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# MULTI-FUNCTIONAL INTERFACE CONCEPT FOR HIGH-RISE HYBRID BUILDING SYSTEMS WITH STRUCTURAL TIMBER

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**ABSTRACT:** Recapturing the 19th century position that timber held as a primary structural material for mid-rise construction, and potentially gaining such a niche in high-rise construction, depends on demonstrating feasibility and advantages of its use. A hybrid construction concept is presented here that utilizes timber and other materials to create multi-functional interfacial slab substructures, that act together with frameworks and shear-walls of various materials to create building superstructures. In this context, multi-functionality concern sufficiency of completed systems from structural and fire safety, sound and vibration serviceability, and durability perspectives. The illustrative example of utilizing cross-laminated-timber as structural spine material of floor substructures is used to demonstrate that timber has a viable future as a high performance construction material for taller buildings.

**KEYWORDS:** Buildings, cross-laminated-timber, fire, hybrid structures, multi-functional interfaces, serviceability.

## 1 INTRODUCTION

Timber was the primary high performance structural material for building superstructures until the late 19th century, but afterwards structural steel and reinforced concrete (RC) have jointly dominated that role. Recapturing its position as primary structural material for mid-rise (up to about 10 storeys), and potentially gaining such a niche for high-rise buildings, depends on demonstrating feasibility and advantages of using timber over alternative materials. Although there is no generally accepted definition, high-rise buildings are widely understood to be those with above ground heights in the range of 35-100m. The focus of this discussion is utilization of timber and other materials to create multi-functional interfacial hybrid substructures that act with frameworks and shear-walls of various materials to create high-rise building superstructure systems.

Irrespective of what materials are employed, performance requirements for high-rise buildings are more stringent than requirements commonly associated with low-rise buildings, because of the higher number of people affected, greater potential for social consequences, and higher buildings remediation or replacement costs. High-rise buildings must be designed and constructed, and fire protected, with great care. Technically this demands optimization of sound and vibration serviceability and durability measures for completed systems, as well as fire and structural sufficiency measures. Also to note is that all the aspects of performance need to be addressed at the system level, and typically with the expectation of longer design lives than are accepted for buildings of limited occupancy. For example, it is not sufficient to assume, as is common in contemporary low-rise timber building design, that checking component strengths and making limited static load deflection checks will ensure that an assembly of components will work well as a high-rise system. Because, high-rise systems are outside the scope of accepted applications to which standard timber design practices were calibrated.

As has been elucidated [1], it is necessary to explicitly perform system level analysis relevant to each measure of functional acceptability of completed systems, and then check for consistency of decisions across functional requirements.

The design decisions, in combination with system size, determine how catastrophic system failures can be. Proof of this emerges through inability of certain types of steel and RC structures to handle the flows of kinetic energy within them each time there is a major earthquake. Inclusion of substantial amounts of material damping in systems controls the development of damaging kinetic energy flows associated with growth of damage. High material damping also facilitates control of serviceability related problems like annoying vibrations.

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This illustrates that structural capacity and serviceability issues are problems that clearly beg for symbiotic solution through use of multifunctional composite isolation layers as shown in the Figure 1 [1].

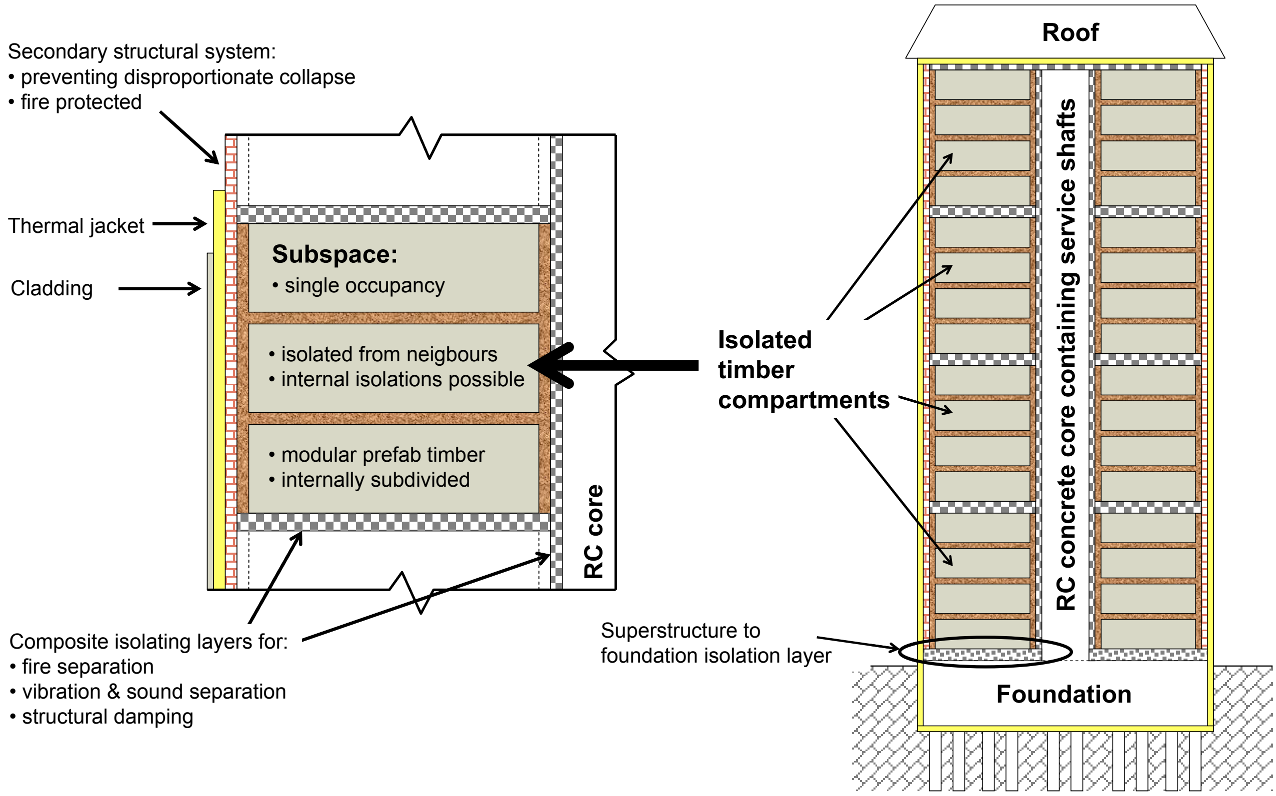



*Figure 1: High-rise building with isolated timber compartments. Isolation to be defined [1].*

## 2 SCOPE OF STUDY

Against the above background, the authors are developing a hybrid construction concept aimed at utilizing timber plus other materials to create multi-functional interfacial slab substructures. With intent that such substructures will act together with framework and shear-wall substructures made from various materials, to create building superstructures. More specifically, the presented concept addresses the need to satisfy multiple performance requirements for:

- Structural integrity at levels of
  - substructure (e.g. basic strength and stiffness)
  - complete system (e.g. control of lateral drift, avoidance of disproportional damage);
- Fire safety at levels of
  - substructure (e.g. non-combustible assemblies)
  - system (e.g. 'total burn-out' compartmentalization); and
- Isolation of occupancies with respect to vibration and sound transmission.

Practical implementation of the idea of multi-functional interfacial substructures is demonstrated below based on the example of utilizing the engineered wood product Cross-Laminated-Timber (CLT) as structural spine material of slab type floor substructures.

## 3 TECHNICAL DETAILS

The primary concerns address the structural integrity on local and global levels and the dynamic response of the substructure while issues related to acoustical and fire performance are subsequently further addressed.

### 3.1 STRUCTURAL INTEGRITY AND VIBRATION SERVICEABILITY

A combination of considerations with respect to horizontal and vertical vibrations of and within tall, slender buildings suggests the use of CLT as the primary structural material. The relatively high degree of isotropy inherent with CLT benefits the vertical motion of floors by enhanced separations of natural frequencies, and together with the generally high strength and stiffness suites the purposes of a rigid diaphragm for in-plane transfer of storey shear or torsional moment to superstructure framework and/or shear walls. The high stiffness to mass ratio of timber leads to relatively light-weight elements, allowing long span horizontal interfaces without susceptibility to resonance vibrations from footfall impacts, and on system level minimizes concerns of undesirable inter-storey drift. To note is that within high-rise buildings having structural steel or RC gravitational load resisting superstructure frameworks use of CLT can reduce the total mass of floor substructures by up to two-thirds, and about halve the effective modal mass in lateral vibration if mechanically equivalent CLT floor slabs are substituted for conventional RC slabs [2],[3]. Structurally the associated gains of such systems can be translated into enhanced systemic structural performance (e.g. reduce expected drift levels under design level winds or seismic base accelerations), and/or reduce the sizes and costs of structural superstructure and foundation systems.

Despite the abovementioned advantages, local and global building motions need to be further addressed. The lateral motion of tall buildings that can be felt by humans or cause damage to non-structural parts of the building may not be sufficiently reflected by relative storey drift levels (alone), but requires consideration of physical quantities like acceleration [4],[5]. Perceptible vertical floor motion can occur commonly due to a summed effect of several natural frequencies interacting [6], depending on the number of modes within a certain frequency range and the modal damping ratios.

Expanding on the above aspects to ensure satisfactory dynamic responses of the sub-structural interface elements, inclusive of beneficial effects for the building response on system level, yielded the following considerations with focus on enhancing the damping.

### 3.1.1 Structural damping

Friction at contact area of support systems and floor structure is a considerable source of damping. Imperfections in the overall system, including those caused by swelling and shrinkage of the wood (out-of-plane), can result in non-contact spots and thus loss of damping capacity. The use of resilient material between support structure and flooring system can be a drawback by means of reducing support stiffness and in turn natural frequencies. Considering that full contact of floor and supports along all edges may not always be achieved, cutting minor shallow notches along the outer longitudinal edges of the CLT plates, ensured major contact along the primary support in width direction. The room between (notch) bottom of the plate and top flange of the secondary edge support may be entirely filled with resilient/damping material (Figure 2); analogous for intermediate supports (sub-beams).

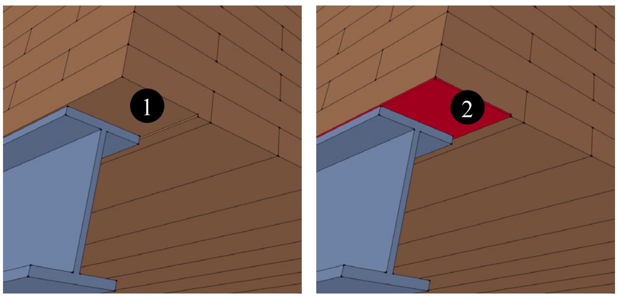



***Figure 2:** Notch cut* ❶*, and damping layer inserted* ❷

This can indeed be a cause for reduced separation between natural frequencies. But the all edge support approach should result in generally well separated natural frequencies due the effective use of the high transverse CLT plate stiffness. With increasing floor width, both effects may diminish. Using resilient material on secondary support beams may thus be a feasible way of enhancing damping without fundamentally harming the actual vibrational floor behaviour.

Friction at joints of CLT plates contributes to enhancements of damping characteristics [7],[8]. A number of joints larger than required may not be desirable with respect to acoustical performances.

### 3.1.2 Passive dampers

The use of distributed liquid dampers (DLDs) [9], which may or may not be frequency tuned, attached to the major structural floor system (Figure 3), is another potential source for damping that is activated when e.g. a person walks over the floor and sets the water into motion. It is automatically activated when the building responds to lateral loading. DLDs may have the potential of deliberately releasing water or other liquids in a worst case fire scenario or they should be insulated to protect them from fire.

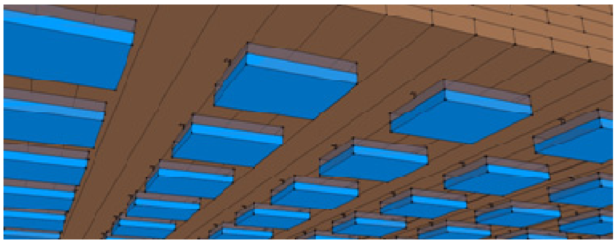


***Figure 3:** DLDs attached to CLT floor bottom*

Those reasons, plus the easy of connecting CLT to structural frameworks, and possibilities for prefabrication and rapid erection of floor substructures, are all arguments for selection of CLT as structural backbone material for slabs.

## 3.2 FIRE DESIGN

The fire design concept adopted for multi-functional floor substructures is that those and other types of interfacial substructures must be capable of containing fires until complete burn-out of a fire compartment, without violation of the integrity of local or system level structural systems [10]. Adopting this concept, surface fire protection layers on interior surfaces of floors and ceiling and wall substructures that define fire compartments may be destroyed but shielded structural layers and connections should not require post-fire repair. Implicitly the fire design concept includes that people, who may not be able to leave the building in a worst case scenario, can survive a fire event outside the effected compartment. This may include creation of safe zones/rooms.

The authors are currently working with colleagues in Canada and Europe to model and experimentally verify fire compartment performance specifications and layering materials that fully protect CLT backbones of interfacial substructures.

### 3.3 ACOUSTICAL PERFORMANCE

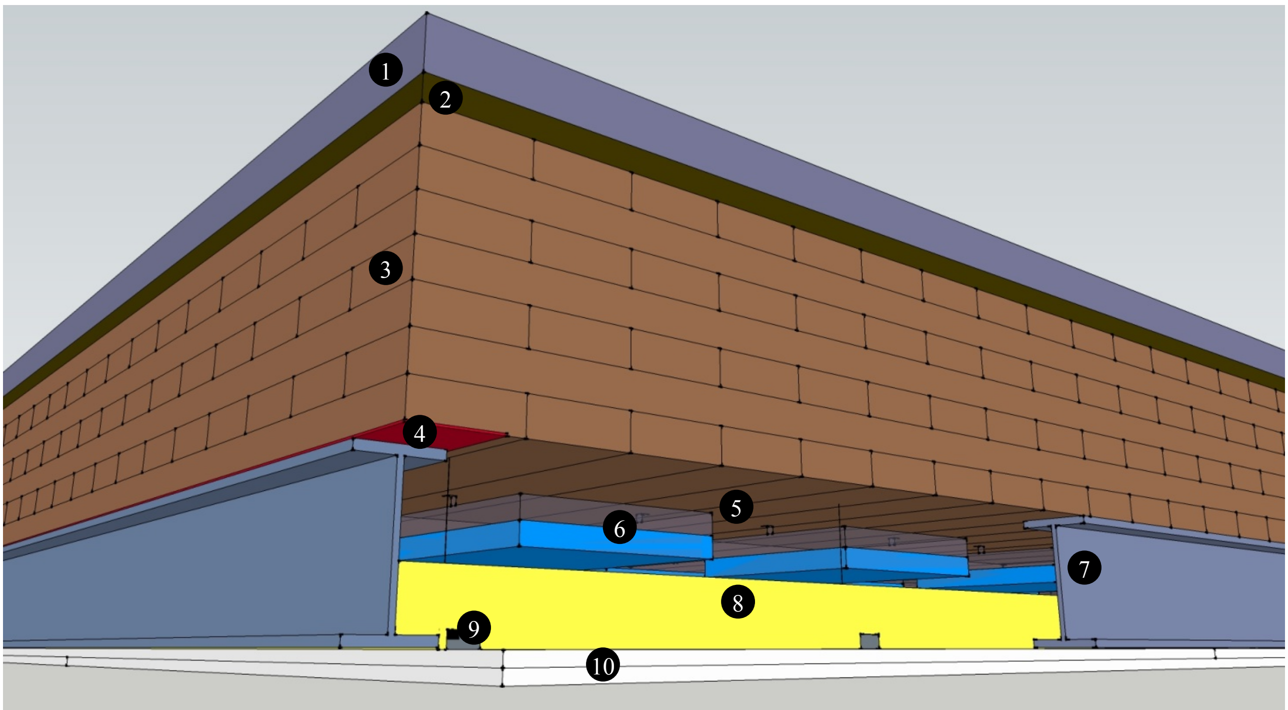
For a satisfactory control of sound transmission, sound energy can be reflected and absorbed by the use of appropriate material. While a non-porous, dense material helps to prevent sound waves from escaping a space, some of the energy passes into the element. The passing energy is absorbed only to a small degree, being converted to heat by friction of the material's molecules. Energy that is not reflected or absorbed is transmitted in part directly through the separating element, and in part indirectly with the energy travelling along one element to the next, and radiated as air-borne sound on the other side. Notable sound absorbing effects can be achieved by the use of porous, usually light-weight, material [11],[12]. The (disturbing) noise in a building is commonly initiated either by direct impacts on a partition, e.g. by footfalls from people, or by airborne sound pressure on the partition, e.g. due to music, conversation, etc.

Practically, with respect to horizontal interfaces, it is required to cushion problematic footfall impacts using soft materials to either create a floating floor or a resilient floor finish. Additional gains of sound reduction may be obtained by resiliently suspended gypsum board ceilings, with greater efficiency when the gypsum board mass or cavity depth is increased or sound-absorbing material added, with respect to both transmission of impact and airborne sound [13]-[15].

### 3.4 TENTATIVE COMPOSITION

Considering all the discussed design aspects, the composition of such a multifunctional interface may tentatively be such as demonstrated in Figure 4.

The CLT plates form the structural backbone of the system with the benefits discussed above. The concrete screed adds a non-combustible layer on top for fire protection following the building encapsulation concept, simultaneously adds mass for reduced acceleration levels and further enhances sound attenuation if employed as a floating layer; similarly for the gypsum boards apart from that they are connected to resilient furring channels, suspended with isolation clips (cf. [16]). The cavity/space between the CLT plates and the gypsum boards can be used for adding sound absorbing material, installing DLDs to control local and global vibrations, and for pipework/sprinkler systems while functioning as insulation itself. Mineral fibre layers underneath the concrete screed for impact sound insulation and damping strips along secondary support beams can further contribute to enhanced serviceability. Optionally, if variations in stiffness are required to e.g. raise the fundamental natural frequency of the interface system, the number of CLT cross plies can be changed (e.g. from 3 to 2, raising longitudinal plies from 4 to 5 for 7-ply CLT) and/or the concrete screed connected to the CLT plates, taking into account the other, possibly detrimental, effects that this will have on vibrational and acoustical performances.



1 Floating concrete floor level
2 Mineral fibre board
3 CLT plate
4 Damping layer
5 Cavity/Space
6 DLDs
7 Steel support I-beam
8 Sound absorbing material
9 Resilient furring channels and isolation clips
10 Gypsum board layers

***Figure 4:*** *Example of tentative composition of a horizontal multifunctional interface for hybrid structures*

## 4 FIRST RESULTS

The simplicity and efficiency of using DLDs is currently investigated with the first results presented in [9], indicating the potential in reducing acceleration levels for lateral building vibrations.

Initial tests with regard to vertical floor vibrations were carried out on 5-ply CLT plate systems supported along two edges, investigating the effect of structural variations with respect to support stiffness, end fixity and floor width. Major conclusions were that two-side supported CLT plate systems possess a damping ratio of below 1% for first order modes, and that the number of vibration modes within a specified frequency spectrum increases considerably for increasing floor width. Damping may increase with increasing number of floor plates due to friction at the joints. More beneficial results are expected for supporting all edges of the floor. All results of the initial tests are presented and comprehensively discussed in [8].

## 5 CURRENT AND FUTURE WORK

The dynamic response of the structural spine is currently investigated on 7-ply CLT plate systems with a span of ca. 6.2 m, consisting of up to 3 plates in width, for different support conditions, ply layups, and floor width, including various damping mechanisms. In addition, a CLT system with floating concrete screed on top of a sound insulation layer is envisaged to conclude this test series.

Future work will furthermore focus on optimization of CLT/concrete slabs that perform multiple functionalities. In terms of structural functionality, emphasis will mainly be on resistance of effects of gravitational forces on lateral loading aspects of system performance. Focus for fire and vibration serviceability functionalities will emphasise on preventing fire spread on the outside facade of the building and ensuring that addition or removal of layers in slabs for particular purpose does not adversely influence performance in other respects. The emphasis will be contextual to high-rise buildings where CLT slabs are used in lieu of RC and other concrete-and-steel hybrid slab systems. It addresses slab situations involving effects of combined lateral and gravity loads on building superstructures. Pros and cons of incorporating resilient materials within large hybrid floors or within supports to such floors in such systems will also be elucidated.

Given that expectations for lifespan of high-rise buildings can be greater than for low-rise buildings, it is important to explicitly address durability of both structural and non-structural components of buildings. The authors are not working directly on those issues but are cognizant of the need for proper attention to issues like decay or other deterioration of timber, engineered wood products and other hybrid construction materials. Thus, state-of-the-art durability design, construction and maintenance strategies are embedded into the interface construction concepts they advance [17].

## 6 SUMMARY

The project presented in this paper focuses on forming horizontal interfacial slabs to be used in high-rise hybrid buildings for separation of compartmentalised occupancies, addressing symbiotically structural integrity, serviceability, and fire design. The general concept was outlined and initial experimental results presented (see also [8],[9]). The exact composition of the interface with types, purposes and dimensions of the materials will be gradually further defined to reach an optimum design level, which will only require few reconsiderations for individual building design of similar purpose.

For fully effective multi-functional interfaces, it will be required to establish complementary vertical separations, and joint connections that ensure good acoustical interface performance (e.g. low flanking transmission).

## 7 CONCLUSION

Even though not all details have been elaborated yet, it is clearly technically possible to create modern high-rise building substructures with timber structural spines. This is achievable economically in ways that exceed public and regulatory performance expectations.


## ACKNOWLEDGEMENT

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