

DEVELOPMENT OF A HYBRID WALL-FRAMED SYSTEM

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Abstract

This paper explores the development of a novel wall-skeletal modular structure using Cross-Laminated Timber (CLT). Research by Design methodology was employed to examine the hybrid system's feasibility and sustainability. The study includes designing and testing a CLT pavilion, highlighting the system's potential in diverse architectural applications. Key findings involve structural load analysis software and the adaptability of this modular approach in various building types.

Keywords

Modularity in architecture, sustainability, cross-laminated timber, wall-skeletal hybrid structure

1 INTRODUCTION

The objective of this paper is to contribute to the field of modular architecture research through insights derived from a comprehensive study of the issue, the analysis of relevant examples and the development of a new hybrid modular structure [1].

An integral part of the research involves the experimental verification and testing of specific modular structures at various scales and environments. The research objectives are centred around the experimental assessment of a pavilion made of CLT panels using an elementary modular 'wall-skeleton' system. The pavilion's design is based on a universal unit composed of three basic vertical and horizontal flat elements. Through the multiplication, rotation, and intercombination of these modular units, avenues for the continued evolution of this structural system are explored. The primary goal is to scrutinize the chosen structure, material, scale, and modular system to substantiate its sustainability.

Limits of modularity

Researching throughout the area of modular architectural and construction concepts, we came across two approaches. The first and most widespread adopted approach in the design of modular systems is the room module system (Fig. 1). In this context, the incorporation of Cross-Laminated Timber (CLT) panels as structural elements for both walls and floors contributes to the establishment of fundamental spatial module units. These modular units, featuring CLT panels, are characterized by their capacity for stacking, akin to the arrangement observed in prefabricated shipping containers [2].

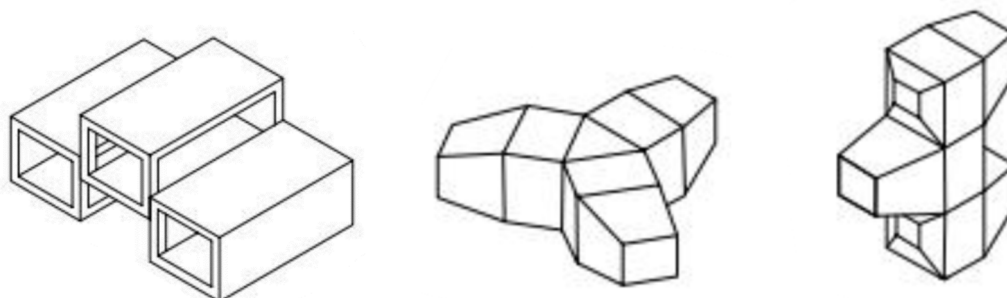


Fig. 1 Different room module arrangements.

Another construction method commonly used for creating modular systems is the timber skeletal system. The term "skeletal system" implies that the primary load-bearing elements are arranged in a framework or skeletal structure, providing stability and strength to the overall structure. Wooden skeletal systems often utilize various wood-based components, such as beams, columns, and trusses, to create the essential framework of a building [3].

Our current research endeavours aim to scrutinize and advance a hybrid wall-skeletal system. Leveraging wall panels as autonomous elements could provide greater flexibility in spatial arrangements while concurrently maintaining the structural rigidity of constructed buildings.

2 METHODOLOGY

In this study, we employed Research by Design (RbD) methodology, a distinctive approach that integrates traditional research techniques with the creative process of design.

In applying the RbD methodology to our study, we focused specifically on the experimental assessment of a pavilion constructed from Cross-Laminated Timber (CLT) panels, forming an elementary 'wall-skeleton' modular system. This pavilion was designed using a universal unit composed of three primary vertical and horizontal flat elements, allowing for variations through multiplication, rotation, and intercombination. Our methodological approach not only facilitated a systematic exploration of the design process but also enabled a detailed examination of this specific modular structure. By integrating traditional research techniques with the creative design process, we were able to closely analyse the sustainability, structural integrity, and spatial flexibility of the CLT pavilion, thereby yielding valuable insights into the practical applications and potential of such modular systems in architecture. This comprehensive approach was instrumental in uncovering new possibilities and enhancing the understanding of modular constructions in sustainable architecture.

Structural material

In the realm of concrete structural systems, two-way flat floor plates have gained prominence in contemporary construction practices. Drawing upon this paradigm, a timber-bearing structure constructed from Cross-Laminated Timber (CLT) has been devised. This timber-bearing structure is characterized by vertical solid CLT plane elements akin to quasi-columns exhibiting a rectangular cross-section and a timber-concrete two-way flat floor plate. This emergent structural system presents diverse architectural compositional possibilities through distinct layouts. The system's requisite spatial stiffness and stability can be attained through the judicious alignment of the vertical elements.

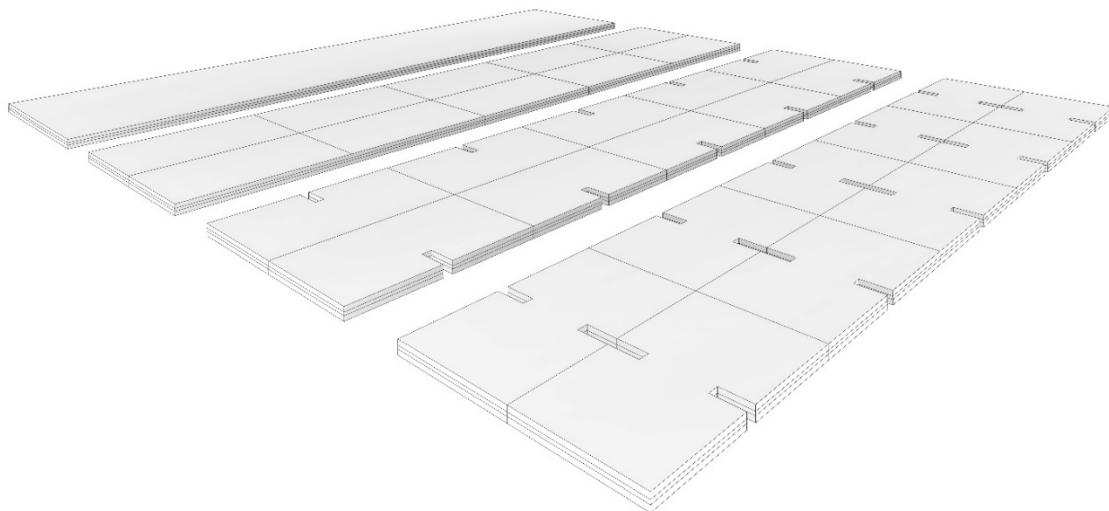


Fig. 2 Cutting plan of one CLT panel board sized 3 × 16 m.

Geometry development

The geometry of the modular element in the experimental structure is derived from the material's inherent characteristics. The choice was straightforward, with a primary condition being sustainability. Consequently,

a clear preference was given to CLT panels (Cross-Laminated Timber), representing planar elements manufactured in standardized dimensions (Fig. 2). Hence, the foremost challenge became exploring innovative and sustainable methods to create a spatial structure from these planar elements.

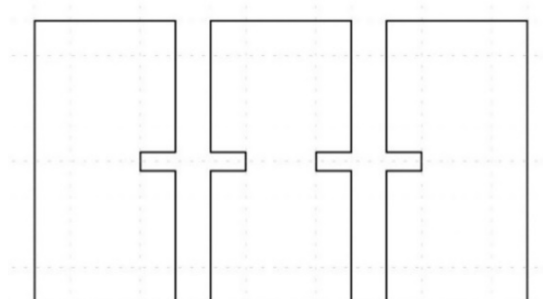


Fig. 3 Shape of basic flat elements of the module.

The genesis of the wall-skeletal system concept has iteratively evolved through the diverse articulation of vertical and horizontal flat elements. Even though a CLT panel is a planar wall element, we have endeavoured to extract the maximum utility from its inherent qualities, aiming to create an intriguing spatial structure. Each module comprises three panels, and its construction is predicated on a singular standardized element: a panel with dimensions of 1.5×3 metres Fig. 3, distinguished by variations in panel cutouts. The modular stacking system is straightforward yet offers a degree of variability.

Jointing as a principle

The most essential subject in the design process was the structural interface between individual structural components, crucial for providing support, stability, and load transfer. Slot joints, groove joints, and dado joints are techniques used to connect panels. Slot joints, particularly prominent in furniture design and panel construction, offer both strength and aesthetic appeal. This joint involves cutting a slot or groove into one panel and inserting the edge of the other panel into it, ensuring a secure connection. Typically concealed, slot joints result in a visually pleasing appearance without visible fasteners. They provide stability and contribute to a clean, continuous surface. Achieving a precise fit is vital for the success of a slot joint, often facilitated by CNC milling. The joint's strength is its significant advantage, offering good structural integrity, especially when combined with other methods like glue or screws. While sufficient for furniture and small-scale objects, larger structures may require additional reinforcement for stability. These advantages of slot joints influenced the overall development of the structure.



Fig. 4 Diagram of the jointing of basic units.

Fig. 4 presents a slot joint, which involves cutting a groove into both panels and inserting the edge of one panel into the slot of the other. The result is a secure and often seamless connection. The joint is hidden, clean, and visually pleasing without visible fasteners on the exterior.

3 RESULTS

Structural analysis of a hybrid structure

Within the domain of concrete skeletal structural systems, structures featuring skeletons with slab-less floors have gained considerable popularity. Drawing inspiration from this concept, a wooden system has been innovatively devised. This wooden system incorporates vertical massive planar elements, resembling quasi-columns with a rectangular cross-section, along with wood-concrete composite floor slabs. The outcome is a novel hybrid structure, a wall-skeletal system with a ceiling devoid of traditional slabs.



Fig. 5 The assembly process of basic units.

This unique construction not only introduces an alternative approach to structural design but also expands the scope of its potential applications from both a typological and layout perspective. The strategic arrangement and orientation of the vertical elements provide an avenue to achieve the requisite overall spatial rigidity and stability for the system (Fig. 5). The versatility of this hybrid system opens diverse possibilities for architectural solutions, making it an intriguing prospect for various construction scenarios [4], [5].

The static analysis was executed utilizing DLUBAL RFEM software [6], a program grounded in the Finite Element Method. The CLT material was simulated with consideration for its distinct cross-layered structure. The upper CLT-lightweight concrete composite slab incorporated a rigid shear connection, reflecting hybrid material properties. The concrete, in contrast, was modelled as an isotropic material.

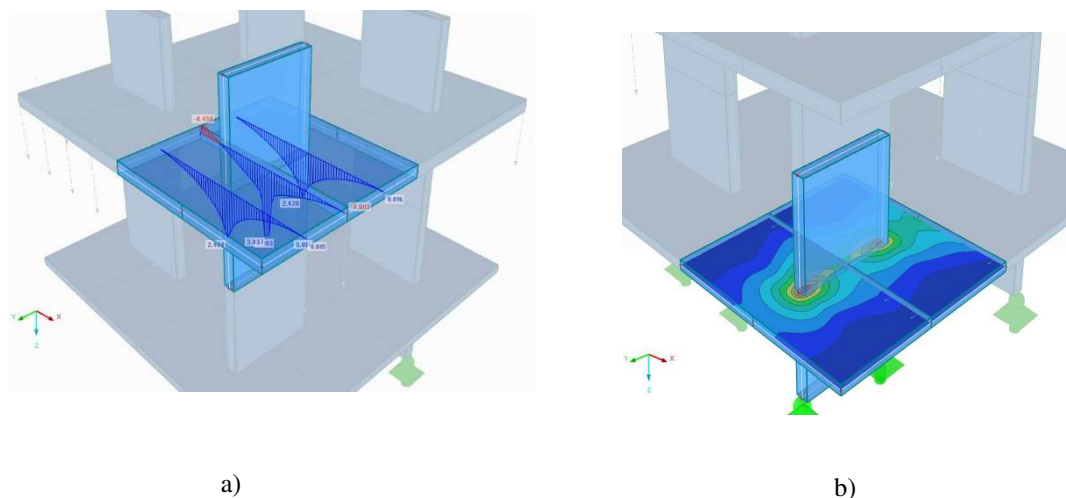


Fig. 6

- a) Tensile stress σ_x on the top surface of the CLT – maximum value 4.97 MPa.
- b) Tensile stress σ_x on the top surface of the concrete – maximum value 3.6 MPa.

The structural loading comprised the anticipated floor finishing load 1 kN/m², the characteristic imposed load for office buildings 2.5 kN/m² in varied positions, and wind loads from multiple directions. These load combinations conformed to EN standards. In the upper CLT-concrete composite slab, the concrete layer experienced tensile stress with a maximum value of 3.6 MPa refer to Fig. 6a.

The maximum normal stress σ_x in the CLT slabs' outer layers was recorded at ± 5.0 MPa in Fig. 6b, while the maximum normal stress σ_y in the cross layers (the second layers from the surface of the CLT) reached ± 6.1 MPa. The highest shear stress observed in the CLT's cross-section was 1.04 MPa.

The observed vertical deformations in the cantilevers were 3.1 mm for the top CLT-concrete composite slab and 8.7 mm for the bottom CLT slab. These results confirm that the structure adheres to the stipulated design criteria.

Vibration analysis, as depicted in Fig. 7a, and Fig. 7b, reveals the concrete layer's impact on the structure's vibrational behaviour. The structure's improved vibrational performance is also attributed to its elements' alternative orientation (rotation). Generally, the vibrational characteristics of timber floors can be enhanced by augmenting mass, stiffness, or damping capacities. An optimal natural frequency threshold for timber floor structures is identified as exceeding 8 Hz. The prototype structure illustrated in Fig. 7b meets this criterion.

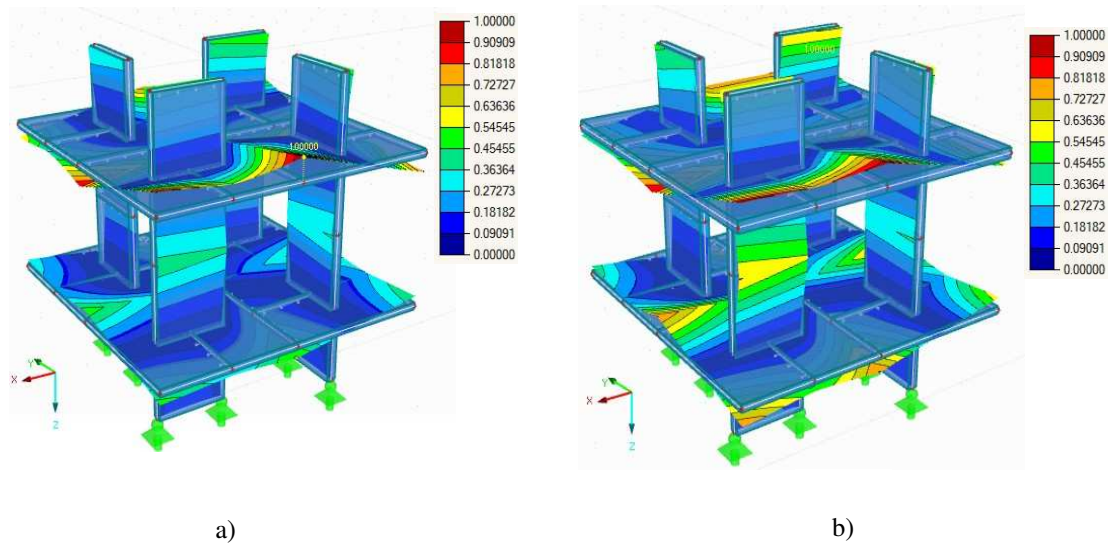


Fig. 7

- a) 1st modal shape of the structure with alternate element orientation and CLT slabs $f_1=13.401$ Hz.
- b) 1st modal shape of the structure with alternate element orientation, bottom CLT slab, and upper CLT-concrete composite slab $f_1=14.441$ Hz.

Disposition analysis of the studied geometric schemes

The developed system of the wall-skeleton structure could be applied in the design of residential buildings, administrative buildings, educational facilities, and many other typologies.

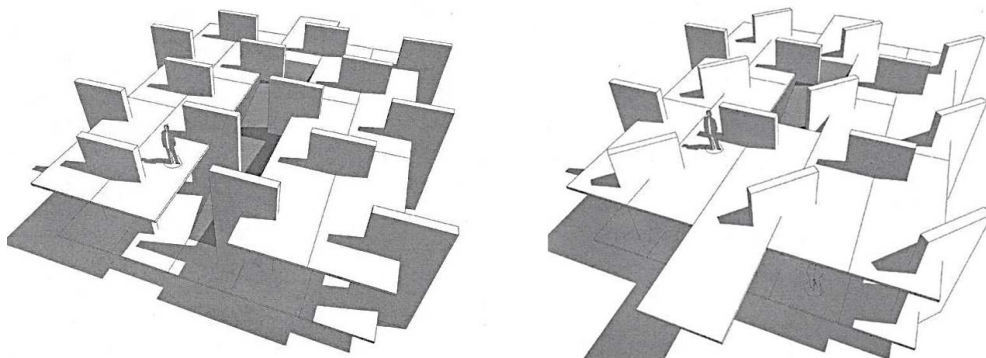


Fig. 8 First conceptual sketches of the modular structure.

The pavilion can be repeatedly utilized for temporary activities. For instance, it can serve as emergency housing in the aftermath of a natural disaster or migration, or as a temporary solution for festivals or sports events. A particularly suitable application of this construction system appears to be in small pavilions, such as those intended to house exhibitions (Fig. 8).

Due to the elementary nature of the basic element of the wall skeleton, this bearing system, based on a trio of CLT beams of the same dimensions connected into one spatial segment, has significant developmental potential. By combining the basic spatial segment, multiplying it, layering it, and rotating it, various layout variations can be achieved. The most significant potential is undoubtedly the modular organization of elements in a 3×3 m configuration Fig. 9 or, alternatively, a multiple of 6×6 m.

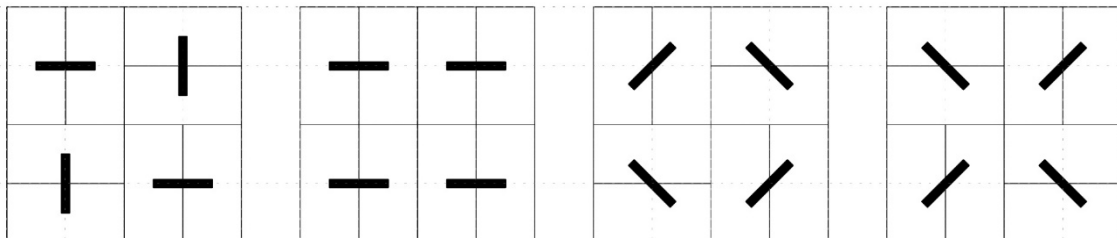


Fig. 9 Options for panel disposition layouts.

Exhibition and gallery spaces could leverage the spatial potential of the wall skeleton, as the segments of wall-bearing elements offer an ideal exhibition surface with the possibility of expansion and supplementation in various directions (Fig. 10). Given its modularity, this construction system could be utilized for structures with a temporary character, such as temporary cultural objects in urban or residential structures. The spacing of the bearing elements can be varied to some extent.



Fig. 10 Potential usability of pavilion.

4 DISCUSSION

We can assess that the execution of the experimental prototype proved that the principle is sound. It brought several positive and negative outcomes. When considering one module, i.e., the basic unit consisting of three-panel segments, we must note that there are significant difficulties regarding manipulation, instability, and lack of autonomy in this element. The structure only acquires meaningful spatial and structural potential when multiple modules are combined. During manipulation and the actual assembly of modules, attaching the vertical panel to the base or at least temporary fixation using slot joints significantly aids in the process.

Subsequent consideration of potential alternative solutions and spatial arrangements of modular segments indicated the possibility of expanding the layout (Fig. 11). Static analyses demonstrated the rigidity of the structure, suggesting the option to extend the spacing between wall-skeletal elements and supplementary horizontal stiffening structures. The result will be a sparser grid of supporting walls and a more open spatial layout.

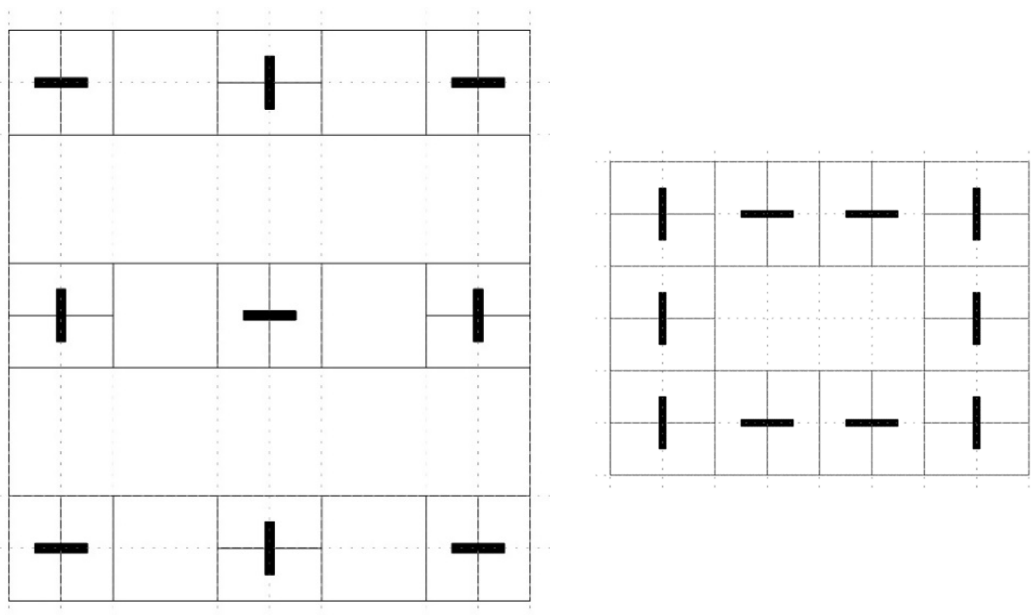


Fig. 11 Extended disposition layouts.

5 CONCLUSION

By employing Research by Design methods, we were able to transcend the boundaries between research and design, thereby opening new avenues for a comprehensive understanding of modular structures and their potential in the realm of sustainable architecture. This framework enabled us to approach design challenges from various perspectives, enhancing creativity and innovation in the architectural solution-finding process.

We firmly believe that the outcomes of the practical phase of the research will contribute to both architectural practice and research in the field of modular construction. The acquired insights and outputs will provide us with fresh perspectives for designing sustainable, efficient, and innovative structures.

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