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A REUSE-READY TIMBER SLAB-AND-COLUMN SYSTEM FOR MODULAR BUILDING STRUCTURES

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ABSTRACT: The construction industry is a significant contributor to resource consumption and waste generation. To address this issue, component reuse has been proposed as a way to prevent valuable building elements from being discarded and avoid producing new ones. However, the lack of circular economy principles in existing structures makes it difficult to extract and exploit reusable components fully. This paper presents a new load-bearing timber system (Pixel Slab) designed for disassembling and reassembling multiple times over the building's lifespan. The system goes beyond the traditional concepts of modularity and reversibility, providing designers with a minimum kit of parts that can be used to make localized adjustments and accommodate a wide range of building designs – such as floor geometry, load conditions, and supports distribution – with little to no new material input. This allows for functional design requirements that are difficult to predict over the long term. The system also focuses on low-tech assembly and disassembly processes, embodied environmental impacts, and manufacturing costs, all of which aim to increase the potential for component reuse. The proposed timber solution proved to be particularly suited to increase the sustainability of short-lived buildings.

KEYWORDS: Component reuse, design for deconstruction, timber structures, circular economy, sustainable buildings, construction and demolition waste, material recovery.

1 INTRODUCTION

Over the last few decades, the construction industry has been at the center of ample criticism because of its role in the climate change emergency that societies face nowadays. Due to the high growth rates of newly built infrastructure and the widespread use of highly pollutant construction materials, the industry has been identified as responsible for 15% of the world's CO2 emissions [1] and one-third of the waste production [2]. Besides, recent research associates it with 50% of the exploitation of natural resources [3,4] and 36% of global energy consumption [5]. As the demand for new housing and civil infrastructure is expected to grow in the upcoming decades, measures are urged by private and public organizations to deal with such a multiscale challenge.

In this context, timber structures arise as an environmentally friendly strategy to tackle the aforementioned issues, providing the means to reduce the carbon footprint of the construction industry. For instance, previous studies have shown that the energy consumption of concrete houses is 60-80% higher compared to timber houses [6], and that the CO_2 production during the life span of a concrete building is 30-130 kg/m^2 greater [7]. In seasonal countries with cold winters and hot summers, it has been calculated that a timber house consumes around 15% less energy for heating/cooling when compared to a concrete or steel house, and over a period of 100 years, it is estimated that a timber house could reduce the net emissions of greenhouse gases by between 20% and 50% when compared to traditional systems [8].

On the other hand, the inclusion of Circular Economy principles into construction practices has also proved to be an effective approach to alleviate the environmental impact of new infrastructure. In particular, the reuse of construction components has been gaining traction lately [9], with the aim of keeping construction components in a closed loop at their highest value and extending their lifespan over several building cycles. This way, components are brought back into the construction supply chain with little/no maintenance after the initial structure reached obsolescence, minimizing new production and diverting valuable resources from landfilling.

The current practice of timber construction does not allow a straightforward inclusion of reuse techniques at the end-of-life phase of existing buildings. Therefore, once timber structures have reached obsolescence, their components are discarded or must undergo time/energy-consuming procedures to be reused in different building applications. And even though mass-timber structures generally employ reversible and standard connections that facilitate assembly/disassembly procedures, their future reuse potential cannot be guaranteed beforehand. This is mainly due to the lack of open-ended reuse principles in current timber construction practices, such as adaptivity to different architectural requirements and load conditions, use of standard and interchangeable components and connectors, embracing long-term purpose uncertainty, and easy repairability, replaceability, and transportability.

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Therefore, this paper presents a novel timber slab-and-column system "Pixel Slab" designed for open-ended reuse over multiple life cycles. The system goes beyond the traditional wooden concepts of modularity and reversibility, providing designers with a minimum kit of parts that can be used to make localized adjustments and accommodate a wide range of building designs – such as floor geometry, load conditions, and supports distribution – with little to no new material input. This allows for functional design requirements that are difficult to predict over the long term. The system also focuses on low-tech assembly and disassembly processes, embodied environmental impacts, and manufacturing costs, all of which aim to increase the potential for component reuse of current timber construction practices.

2 MATERIALS AND METHODOLOGY

This study follows a Research-through-Design (RtD) approach in the development of the Pixel Slab system. The RtD methodology generates new knowledge through a systematic and iterative process of evaluating design results and feedback [10]. This approach combines theoretical concepts with design and development, allowing for exploratory ideas and a disruption of the status quo in a scientifically controlled environment. The RtD framework for this investigation, as shown in Figure 1, consisted of six main stages: (1) goals and functional requirements definition, (2) iterative design sessions, (3) conceptual design, (4) structural implementation, (5) feasibility analysis, and (6) full-scale validation.

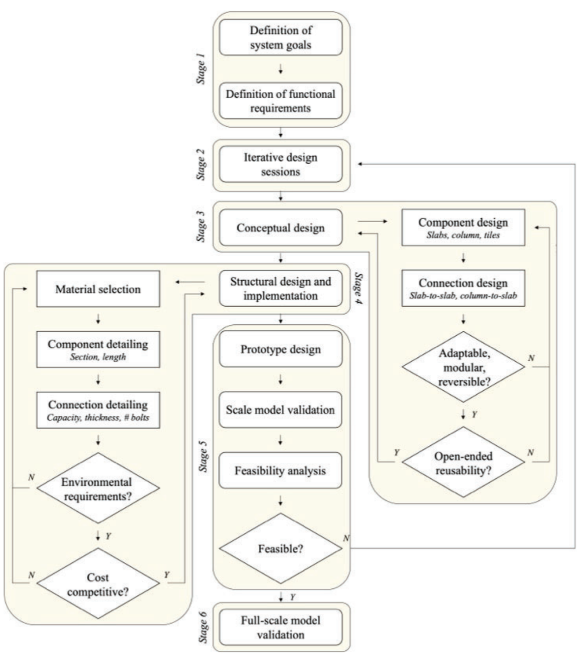

Figure 1. *Methodological workflow for the development of the Pixel Slab system.*

A set of system goals was defined early in the development of the Pixel Slab system aiming at guiding its design principles and requirements. Adhering to a downstream component reuse philosophy [9], the system aims to bridge the gap between reusability and its practical application in timber construction. At the same time, it incorporates Circular Economy principles into the design phase to account for future uncertainty and maximize the potential for open-ended reuse. The goal is to design timber structures that are easily repairable, replaceable, demountable, and transportable. Accordingly, the system goals are stated as follows, in descending order of hierarchy:

- To maximize the open-ended reuse potential of timber structures by implementing design-for-reassembly principles in such a way that it can meet unpredictable scenarios and boundary conditions.
- To minimize the detrimental environmental impacts related to manufacturing, handling, maintenance, and end-of-life.
- To reach manufacturing and operation costs that are competitive to conventional products in the long term and over several life cycles.

A comprehensive set of functional requirements was established to provide a clear research framework by considering past, present, and future reuse practices, and to establish the boundaries and conditions for the new timber solution. The requirements aim to ensure the structure's technical and economic appeal under various future scenarios and promote the open-ended reuse of the structural system and its components. To facilitate the implementation during the conceptual design phase, the functional requirements were grouped into three categories: (1) structural, (2) assembly and disassembly, and (3) versatility and modularity.

The structural requirements establish the scope and niche of the proposed timber system in terms of its intended applications and performance:

- To provide a load-bearing structural system for low- to mid-rise office or residential timber buildings.
- To create a continuous load path and carry vertical loads down to the foundation system. The system is not intended to carry horizontal loads and should be designed along with a lateral resistant system (e.g., core walls, bracing system, among others).
- To allow versatility of vertical load levels and spans between vertical supporting elements.
- To provide an effortless installation of vertical shafts, pipes, and non-structural elements.

Assembly and disassembly requirements define the design boundaries with the aim of maximizing the structure's reuse potential in unspecified future scenarios:

- To employ dry, readily accessible, reversible mechanical connections for assembling elements and components.
- To minimize the number of connections between elements, assemblies, non-structural components, and the main structural system.
- To maximize the use of standard connections across the different system levels (substructure, superstructure, flooring, and non-structural components).
- To employ only low-tech tools and procedures for assembling and disassembling. Likewise, to provide means for easy handling and transportation of components.

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Versatility and adaptability requirements aim to ensure that the Pixel Slab system can be adjusted and reconfigured for future reuse scenarios, making it flexible and capable of being used in a wide range of applications:

- To allow open-ended re-arrangements of structural and non-structural components in the system.
- To employ interchangeable modular elements and connections, facilitating reorganization and replacement of system components.
- To allow unplanned inclusion or removal of openings across the floor layout, e.g., for staircases, elevators, shafts, technical installations, or building extensions.
- Not to restrict the inner partitioning layout and to ease parallel disassembly if modifications are required.

3 RESULTS: PIXEL SLAB

Figure 2 shows the resulting timber Pixel Slab system. It comprises slab elements set horizontally to create a lateral surface and column elements to transfer vertical forces to the foundations. Slab elements are made up of glue-laminated timber beams connected orthogonally to form a uniform flat grid. Individual beams are 80×240 mm spaced at 400 mm from their longitudinal axis. Beams are manufactured by gluing eight timber laths (80×30 mm each) with alternating discontinuities, as observed in Figure 3. This allows a grid-like slab with uniform properties in both directions. This configuration achieves spans of up to 6 meters based on the loading requirements specified in the Swiss SIA 261 standard [11] for office and residential buildings. Slabs are 2.4×2.4 m to facilitate handling, transportation, and storage. Besides, the beams' discrete placement results in a uniform distribution of slab openings that makes room for columns, vertical shafts, or non-structural elements, resulting in a low-weight solution compared to traditional flooring systems.

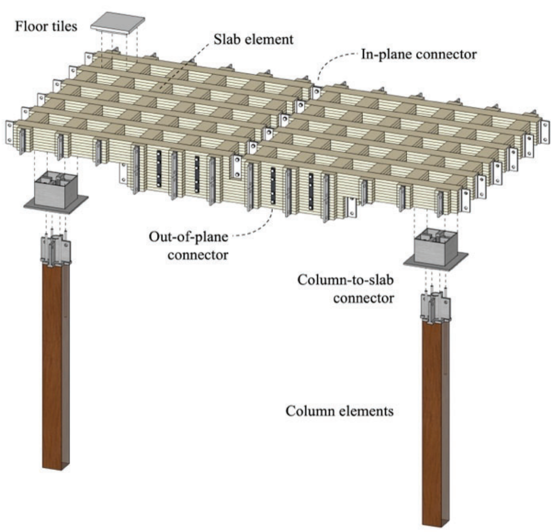


Figure 2. *Overview of the Pixel Slab system and its components.*

Flexible floor configurations can be designed by attaching slab elements with in-plane connectors, which transfer axial, bending, and shear loads between two adjacent slabs. In-plane connections were designed employing 240×83×15 mm steel plates grade S355, 660 mm long threaded steel rods grade 8.8, and two M27 steel bolts class 10.9, as per Figure 3. Threaded rods are embedded into timber into pre-drilled holes and glued-in employing epoxy resin, and subsequently welded to the steel plates. This way, in-plane connections are reversible and allow effortless construction, deconstruction, and reuse.

The structural capacity (strength and stiffness) of slab elements can be increased by stacking them vertically with out-of-plane connections, which are designed to bear the shear and axial loads that arise at the interface between slabs while not blocking the installation of vertical pipes or shafts through the openings. Out-of-plane connectors employ 380×60×5 mm steel plates grade S235 and four M16 steel bolts class 8.8, as Figure 3 shows. With this design, out-of-plane connectors provide a convenient and reversible method to reinforce areas that experience high demands or to accommodate longer spans.

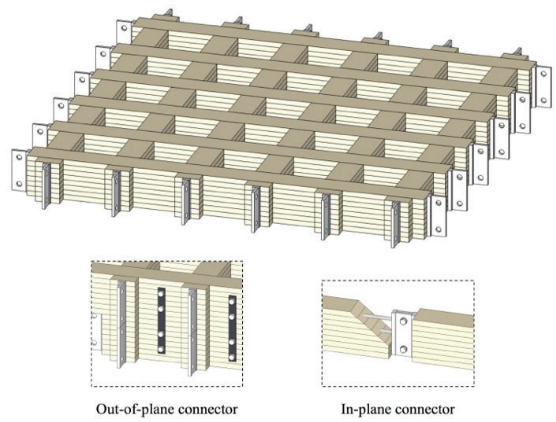


Figure 3. *Slab element with in-plane and out-of-plane connectors.*

Vertical loads are transferred across stories down to the foundation through conventional mass-timber columns. Forces between slabs and columns are taken by column-to-slab connectors that fit into the slab openings and nest the upper and lower columns, as Figure 2 depicts. Column-to-slab connectors employ high-strength steel and bolts, and their dimensions might vary based on the column sizing. Thanks to this versatile design, columns can be placed at any slab opening across the floor plan to accommodate different engineering or architectural requirements. It should be noted that the system described here is not intended to bear lateral loads, such as wind or earthquake, and should be designed as a gravity frame system without ductile capacity. Yet, the slab components must have adequate in-plane stiffness to effectively transfer lateral loads to the stiff core or bracing system.

Finally, floor tiles are installed on top of the slab elements to create a continuous surface for other finishing layers to be added, as illustrated in Figure 2. The dimensions of the floor tiles are designed to fit into one or multiple slab openings at once, with joint lines of minimum thickness to ensure proper sealing between components. This allows the tiles to meet technical requirements and fulfill non-structural functions such as smoke barriers or sound insulation. Tiles are attached to the slab components through reversible connections (i.e., bolts and nuts), allowing for future replacement of units and simple construction/deconstruction processes.

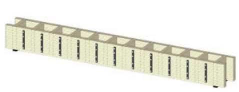
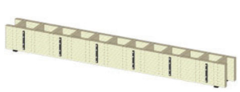
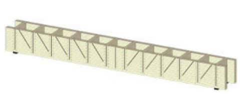
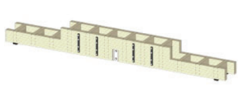
4 EXPERIMENTAL TESTING

A full-scale experimental campaign was carried out to evaluate the structural performance of the Pixel Slab system, and 19 different specimens were tested under bending load. Each specimen consisted of single-span components designed to be representative of the GLT beams used for the Pixel Slab system shown in Figure 2.

Beams were manufactured using mechanically graded GL32h timber with an elasticity module E = 13000 MPa and characteristic bending strength $f_{m,k}$ = 32 MPa. Single beams were 80×240 mm made up of 8 timber laths glued with polyurethane adhesive. The beams' span was 4800 mm, equal to the length of two Pixel Slab modules together. For double beams (laterally adjacent), the distance between their longitudinal axis was 400 mm. Besides, specimens had alternating discontinuous laths to simulate the discontinuity of orthogonally intersecting slabs. Finally, in-plane and out-of-plane connections were manufactured as per the specifications listed in Section 3.

Single-layer specimens ("S", "D", and "IP") were tested with a 4-point setup, while double-layer specimens ("OP" and "IPOP") with a 3-point setup. This was done to guarantee a bending failure in double-layer beams and not to reach the max shear strength. All tests used a 200 kN hydraulic jack fixed to a steel reaction frame and a loading beam was used to transfer the load from the jack to the specimens at the application points. For the 4-point setup, point loads were applied at 1800 mm from the beam ends.

Table 1. *Labelling and description of tested specimens.*

Test ID	Configuration	Description
S		Traditional GLT beam (×3).
D		Double beam with discontinuities (×4).
IP		Two discontinuous double-beams with in-plane connectors (×3).
OP(a)		Two stacked discontinuous double-beams with 11 out-of-plane connectors (×2).
OP(b)		Two stacked discontinuous double-beams with 6 out-of-plane connectors (×1).
OP(c)		Two stacked discontinuous double-beams with 90º and 45º screws (×1).
IPOP(a)		Two stacked discontinuous double-beams with in-plane and out-of-plane connectors (×4).
IPOP(b)		Two stacked discontinuous double beams only with in-plane connectors (×1).

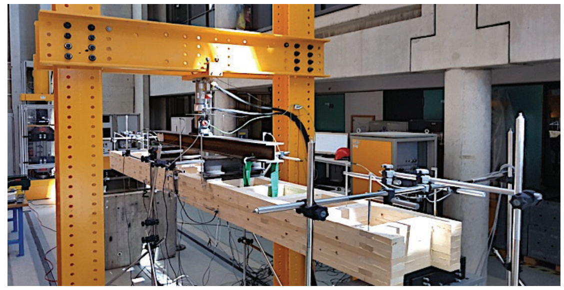


Figure 4. *Testing setup for "D" specimens.*

Specimens were installed on top of steel bearings and support beams placed 200 mm from the ends to allow free rotation under bending deformation. Displacement transducers (LVDTs) were installed to measure mid-span displacements, settlements at supports, slip between steel plates, and relative displacements between two stacked beams. Tests were conducted by applying load until the specimen's failure, defined as a 20% drop from the maximum recorded load. Figure 5 shows the force-displacement results for all "D" beams.

Test results showed that, when compared to traditional GLT specimens, beams with discontinuities had a reduction in the maximum moment M_{max} and elastic stiffness EI of 58.9% and 40%, respectively. This is mainly due to the presence of discontinuities along the longitudinal direction of the beam, which does not allow exploitation of the full cross-section and forces the continuous laths to take most of the tensile and compression stresses. Besides, the use of in-plane connections proved to be an efficient solution to join two GLT beams along their longitudinal axis, properly transferring axial, shear, and bending loads between the members. In this sense, employing glued-in rods showed to have a reinforcement effect on the capacity of the specimens, increasing the maximum moment M_{max} and elastic stiffness EI by 13.67% and 10.56%, respectively.

Finally, it was found that conventional beam design equations can be used to estimate the strength and stiffness of discontinuous GLT beams. To do so, the negative effects of the discontinuities can be considered as a reduction of the beam height, since fewer laths contribute to its capacity. To compute the maximum moment M_{max}, a reduced height $h_{red} = 0.6 \times h$ was found to be consistent with the lab results. To estimate the stiffness EI, a reduced height $h_{red} = 0.75 \times h$ is recommended.

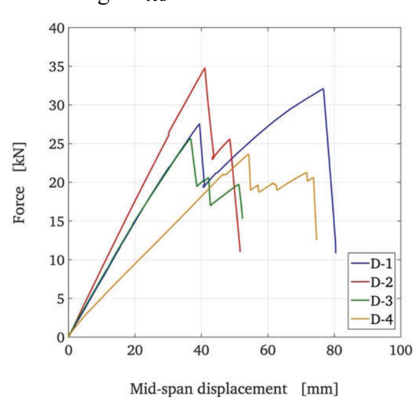


Figure 5. *Force-displacements data for "D" specimens.*

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5 CHALLENGES AND FUTURE WORK

As part of the development of the Pixel Slab system, a full-scale prototype was manufactured following the specifications outlined in previous sections, as show in Figure 6. After conducting a set of detailed evaluations, results showed that the manufacturing processes do not require specialized knowledge and can be performed by traditional companies and assembly lines. However, more development is needed to further reduce the manufacturing costs of the connections and/or their quantity per linear meter of interface.

Additionally, the results confirmed that the construction and deconstruction process is straightforward and does not require particularly trained workers or special tools, making it well-suited for prefabrication and dry procedures. Yet, it highlighted the relevance of paying close attention to dimensional tolerances to prevent deformation of components due to manufacturing imperfections, thermal effects, and creep or shrinkage.

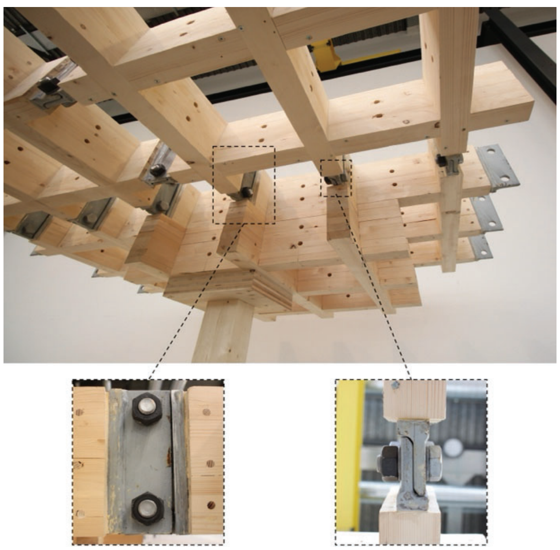

Figure 6. *Full-scale prototype of the Pixel Slab solution and connection details between beams.*

On the other hand, it is important to note that the full environmental benefits of the Pixel Slab system may only be realized over the long term. As part of the present research project, a preliminary life cycle analysis (LCA) was performed to compare the Pixel Slab system with a typical reinforced concrete system. The outcome of the analysis revealed that if only a single building lifespan is taken into account, the Pixel Slab system generates higher levels of emissions compared to the concrete solution. The primary reason for the higher emissions in the Pixel Slab system is the considerable amount of steel connections involved in the reusable solution. The production of steel accounts for a substantial portion of the total CO2 emissions. Nevertheless, when multiple lifespans are considered, the environmental impact per cycle of the Pixel Slab system decreases, and it becomes significantly lower than that of conventional systems. For instance, in a scenario with four lifespans, the emissions from the concrete system were ~80% higher compared to those generated by the Pixel Slab system. These results suggests that a potential entry market for the Pixel Slab are short lifespan buildings such as temporary classrooms or offices for ephemeral cultural or sport events.

These findings emphasize the potential of the Pixel Slab to decrease the carbon footprint in the construction sector. However, prior studies have highlighted that the emissions resulting from the disassembly and transportation of recovered components might have negative impacts on the environmental footprint [12–14]. This latter is largely due to the prominent levels of greenhouse gases associated with longer demolition periods, the use of heavy machinery, and the long-distance transportation of components (>1000 km) [12]. Further research is necessary to examine the relationship between these implications and the emission savings achieved through reuse, reduced landfilling and recycling, and lower production of new components.

6 CONCLUSIONS

This paper presents a new load-bearing timber system (Pixel Slab) designed for deconstruction and reuse over multiple building lifespans. The Pixel Slab system offers an alternative timber structural system for buildings designed for assembly and deconstruction by employing reversible connections and standardized components, with the main goal of increasing the open-ended reuse potential of building elements. In this sense, the proposed system incorporates a modular nature that provides constructors with an adaptable design framework with respect to floor geometries, spans, load conditions, and component distribution, making room for a diverse range of realistic solutions regarding architecture and engineering. Widespread implementation of the proposed solution is expected to support reducing global warming levels, resource depletion, and waste generation caused by the construction industry. The main features of the proposed system can be summarized as follows:

- The system is reversible and can be easily disassembled without damage to its components.
- The system is transformable into diverse floor plans and layouts since the columns' placement is highly flexible and slabs' thickness is reconfigurable.
- The system is adaptable and allows parallel assembly and disassembly, i.e., slab modules and tiles can be installed, removed, or replaced without disturbing adjacent components.
- The system allows full integration with non-structural components and sub-systems.
- No high-tech procedures and tools are required for the assembly and disassembly of the system and common equipment can be employed.
- Handling, storage, and transportation of components are facilitated due to compact dimensions.
- The construction process is dry and produces no waste on-site.

Future research is needed to propose standard procedures to estimate the residual properties of demountable elements and the environmental impacts of deconstruction and transportation related to disassembly and reuse. Likewise, further policy work that encourages reuse is still deemed necessary to boost reuse in the upcoming years.

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