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Authors: Robert Foster, Senior Lecturer, The University of Queensland
Michael Ramage, Director, University of Cambridge
Thomas Reynolds, Chancellor's Fellow, University of Edinburgh

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Robert M. Foster


Dr. Michael H. Ramage


Dr. Thomas Reynolds

Authors

Robert M. Foster, Senior Lecturer
School of Civil Engineering
University of Queensland
49 Advanced Engineering Building
Staff House Road
St Lucia QLD 4072, Australia
t: +61 7 3365 3619
e: r.foster@uq.edu.au
http://www.civil.uq.edu.au

Dr. Michael H. Ramage, Director
Centre for Natural Material Innovation
Department of Architecture, University of Cambridge
1 Scroope Terrace
Cambridge CB2 1PX, United Kingdom
t: +44 1223 760 121
e: mhr29@cam.ac.uk
www.natmat.group.cam.ac.uk

Dr. Thomas Reynolds, Chancellor's Fellow
Institute for Infrastructure & Environment
The University of Edinburgh
1.22 William Rankine Building, The King's Buildings
Edinburgh EH9 3JL, United Kingdom
t: +44131 650 5633
e: t.reynolds@ed.ac.uk
www.eng.ed.ac.uk/research/institutes/iieof

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International Conference

Robert Foster will present this paper and provide an update on the results of the **"Pre-Conference Workshop on Tall Timber"** in Session 3C: *Tall Timber,* Monday 30 October at 1:45 p.m.

Abstract

Recent developments in the design and construction of progressively taller buildings using engineered timber as a structural material raise important questions about the language that is used to describe tall buildings. This paper discusses the role of the CTBUH Height Criteria in classifying tall buildings and the challenges raised by the emergence of engineered timber as a contemporary structural material alongside steel and concrete. The paper concludes by presenting a proposal for updating the existing terminology to accommodate the use of timber and other new materials in the design of tall buildings. This paper will be used as a basis for discussion at the ***CTBUH Workshop on Tall Timber,*** *held in conjunction with the 2017 Conference, with a view towards the future revision of the CTBUH Criteria to include timber.*

Keywords: Height Definitions, Building Criteria, Timber, Materials

Introduction

Between 1885 and 1913, the development of steel-framed structural systems permitted the heights of skyscrapers to leap from the 10-story Home Insurance Building in Chicago, to the 60-story Woolworth Building in New York. Only 18 years later, the Empire State Building was completed at a height of 102 stories. Between 2008 and 2016, the height of modern buildings using engineered timber increased from the nine-story Stadthaus building in London to the 17-story TallWood at Brock Commons building in Vancouver (see Figures 1 and 2) (CTBUH 2017). Designs have also been presented for timber skyscrapers at heights up to 80 stories, including the River Beech Tower, Chicago and Oakwood Tower, London (see Figures 3 and 4) (Green & Karsh 2012, SOM 2013, Foster & Ramage 2016). Although it is impossible to know what heights tall buildings using engineered timber might ultimately reach, the historical precedent and the potential identified in recent design proposals suggest that genuinely tall timber buildings are likely to become a reality in the very near future.

The opportunities for better, more sustainable tall buildings afforded by new materials, new construction technologies and new architectural forms bring with them a range of

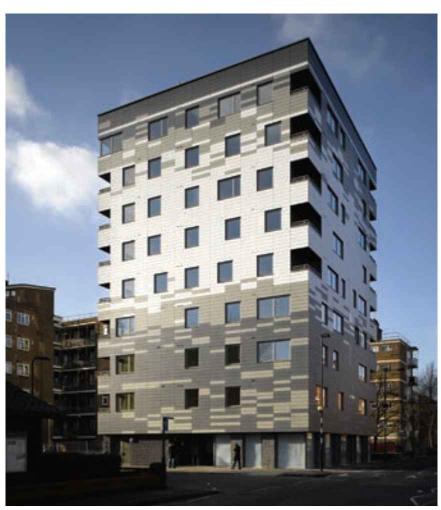
Figure 1. Stadhaus, London. © Will Pryce


Figure 2. TallWood at Brock Commons, Vancouver. © Acton Ostry Architects & University of British Columbia

new challenges. Among these is the need to update the language that is used to describe tall buildings; to move beyond descriptors suited solely to a palette of materials limited by the historical duopoly of steel and concrete. A proposal addressing this challenge was presented previously by the authors for discussion within the structural engineering community (Foster et al. 2016). This version of the paper provides a summary of the supporting discussion to the wider tall building community.

The generally accepted terminology for the classification of tall buildings is set out by the CTBUH Height Criteria and this has been shown to be highly appropriate for the tall buildings of the last century. However, in order to encourage productive discussion and ensure that meaningful comparisons can be made between a wider range of emerging building systems and materials, it is useful to revisit and perhaps clarify these criteria. The basis for this clarification is both the historic and commonly understood thinking behind the existing terminology and definitions, and also an understanding of the future directions of tall building construction.

Tallness

Definitions of "tallness" are subjective and dependent on context. In historical terms, a building that is taller than previous buildings of a particular material or type might be said to be "tall," in the sense of "tall for a timber or unreinforced-masonry building." Tallness in this sense is important to the design community, because the practice of design must draw on both experience and theoretical understanding. Buildings that exceed the height of precedents using similar materials or systems thus present additional challenges to designers.

Another contextual consideration that has historically played a role in the technical definition of a building's tallness is that of fire. A building has often been considered "tall" in this sense if its height is such that a fire cannot be fought using ground-based equipment. This has constituted an historical "basic height limit" in North America and elsewhere (Calder et al. 2014).

The CTBUH identifies three further qualities that can be used to define tallness: height relative to context, proportion, and use of tall building technologies.

Height relative to context acknowledges that a building's surroundings play an important part in assessments of tallness. A 14-story residential building sited in a suburban neighborhood might be described as tall, while the same building situated in a high-rise cityscape might not be.

Figure 3. River Beech Tower, Chicago. © Perkins + Will

Proportion can be thought of as considering a building in the context of its own geometry and massing. A 14-story building on a small footprint might be slender and thus appear tall, in a way that a 14-story building covering an entire city block might not. An indicative characterization of tallness with respect to *height relative to context* and *slenderness* is shown in Figure 5.

Tall building technologies are features such as advanced vertical transportation and enhanced lateral force-resisting and damping systems that are particular to the design of tall buildings. Enhanced lateral force-resisting and damping systems are closely related to the slenderness of a building. This aligns with the structural engineer's definition of "high-rise

Figure 4. Oakwood Tower, London. © PLP Architecture

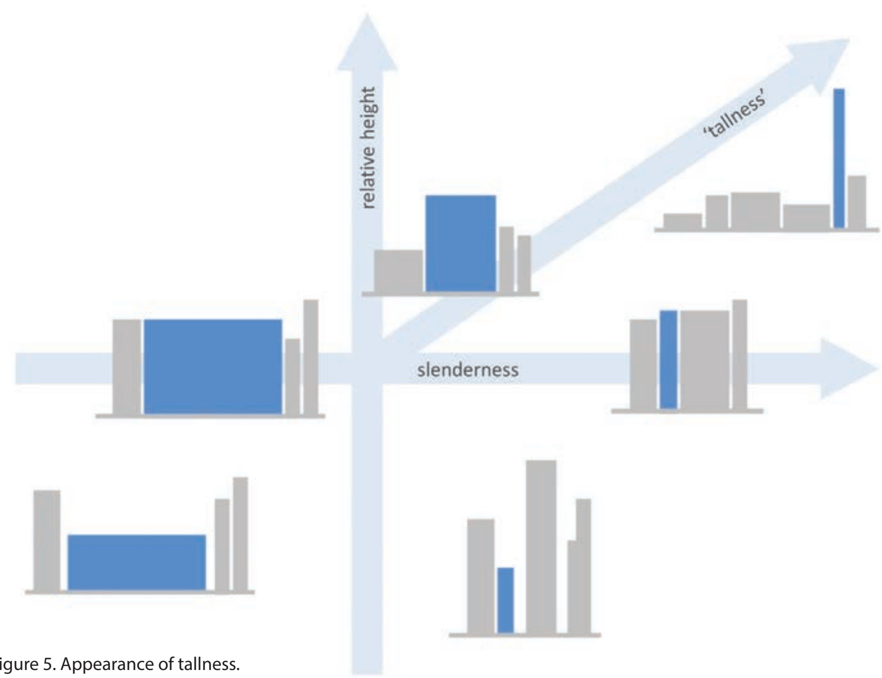

Figure 5. Appearance of tallness.

construction" (Khan 1969) considering the relative significance of lateral forces due to wind and seismic actions, actual lateral sway, perceived lateral sway, and differential vertical movements due to thermal effects or axial shortening.

Considering tallness presents challenges in the context of novel structural systems and new materials such as engineered timber. The apparently lower stiffness and mass of timber could lead to wind or seismic actions governing design at considerably lower slenderness ratios, giving rise to the earlier use of steel and concrete structural systems. This might be taken to suggest that buildings using timber should be considered "tall" at lesser heights than similarly-sited and proportioned buildings using steel or concrete. However, recent research shows that the lateral performance of framed buildings using engineered timber, such as the Treet in Bergen, Norway, may not be dissimilar to that of a steel-framed equivalent (see Figure 6) (Malo et al. 2016, Reynolds et al. 2016). This suggests that it may be not be necessary to establish different criteria for tallness of timber buildings – using structural timber, on the basis of material properties alone.

Height

Definitions of height are objective and are largely independent of context, provided that there is common understanding of the beginning and ending measurement points. Although variations in building form can make definitions of the bottom and top of a building somewhat arbitrary, several broadly agreed measures are currently in use for the reporting and cataloguing of building height.

The CTBUH recognizes three categories of tall building height: height to tip; height to architectural top; and highest occupied floor. These heights are measured from the finished floor level of the lowest, open-air pedestrian entrance leading to the main vertical transportation conduit. The *height to tip* measurement includes projections such as antennae that are not integral and may not be permanent features of the building. The *height to architectural top* or gross height is the basis for the CTBUH list of World's Tallest Buildings and is measured to the permanent top of the building. This includes features such as spires but excludes antennae. Building classifications of supertall and megatall are based on this gross height (CTBUH 2009).

The difference between the height to architectural top and the *highest occupied floor* can impede meaningful comparison between buildings. The measurement to the highest occupied floor or "net height" is of greatest practical interest for tall buildings in terms of their utility, and thus the measure of greatest interest for meaningful comparison. Although a net height of approximately 14 stories or 50 meters is indicated by the CTBUH criteria as a starting point for consideration of a building as "tall," a building of lesser height could be considered based on how it uses tall building technologies.

Figure 6. Treet, Bergen. © Rune Abrahamsen

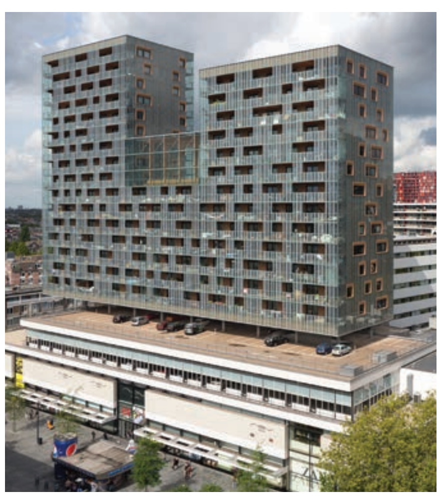

Figure 7. De karel Doorman, Rotterdam. © Ossip van Duivenbode/Ibelings van Tilburg

Building Material

Timber was a widely-used material in the construction of churches and spires that would have been counted amongst the tallest man-made structures until the early 20th century (Constantinescu 2008). The tallest timber structures ever constructed are transmission masts, reaching up to 190 meters (Langenbach 2008). However, structures such as spires and transmission masts are rather different sorts of structures to the occupied multistory buildings that are of interest here. In fact, such structures would be excluded from consideration as tall "buildings" by the current CTBUH criteria, because less than 50% of their height can be considered as "occupied by usable floor area."

All existing supertall and megatall buildings are constructed using steel, concrete or a combination of the two. While no large or tall building is constructed entirely of one material (Gunel & Ilgin 2007), it can be informative to consider broad classification on the basis of principal building material. Tall buildings are currently classified by CTBUH into four typologies, according to the material(s) adopted for the construction of the "main" vertical and lateral structural elements (CTBUH 2009). These categories are steel, concrete, composite and mixed-structure.

A *steel or concrete* building is defined as a building in which all of the main structural elements are constructed from steel or concrete. A *composite* building is defined as a building in which both steel and concrete elements are used to construct the main vertical and/or lateral load-resisting systems. This includes a steel-framed building with a concrete core. A mixed-structure building is a building that uses distinct steel and concrete structural systems above or below each other. A steel/concrete building uses a steel structural over a concrete structural system; and a concrete/steel building uses a concrete structural system over a steel structural system. The upper structural system of a *mixed-structure* building can thus be thought of as a separate building structure founded on the lower.

A building with a steel frame but with a flooring system of concrete planks or slabs supported by steel beams is considered by the CTBUH as a "steel building." As such the floor system is not considered to form part of the "main" structural system, even though considerations such as diaphragm action or mass contributed by the flooring system may form an important part of the design of the "main" structure. Similarly, the lightweight timber floor system that makes possible the 16-story extension of the Karel Doorman building in Rotterdam would not be included in the building material classification; it is listed as a "composite" building (see Figure 7) (Hermens et al. 2014; CTBUH Skyscraper Center 2017).

The thinking behind the existing criteria can be applied to extend the definitions to include timber, or indeed other structural materials such as bamboo or fiber-reinforced polymer composites, in tall building construction. This can be done by rationalizing the existing definitions and categories of building structures into "single-material," "composite," and "mixed."

A *single-material* tall building, whether steel, concrete or timber, is thus a building in which the main structural elements are constructed principally from a single material. This leaves the definition of existing steel and concrete buildings unchanged, but brings them under the umbrella of the single-material category, rather than privileging these conventional materials over other potential structural materials. As is currently the case, the materiality of any secondary flooring structure would not be considered as part of the "primary" structural material classification. This is compatible with the current guidance for the definition of a tall steel building with a concrete floor slab supported on steel beams.

The definitions of "composite" and "mixed-structure" buildings would remain unchanged, except when the reference to steel and concrete might be replaced with a reference to a wider range of materials. It might also be informative for a composite building to be designated by the constituent structural materials, hyphenated, in order of prevalence by mass in the building structure. Thus, a composite building with an extensive concrete core and limited timber framing would be designated as a "concrete-timber composite" building, while a predominantly timber building whose lateral stability relies on continuous steel ties would be designated as a "timber-steel composite."

It may be useful at times to consider the upper structural section of a mixed-material building as a single-material building measured from the height of the lower structure from which it takes support. Similarly, where a building is a mixed composite – for example a building with a full-height concrete core, a lower section of steel framing and an upper section of timber framing – the upper section might be considered as a concrete-timber composite building, measured from the height of the concrete-steel composite structure. This treats the lower structural section as an elevated foundation or plinth, and is particularly relevant for the description of buildings using materials such as timber, which often incorporate a concrete structure up to the first- or second-floor level. Examples of the proposed classifications with respect to various notional building arrangements are shown in Figure 8.

While useful for detailed comparison, the consideration of the height of a single building under multiple categories may be disadvantageous for the purposes of general categorization. The CTBUH definition of building use considers a mixed-use building to be one in which more than one function occupies a significant proportion of a building's total space. A "single-function building" is thus taken to be a building in

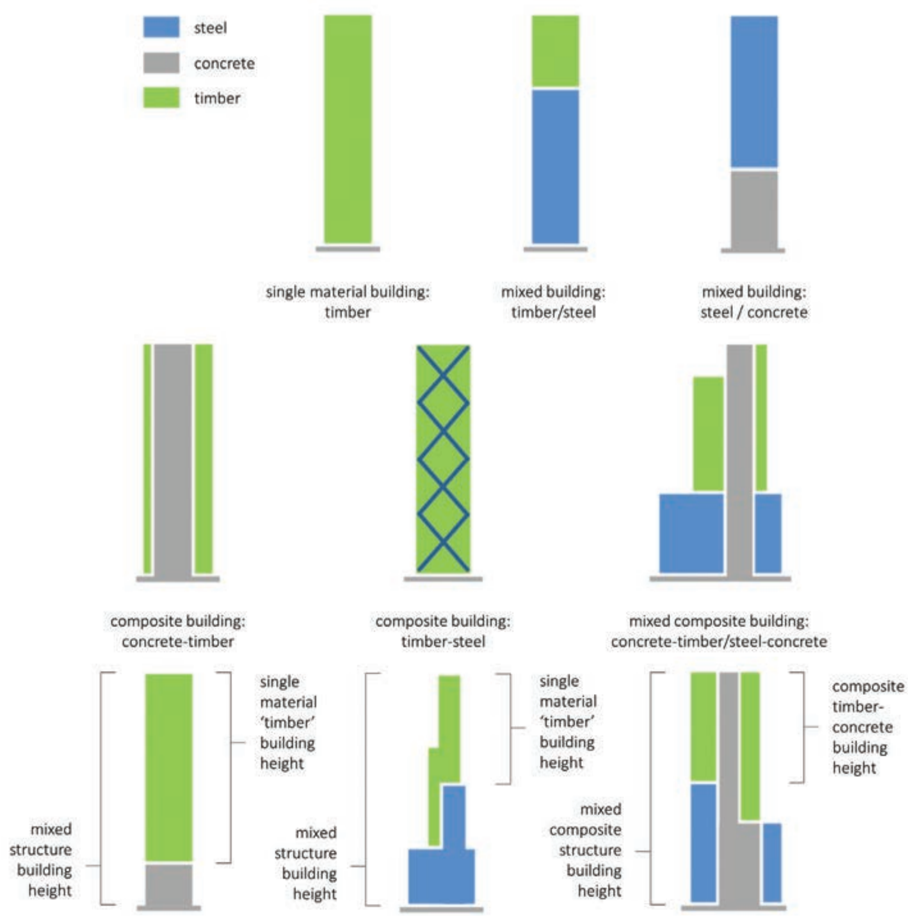

Figure 8. Examples of building typology by structural material.

Figure 9. Limnologen, Växjö. © Arkitektbolaget Kronoberg AB

Figure 10. Strandparken, Stockholm. © Petra Bindel (cc by-sa)

Figure 11. Framework, Portland. © LEVER Architecture

which a single function occupies 85% or more of the building height or floor area. Adopting this approach for building material, a "single-material building" might be taken to be a building in which a single-material structure occupies 85% or more of the building height or floor area. This provides a sensible compromise between accuracy and simplicity, and is consistent with the commonly encountered case of buildings having a change in structural arrangement associated with a change in function after the first few stories.

"Hard" Cases

As with any attempt at systematic categorization, some examples will present challenges. Rather than looking to the extrema, the authors have adopted the maxim that "… hard cases make bad law" (Shapiro 2006). Therefore, categorization has been carried out with reference to the basic principles discussed above, rather than introducing an ever-more complex system of classification.

The 14-story glue-laminated megatruss Treet building, for example, incorporates 200-millimeter-thick concrete topping slabs at the transfer stories in order to provide additional mass to the building. While this supplementary mass and the diaphragmatic stiffness of these slabs is considered in the structural design – as would be expected in a steel building with concrete decking on steel beams – the slabs do not in the authors' view provide a primary load path. This building is therefore considered to be a single-material timber building.

In contrast, existing European buildings such as Sweden's Limnologen in Växjö and Strandparken in Stockholm; and the US project Framework in Portland use systems of cross-laminated timber (CLT) shear walls in conjunction with continuous steel ties (see Figures 9, 10, and 11) (Robinson et al 2016). These ties thus form the primary tension force path of the lateral load resisting systems; thus, these are timber-steel composites. The Strandparken and Framework buildings are therefore considered to be timber-steel composite buildings under this classification scheme, while Limnologen, which has a concrete first story, is classified as a "mixed structure timber-steel composite/concrete building" or simply a "timber-steel composite" if the 85% rule is adopted.

Methods for forming timber connections without the introduction of other materials are well-established in the carpentry traditions of many countries. However, such connections are not generally used in modern buildings, in which localized steel connections using plate-and-dowel, nailed bracket or self-tapping screw systems are the contemporary norm (Foster et al 2016). For this reason, the materiality of connections between timber elements is not considered in the classification scheme presented. This is comparable with the use of steel connections in a tall building with a precast concrete frame, or with reinforcing bars crossing a cold joint in a tall building with a monolithic concrete frame, both of which would in most cases be regarded as concrete rather than composite tall buildings.

Conclusions and Proposals

Although there are some reasons why it might initially be suggested that timber buildings be defined as "tall" at lower heights than steel and concrete buildings, these reasons are primarily a result of the relatively early stage of development of engineered timber as a structural material for use in taller buildings. There is great potential for structural systems

"A 'single-material building' might be taken to be a building in which a single-material structure occupies 85% or more of the building height or floor area."

using engineered timber that will allow timber and timber composite buildings to reach much greater heights than at present. This potential is indicated by a range of factors, including the comparable specific strength and stiffness of engineered timber and steel, the performance of existing timber buildings and the ambitious concept designs being put forward by leading designers. While it might be tempting in the short term to "lower the bar" for timber and other new materials, the authors contend that to do so would be to underestimate the potential of the material and of tall building designers.

The discussion has also shown that the existing terminology for tall buildings in relation to structural material may be applied in a consistent manner to buildings that use timber as a structural material. Although there will inevitably be some "hard" cases, a classification based on the materiality of the primary structural load paths provides a generally consistent basis for understanding and comparison. This system has the advantage of being readily applied to buildings using new structural materials, and of being aligned with the existing CTBUH terminology and thinking.

The following criteria developed by the authors are proposed for consideration by the CTBUH Height Committee as a possible basis for the extension of the existing guidance to the description and classification of tall buildings using timber and other new materials (Foster et al. 2016):

- A single-material tall building is defined as one where the main vertical and lateral structural elements and floor systems are constructed from a single material. As such, a steel, concrete or timber tall building is defined as one in which the main vertical and lateral structural elements and floor systems are constructed from steel, concrete or timber, respectively.
- A composite tall building utilizes a combination of materials acting compos-itely in the main structural elements, thus including an otherwise steel or timber building with a concrete core. Materials may be listed in order of prevalence by mass in the building structure.
- A mixed-structure tall building is any building that uses distinct single-material systems above or below each other. There are three main types of mixed structural systems: a steel/concrete or timber/concrete tall building indicates a steel or timber structural system located above a concrete structural system, with the opposite being true of a concrete/steel building.
- If a tall building is of steel or timber construction with a floor system of concrete planks or a slab supported on steel or timber beams, it is considered a steel or timber building.
- If a tall building has columns or walls of one material and a floor system supported on beams of a different material, it is considered a composite tall building.
- If a tall building is of timber construction with local connections between timber elements formed using steel or another material, it is considered a timber building.

It is further suggested that a building in which a single-material structure occupies 85% or more of the building height or floor area be considered as a single-material building. ■

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