inches of additional floor-to-floor height in order to maintain the same floor-to-ceiling height as the Benchmark building. This has impacts on wind loads on the building, and non-structural costs such as the exterior wall system.

Conclusion

SOM believes that the proposed system is technically feasible from the standpoint of structural engineering, architecture, interior layouts, and building services. Additional research and physical testing is necessary to verify the actual performance of the structural system relative to the theoretical behavior. SOM has also developed the system with consideration for constructability, cost, and fire protection. Reviews from experts in these fields, and physical testing related to fire, is also required before this system can be fully implemented in the market. Lastly, the design community must continue to work creatively with forward thinking municipalities and code officials using the latest in fire engineering and performance based design to make timber buildings a viable alternative for more sustainable tall buildings.▪