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Developing Hybrid Timber Construction For Sustainable Tall Buildings

Carsten Hein

In the near future, timber will form a much bigger part of the built environment. This paper chronicles projects that redefine the possibilities of timber to help support this development. Working on the LifeCycle Tower (LCT), the author and colleagues investigated the full and still largely-undiscovered potential of using wood for high-rise buildings. Using engineered wood combines the potential for prefabrication and rapid construction with lower embodied energy and the potential to delay carbon emissions for a building's lifetime. It recognizes that timber is best used in conjunction with other materials, taking advantage of the attributes of each material. Use of timber is optimized when it achieves full integration with building services, matching the acoustic, dynamic and fire performance of conventional alternatives.

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Carsten Hein
Carsten Hein is a structural engineer by profession and joined Arup in 1996, where he developed a strong interest in designing timber structures. In 2004 he started working with Jürgen Mayer H. on the Parasol Metropol in Seville, Spain, leading the timber team in the office. In 2009, he led the design team for the multidisciplinary research project LifeCycle Tower. At the same time, the Multi-story Timber Research Network global timber network within Arup began operations.

Carsten has worked on various timber projects, always investigating the possibilities of the material and trying to push the boundaries for the use of timber.

"The floors of the LifeCycle Tower were conceived as timber-concrete-composite slabs, using a concrete slab supported by timber beams, with a stiff connection between the two to provide composite action."

CREE/Haus der Zukunft Project, 2009

A multidisciplinary approach is essential to achieve the aim of sustainably using timber in the urban environment. While the environmental advantages of timber are widely recognized, the cost efficiency of sustainable construction will be the main driver of an increased use of timber. In 2009, the Arup team carried out research in cooperation with the Austrian developer CREE, funded by the Austrian government initiative "Haus der Zukunft." The architect was Hermann Kaufmann ZT GmbH, Austria. Further collaborators included Wiehag, an Austrian timber fabricator, and the Technical University of Graz, with a former colleague of the author, Prof. Brian Cody.

From the outset, the team considered a modular construction system to allow for maximum prefabrication capability. The team developed the concept for a 20-story high-rise tower, attempting to use timber for as much of the structure as possible. The research comprised building permit calculations for all engineering services involved, including structure, MEP, façade, fire, acoustic, and building physics. The construction was designed to meet the requirements of European standards, and of the German and Austrian building regulations.

The floors of the LCT were conceived as timber-concrete-composite (TCC) slabs, using a concrete slab supported by timber beams, with a stiff connection between the two to provide composite action (see Figure 1).

While the structural requirements could have been fulfilled by timber alone, or by a 60- to 80-millimeter-thick concrete flange for the timber beams, fire regulations required 100 millimeters of thickness; acoustic requirements called for 120 millimeters. Notches in the tops of the beams created a structural interlock

Figure 1. Timber-Concrete-Composite (TCC) slab. After all the walls are installed, the floor slabs, which were fabricated with a hole in each corner, slide over the pins in the glulam posts. © CREE

Figure 2. LCT One, Dornbirn, Austria. © CREE/Architekten Hermann Kaufmann

Figure 3. Illwerke Zentrum Montafon, Montafon, Austria. © CREE/Norman A. Müller

between concrete and timber to enable composite action. The stability core and the columns were designed to use glue-laminated wood panels (glulams), the core being assembled from 2.4-meter panels. The façade was conceived as consisting of 2.7-meter-wide modules with integral glulam columns. An approximate cost comparison of the chosen TCC construction for the LCT with a traditional concrete frame structure indicated that using timber would generate 10% to 15% higher costs. It was therefore agreed that a prototype would be constructed, minimizing the sizes of all the members to achieve a more economical solution.

LCT One: The Prototype, 2011

Based on the engineer's concept, the developer built an eight-story prototype in Dornbirn, Austria (see Figure 2), followed by a 10,000-square-meter office building nearby in Montafon (see Figure 3). These projects were designed by local engineers Merz Kley Partner, with Hermann Kaufmann again as architect. As agreed during the research, both these projects pushed the boundaries of timber construction, as all the main elements were slightly undersized compared to code-based fire and acoustic calculations. Testing was then undertaken of the slab system to demonstrate compliance. The test results were used to further develop the system.

The slab had been built with concrete of 80 millimeters' thickness. Additional aggregates had to be used for production of the concrete slab to avoid flaking of concrete cover, and to guarantee concrete integrity for the required 90 minutes. For acoustic performance, a sound-absorbing raised floor was required, as well as an additional self-levelling floor screed. The system returned an adequate performance. As expected, tests proved a 3-to-6-dB higher sound insulation than listed by product specifications. But it remained questionable if this was the most cost-effective solution.

However, in terms of fire performance, it was very successful, achieving an REI 90 (90 minutes fire resistance) certificate from the PAVUS Test Institute in the Czech Republic (see Figure 4). As the concrete contractor was not commissioned at this point, it was decided to use the Czech facility and a nearby concrete contractor to build the test elements – so only the timber had to be transported from Austria.

The eight-story LCT One used a concrete core for stability, which also provided the main exit route in case of fire. While the fire concept had envisaged a fully-sprinklered system, the building permit allowed removal of the sprinkler system because of the robust fire-safety strategy.

The façade system was also slightly modified from the research concept. It now featured up to 12-meter-wide prefabricated panels, with the columns mounted to the back of these panels. This was a valuable step to reduce the cost of construction and to improve the speed of erection.

At this point, the cost assessment was still not satisfactory; additional measures for the concrete and certification for fire resistance resulted in extra costs. The cost comparison became more difficult with more details at construction stage – there was no corresponding concrete version against which

Figure 4. The prototype slab of LCT ONE was tested for fire resistance. After some modification the test proved 92 minutes of fire resistance, confirmed by an REI 90 certificate from PAVUS.

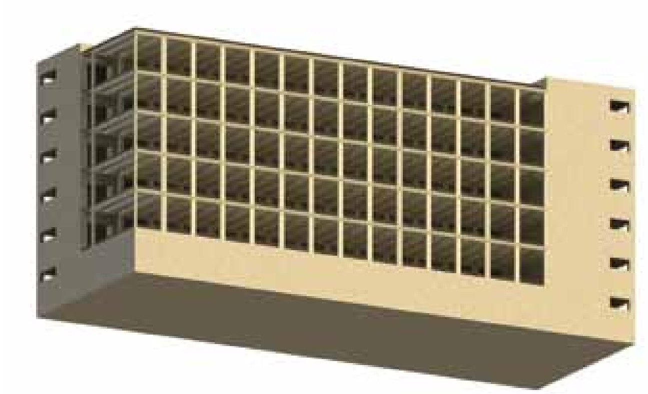

Figure 5. Revit model of the LCT system for California.

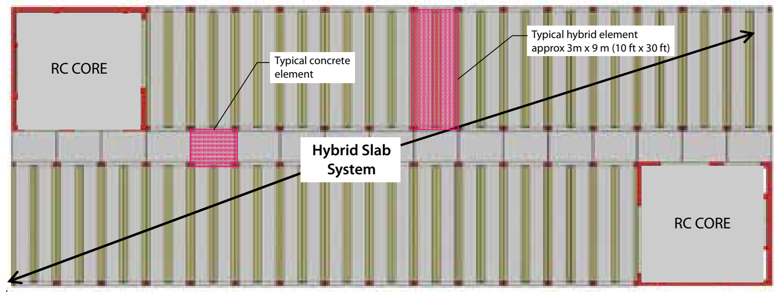

Figure 6. Typical level slab finite element model showing exaggerated deflections due to lateral loading. Deflected shape indicates that lateral movement is largely restrained by the core structures.

the timber project could be compared. Slabs had different thicknesses (resulting in different acoustical and fire resistance performance), and MEP installation was different, as was building skin performance and consequently, energy performance. Finally, accepting that there was no similar type of building, the cost comparison was based on standard construction costs for the planned function of the building as an office. The LCT concept was assumed to cost 105 to 110% of a typical office building.

Tall Timber Campaign, 2012

In 2012, the developer again commissioned the engineers to further engineer the system, to investigate several projects in Germany and Austria as candidates for hybrid timber construction, and to assess the system for application in the North American market (see Figure 5), with its high seismic loads. Based on data gained from testing the prototype, the modular system was optimized. The core was considered to be concrete, because that would reduce construction cost and make it easier to get building permission regarding fire safety. The grid of the design was "Americanized," resulting in a roughly 3 by 9 meter (10 by 30 foot) slab module.

The slab modules were now assumed to be composites, based on separate production of the precast concrete slabs and the timber beams. The thickness of the concrete slab was considered to be up to 100 millimeters to achieve cost reduction, while obviating the need for fire-testing at the same time. In this phase, different types of shear/composite connections between timber and concrete were also investigated (see Figure 6).

For the German and Austrian projects, different floor plans were considered, so that they were using different spans from the original 8.1 meters, or introducing a supporting beam to increase column spacing along the central corridor. Also, the standard module width of 2.7 meters, which had been ideal for offices, but might not be for hotel use, was challenged.

For North America, the structural system had to be designed for seismic loads. The first approach was to limit the building height to six stories. By doing this, the concrete cores would provide sufficient stiffness, while the prefabricated slab elements had to be connected for diaphragm action so as to carry much higher loads from seismic forces than would be necessary for typical wind loads. The challenge was achieving a ductile connection between the concrete slabs to allow for some energy absorption. Bolted steel connections were discussed, as were reinforcement links (see Figure 7).

Multi-story Timber Research Network, 2013

During this phase the Arup internal Multi-story Timber Research Network (MSTRN) was founded. Organized in the MSTRN, offices across the firm are talking to each other and exchanging knowledge about timber construction. Based on previous work in support of the LCT, the timber competence team in Germany put together a report gathering all findings about modular TCC and timber construction for a high-rise building.

LifeCycle Tower Goes Taller, 2014

In 2014, the effort has resulted in two projects. The first is a seven-story timber office building in Germany; the second is the realization of the LCT in Austria, rising 20 stories. As part of the project, the team will develop a multidisciplinary design manual for timber buildings, then present the manual as a challenge to the timber enthusiasts around the wider Arup organization to develop their own solutions or variants. This internal competition across the MSTRN to further optimize the concept for Tall Timber aims to develop a system that allows a cost-competitive solution in all-timber and hybrid timber construction. The modular elements of the LifeCycle Tower have also further evolved. The approach to design and optimization has changed, as has the concept for the various modules.

Hybrid systems as a sustainable approach to high-rise structures

Based on research and previous projects, the design team reconsidered the approach to the use of timber. While the research project aimed for a maximum use of timber, the construction of the prototype taught the engineers that "less might be more." Hybrid construction is the sustainable approach that now forms the basis of design. Materials are combined to take advantage of their specific properties, depending on requirements. Timber is still the primary element, but the material's weaknesses must be acknowledged. Connections are one issue – traditional timber-to-timber connections are relatively weak. Glued or steel connections are stronger, and also quicker to install, which can improve connection integrity. Another issue is mass – thermal mass for room conditioning and physical mass for control of

Figure 7. Integrated connections in prefabricated panels.

sound transmission and vibration. This is where concrete comes into play – it is heavy, easy to install, cheap, and fireproof. Thus, all elements of the Tall Timber project are considered as hybrids.

Slab system

Slabs are the main construction element in tall buildings, and wood/concrete composite floors can match the performance of concrete at about half the weight and half the embodied carbon, therefore offering a sustainable solution that is ideal for off-site prefabricated construction. During the LCT research, the engineers also issued a sustainability report looking into the CO_2 footprint of the project – showing an embodied-carbon reduction of about 50% by using the wood/concrete composite floors.

Already in the development of the LCT One prototype, it had become obvious that a fully prefabricated timber-concrete composite (TCC) slab had disadvantages. The slab deforms and shrinks when the concrete hardens. This causes an initial deformation of up to 40% of the long-term deflection. The design criterion is 1/300 for long-term deflection, including effects from creep and shrinkage, and approximately 10 millimeters (absolute) for short-term deflection under full live load. To avoid this, separate production of the timber and concrete elements was considered for post-assembly on-site or in the shop. The design criteria for the LCT slab were in three areas: structural performance, fire protection and acoustic isolation. In addition, vibration also needed to be investigated, as lightweight structures are likely to be responsive to footfall-induced vibrations.

Well-engineered slabs are key to achieving a cost-efficient structure. To optimize the assembly of slab modules, the team put considerable effort into developing the assembly method, in conjunction with timber contractors.

The typical LCT slab is 8.1 meters long, while the optimum range for this type of slab is approximately 5 to 10 meters. For spans shorter than 5 meters, the hybrid structure becomes inefficient, as the concrete could span the distance on its own. The maximum span has not been investigated in detail yet.

Connection systems

Various connection systems are being considered.

Kerven (notches)

The original option is to use kerven (notches) as in LCT One, but with optional post-assembly. That approach would require openings to be formed in the prefabricated concrete slabs to accommodate the notches in the timber beams (see Figure 8). This connection type would require two to three notches at each end of the beam, and some additional connectors to resist tension perpendicular to the grain of the glulam beam. At the ends of the span, the timber beam would be fully anchored into the concrete slab, enabling the concrete slab to be used as a corbel to transfer load into the façade columns (and thus eliminating cross-grain compression of the beams).

Proprietary Würth connectors

The use of a proprietary connector from Würth FT Verbinder is also being investigated. This anchor system consists of screws in plastic tubes embedded in the concrete slab, fixing the slab into the beam underneath (see Figure 9). The system was developed for on-site assembly; therefore, small screw diameters had been selected, enabling the use of lightweight equipment on-site. This requires approximately 30 connectors for each 8.1-meter beam, making for a time-consuming and costly approach.

Fully threaded screws

Currently the team is investigating a shear connection using long fully threaded screws, with a larger diameter than the proprietary Würth connectors (see Figure 10). If the whole shear connection zone is cast at a later time, then no specific certifications are required, since the screws are already approved by regulators and the remainder of the connection system can be designed according to codes. This will allow a reduction in the number of screws and make the system more cost-effective. The use of larger tools is not an issue in the prefabrication workshop.

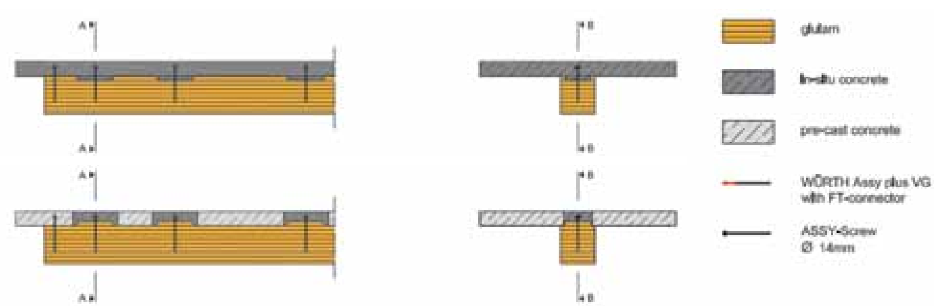

Figure 8. Kerven – notches interlocking concrete and timber. Both recesses into beams and slabs were investigated

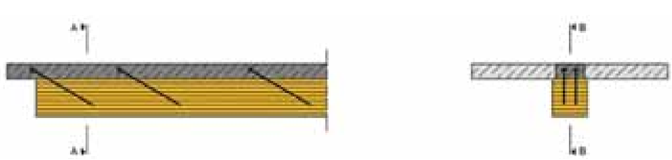

Figure 9. Würth connector – certified connecting system with plastic and/or steel washers as anchors embedded in concrete and screwed into the timber beams.

Figure 10. Fully threaded screws – same concept as Würth connector, but not requiring special certification.

Figure 11. The opaque façade area can be used to accommodate structural elements.

This option aims for post-assembly, with separate production of timber and concrete elements for assembly on-site. This allows for easier production and transport to site. The construction/assembly on-site requires more lifting time, but with less weight. All of the above-mentioned options aim for a "dry" assembly, keeping the amount of mortar/concrete poured on-site to a minimum. For sustainability reasons, dismantling the system at the end of its life cycle is also being considered.

"Wet-on-wet" connections
The Technical University of Berlin is researching construction with lightweight concrete and "wet-on-wet" gluing of concrete to timber. This is the only connection option that will support the complete off-site assembly of the slab modules. The concept for construction is as follows:

Beams are prefabricated and placed in formwork. The top of the beam is coated with glue/resin, thus treating it for very slow hardening. The slab is poured on top – thus treated for quick hardening. After the concrete has reached a certain degree of stiffness, the glue seals the connection between concrete and timber. The advantage of this concept is that no additional connections are required, except for a few screws to control any incidental cross-tension in the timber elements.

Stability core
Based on previous experience, a concrete core seems most cost-effective and allows an easier approval process (in terms of fire safety). The prototype and the second building in Austria both feature concrete cores to provide building stability. For mid- and low-rise buildings, these types of cores contain stairs and elevators, providing sufficient stability, while at the same time fire-protecting the building escape route through the core. The minimum size of the core is defined by the size of stairs and fire elevator. For taller buildings, this minimum core is no longer sufficient for stability. While consisting only of a staircase and a small elevator fit in a square core of approximately 5 by 5 meters, this concrete structure is sufficient to stabilize a building up to 35 meters' height, depending on the floor plan.

Beyond this critical height, a hybrid structure can provide additional stiffness; with a small amount of material the stability and horizontal stiffness can be improved by additional structure located in the plane of the façade. As this is only required to resist infrequent design events, no fire protection is required for the additional stiffener elements. Stiffeners can be constructed as structural, non-fireproofed timber walls or struts, or with steel bracing.

During the research in 2009, the high-rise was analyzed for dynamic behavior with a solid timber core. Timber proved to provide a very good combination of damping and flexibility to absorb vibration and sway. This effect can be improved in combination with a concrete core, because the two different stability systems can be tuned to act at different frequencies at the same time, so that they damp each other.

Façade system
Nowadays, façade systems provide not only the skin to the building, but also provide insulation, carry vertical and horizontal loads, act as fire protection to avoid "flash-over" (fire jumping from one compartment or building to the next) and can be mapped with additional functions, such as vertical gardens, photovoltaic (PV) elements, or solar collectors. The original design for the LCT assumed that vertical forces would be carried by glulam columns. Due to the increasingly stringent energy-saving standards, the amount of glass and windows in façades is decreasing. As area of opaque façade increases, additional functions can be accommodated, and structural elements can be introduced, providing additional stability and cost saving (see Figure 11).

Fire Protection Considerations

Fire protection is one of the driving design factors when developing timber or timber-hybrid structures. The 2009 study considered a full timber core, while the latest developments suggest that applying standard concrete structures for fire protection of the escape routes might be the easier way to obtain building permission. Currently, the fire concept uses concrete for the minimum core (with escape routes and fire elevators). The slabs are considered a fire barrier between floors. The beams of the slab and the structural elements of the façade are considered combustible, but are designed to withstand 90 minutes of fire.

Fire strategies are still being investigated. For the slab, the potential of a full beam collapse (assuming the fire will continue even after the heat source has been extinguished) has been checked. The remaining slab can be designed to span like a net between vertical supports, without losing its structural integrity – though

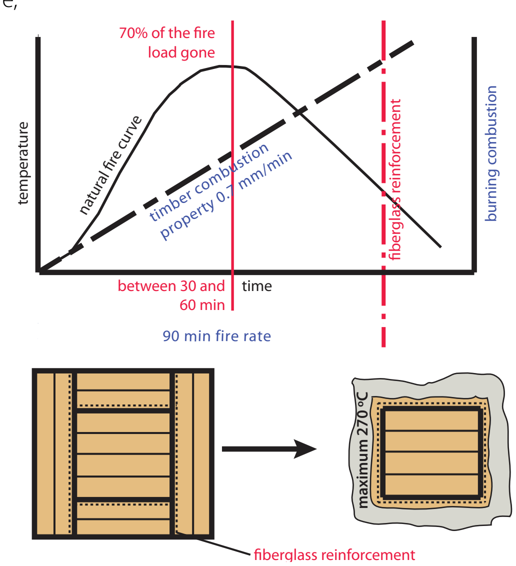

Figure 12. Double-layered timber column, with the structural core inside and a sacrificial layer outside, providing additional load capacity under "normal" use.

it could have very large deflections. For the columns, a built-up timber firestop has been investigated. The double-layer columns consist of a structural core – designed to carry loads in case of fire (limited life load and safety factor = 1.0), a firestop interlayer (glass fiber or cardboard) and an outer timber layer – designed to carry additional loads during normal use of the building (full life load and safety factor according to Eurocode = 1.35 and 1.5, respectively). Both the timber core and outer timber layer are designed to carry the loads during operation of the building, while the outer layer can be sacrificed in case of fire. The interlayer protects the inner core from combustion (see Figure 12).

Further Research

There is still a need for research, and two new projects are showing a path forward. Andreas Heupel Architekten BDA have commissioned the author's firm for an office building in Münster, Germany (see Figure 13). This is contemplated as a full LCT system with a concrete basement and a concrete base at the ground floor. The structure for the six stories above ground floor are: slabs spanning 6.2 meters, with a 3-meter corridor on the central axis. This layout has also been used for the LCT in California.

The second project is the realization of the LCT 20-story research concept on a site in Vienna, Austria (see Figure 14). It uses a 24-by 40-meter hybrid slab structure, timber construction for columns and façade, and a stability core built in concrete. The use and construction is very similar to the LCT research project in 2009. The basement and two floors above ground will be concrete construction, accommodating special functions such as parking and mechanical plant (below ground) and restaurants and retail at the ground and first-floor levels. The timber tower above will be used for offices, while a top-floor hotel function is considered. The engineers will undertake a reviewing role on the project, and will consult with the MSTRN team in support of the development, architecture and engineering firms. ■

> "Beyond 35 meters' height, a hybrid structure can provide additional stiffness; with a small amount of material the stability and horizontal stiffness can be improved by additional structure located in the plane of the façade."

Collaborators

Andreas Heupel Architekten BDA, architecture for seven-story project in Münster - http://www.heupel-architekten.de/

Arup MSTRN represented through Richard Hough, Andrew Lawrence, Adrian Campbell, Jan-Peter Koppitz and Hans-Eric Blomgren - http://www.arup.com

CREE by Rhomberg - http://www.creebyrhomberg.com

Hermann Kaufmann ZT GmbH, architecture for LCT, LCT ONE, IZ Montafon and LCT Vienna - http://www.hermann-kaufmann.at/

Merz Kley Partner ZT GmbH, Dornbirn, Austria - structural engineering for LCT ONE, IZ Montafon and LCT Vienna - http://www.mkp-ing.com/

WIEHAG GmbH - http://www.wiehag.com/

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Arup will be speaking at the Shanghai Conference. **Craig Gibbons** will be delivering the presentation "Towards 2050 – The Challenge for Tall Buildings" in Session 2: ***Rethinking the Skyscraper*** Wednesday, 17th September, 11:15 a.m. – 12:45 p.m.

David Farnsworth will be delivering the presentation "Modular Tall Building Design at Atlantic Yards B2" in Session 12: ***Prefabrication & Other Construction Advances,*** Thursday, 18th September, 11:15 a.m. – 12:45 p.m.

Figure 13. SuperBioMarkt, Münster, Germany. © Andreas Heupel Architekten BDA

Figure 14. Proposed 20-story LCT, Vienna. © CREE/Architekten Hermann Kaufmann