Supertall Timber: Functional Natural Materials for High-Rise Structures

Michael Ramage, University of Cambridge

Wood and wood products have been used as building materials since before recorded history, but we have not yet realized the full potential for timber and other plants as building materials. Engineered timber materials, among them cross laminated timber (CLT) and laminated veneer lumber (LVL), have allowed architects and engineers to design and build larger and larger timber buildings. The tallest timber building currently is Brock Commons, a 55m, 18-story student dormitory completed in 2016 at the University of British Colombia in Vancouver, Canada. Prior to that, the tallest building was Treet, a 49m, 14-story condominium completed in 2015 in Bergen, Norway. Brock Commons has two concrete cores, while Treet is a fully timber structure, so each may be the tallest of its type (Foster et al. 2017). The scale of these contemporary buildings is significant, as the first metal-framed skyscraper, William Le Baron Jenney's 1885 Home Insurance Building in Chicago, was 55m tall when fully completed in 1891. From then it was less than 50 years to the 1931 completion of the Empire State Building in New York City at 381 meters (and the demolition of the Home Insurance Building.) Innovation in natural materials, design and construction may allow a similar increase in the height of timber skyscrapers.

Timber has exceptional properties for building, many of which have been overlooked in the past century. We are at a time when biological understanding, engineering of plant-based materials, and interest in renewable construction are converging to create new possibilities for materials and allowing for larger, taller and more natural engineered wood buildings (Green 2012, SOM 2013, Ramage et al. 2017a). Simultaneously, we are witnessing competition in the industry to build the tallest timber tower. Height increases are currently incremental, but through a combination of theoretical design and physical testing, we can demonstrate the viability of timber buildings at much greater heights than has previously been possible (Ramage et al. 2017b). By pushing the limits of theoretical designs into the realms of the supertall, and sometimes beyond that which is feasible using current materials and construction technologies, our research also sets out the requirements for the next generation of engineered plant-based materials. Research, design and construction of contemporary large-scale timber buildings furthers the architectural and structural engineering knowledge necessary to make tall timber buildings a reality. Natural materials in taller and larger buildings can substitute for steel and concrete, reducing carbon emissions.

Materials science has advanced the industrial production of steel and reinforced concrete since the mid 19th Century and continues actively to this day. Our understanding of the materials science of natural materials is less developed, but the advent of biofuels has helped drive fundamental research into the makeup of plant cells and their constituent parts. Our improved understanding of how to break plants down into useful components can also lead to better understanding of whence their underlying properties arise. As an example, the model plant *Arabidopsis thaliana*, whose genome is well-understood and editable, is essentially the mouse of plant science. Through biochemistry, it can be grown with lignin-depleted cells, so that we can try to understand the role of lignin in giving plant cells their characteristic properties. In *Arabidopsis,* it appears to help control the way cells move past each other as they are pulled apart in tensile tests. If we can better understand how the elements of cell wall contribute to the properties we ascribe to plants and forest products, we may be able to breed or genetically engineer plants with specific functional properties that are more favorable to construction.

Novel properties from trees may give rise to a new class of natural materials, but already engineered timber products on the market are giving designers around the world opportunities to innovate with large scale construction. Cross laminated timber can be used much like slabs of concrete in walls and floors, and glue laminated timber and laminated veneer lumber can be used like steel or concrete columns and beams. As such, existing modes of construction allow buildings to be built in ways that are familiar but with new materials. Yet there are limitations – for example, platform construction with CLT is limited by perpendicular to grain crushing of panels at the floor junctions; this phenomenon is difficult to overcome above 10 stories or so. The axial strength of some hardwood LVL in compression and tension is sufficient to engineer very large buildings, yet the ability to transfer tensile loads that can be carried by the full section from one member to another remains to be discovered. Our supertall timber project, in which we have designed wooden skyscrapers, shows the viability of commercial and residential buildings at a new scale in timber, using components and materials that are commercially available today. The design and research demonstrates the benefits and potential for thinking about traditional materials in new ways, and the architectural, engineering, and economic possibilities that stem from this approach to natural materials.

A variety of plants may add to the materials available. Bamboo has excellent properties in tension and compression, and is among the world's fastest growing plants. It can be harvested every few years, and a number of processing methods exist to turn the raw product into an engineered material (Sharma et al. 2015). More are frequently being developed. Engineered bamboo looks like wood, and is crafted with woodworking equipment, but behaves differently as a structural material (Reynolds et al. 2016), making new engineering codes necessary. Other crops, such as flax and hemp, are being used to make structural composites for automotive and industrial design. As we push these plants to deliver higher properties, we discover their potential to do so. All of these crops are available at a scale necessary for construction. CLT construction uses approximately $30m^3$ for an apartment of two – using wood from only 30% of Europe's managed forests with current practices, the entire population of Europe could be housed in perpetuity, even assuming the entire housing stock was renewed every 50 years (Ramage 2017a).

Construction with timber has many advantages, not least for the environment. Timber is the only major building material that we can grow, and the sustainable harvest of lumber is vast; crop planted forests around the world are expanding. Timber is five times lighter than concrete, so to construct an equivalent volume of building, only one timber truckload is needed, as compared to five concrete mixers. Moreover, there are further savings as no formwork needs to be brought to site (and removed) and no reinforcing steel is necessary. The steel in timber connections is negligible. We roughly redesigned the Treet building in Bergen in reinforced concrete for comparison, and discovered that it would have five times as much steel in it as the timber building has. Seagate Structures, who have built a number of large scale timber buildings in Vancouver, suggest that the savings multiplier on construction truck traffic can be as high as eight (Austin 2017). These savings have implications for today's crowded metropolises: smaller foundations, or indeed no new ones, as existing foundations for a demolished 10-story concrete building can hold a timber building three to four times as tall, quieter construction, and smaller cranes.

Contemporary timber buildings are largely prefabricated for component assembly, meaning they are quick to erect accurately on site, and tend to be naturally draft-proof and efficient. This saves time and energy, and improves overall quality. As manufacturers, architects, engineers and contractors learn to expand what we can do with large-scale engineered timber, a new architecture of 21st century timber will arise, drawing on a rich tradition of centuries of wooden construction, but reaching higher to embrace the full potential of innovation and construction with natural materials.

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