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Advancing Timber for the Future Built Environment

Concept to Construction: Co-Design and Integrative Development Processes for the IntCDC Multi-Story Timber Building System

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ABSTRACT: In the context of the climate crisis and increasing urbanization, there is an urgent necessity to expand the typological possibilities in timber construction. Wide-span, point-supported timber systems for multi-story buildings offer the potential to substitute CO_2-intensive construction materials such as concrete and steel, utilize buildings as carbon sinks, and provide additional qualitative living and working spaces in urban areas. The development and incremental refinement of bespoke systems from initial conceptualization to technical feasibility and regulatory approval require the integration and coordination of comprehensive expert knowledge. A highly integrative approach and interdisciplinary exchange of expert knowledge within the research team, as well as iterative and reciprocal expert knowledge exchange with innovative stakeholders from the construction industry, are imperative. This paper presents the development of a co-design framework for the *IntCDC Multi-Story Timber Building System* (*MSTBS*), which facilitates reciprocal and iterative knowledge exchange within the interdisciplinary core research team, as well as between researchers and stakeholders from the construction industry. The research demonstrates how an organizational co-design framework fosters the methodical collaboration between research and industry partners and enables the development of a novel timber building system, contributing to the transition towards more sustainable building practices.

KEYWORDS: co-design, integrative design, timber building system, timber slabs, multi-story

1 – INTRODUCTION

Timber, as a construction material, has a significant potential to lower the CO_2 emissions of the building industry [1, 2] and to increase the quality of architectural spaces [3]. Typological restrictions, such as limited spans and excessive cross-section heights of current multi-story timber systems, are often reasons against the implementation of timber systems in buildings. A global review of current multi-story timber buildings reveals that 98.9 % are based on regular grids, 98.2 % are single-span, and 77.4 % are timber hybrids [4].

To expand the architectural possibilities of timber structures, one focus of the *Cluster of Excellence IntCDC – Integrative Computational Design and Construction for*

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Architecture (EXC IntCDC) is drawn on the development of novel timber building systems, that employ computational design and digital fabrication methods. The *EXC IntCDC* is a multidisciplinary research cluster that focuses on the redefinition of design, fabrication, and construction processes by exploring the potential of digital technologies. Research questions, ranging from fundamental research to the development of advanced building systems, are addressed under perspectives from multiple disciplines, following the principle of co-design [5]. An integral part of the research methodology involves the implementation of new developments in large-scale research demonstrators to test and communicate innovations.

Within the research framework of *EXC IntCDC*, a new multi-story timber building system has been developed. This system provides a more sustainable approach to multi-story construction compared to carbon-intensive concrete systems, through the use of renewable materials, minimized material consumption, and overall lower embodied energy, while maintaining comparable technical characteristics. To achieve advanced sustainability and compatibility with concrete systems, four key objectives have been pursued:

1. A point-supported structural system capable of accommodating irregular building layouts, thereby increasing design flexibility.

2. Span widths exceeding 10 meters to enable programmatic adaptability and enhance the long-term resilience of buildings by facilitating future repurposing.

3. A depth-to-span ratio of 1:25 to 1:30 within a flat slab typology, facilitating the efficient integration of building services and ensuring optimal utilization of story height.

4. Acoustic sound insulation strategies to achieve user comfort comparable to conventional building standards without the addition of mass.

Considering these key objectives, the development of the *MSTBS* has been characterized by a high degree of innovation, with few comparable timber building systems available for reference. To create a system that not only excels in structural and architectural performance but also addresses aspects of building physics, manufacturing, assembly, and economic efficiency, it was essential to establish a comprehensive development framework. This framework had to integrate various disciplines and foster reciprocal exchange between them.

An interdisciplinary core research team had been established to lead the development of the *MSTBS* while collaborating with stakeholders from other research teams and the construction industry, integrating expertise from various domains to achieve the outlined objectives. In parallel with the development of the building system, its application was being planned within a building demonstrator, the *IntCDC Building*. This approach enabled an inductive development process that directly incorporated the requirements of planning and construction workflows, ensuring a practice-oriented refinement of the building system.

This paper provides a comprehensive description of the research project, where the building system and the *IntCDC Building* are described in detail. A particular focus is drawn on the development process of the *MSTBS*, with the *IntCDC Building* being planned in parallel. Central to this is the implemented co-design framework with the integration of industry stakeholders into the academic development process. Finally, the co-design method is demonstrated through the development of a specific connection detail. This example illustrates how co-design principles were applied to resolve a particular challenge within the development process, showcasing the method's efficiency in fostering innovative and practical solutions.

2 – PROJECT DESCRIPTION

The multi-story building system follows the construction method of a hollow slab. Using Cross Laminated Timber (CLT) for the panels, a biaxial load transfer is achieved. The hollow space of the slab is filled with discretely distributed shear ribs, which are aligned with the vector field of the shear forces and placed with variable density according to the local shear stress level [6]. Highly stressed regions, such as areas around the columns, are reinforced with solid laminated veneer lumber (LVL) plates within the hollow space [7]. To address the critical load conditions at the column heads, different beech wood components are used for local reinforcement. In an automated process using robotic fabrication, the slabs are prefabricated in segments, which are later joined on-site.

To structurally join the slab segments and enable a biaxial load transfer, three different types of edge connections – type A, B, and C – were developed to balance fabrication complexity and structural performance. Type A features a glued connection, with finger joints extending through the full depth of the slab's cross-section. Due to an intensive milling process, this joint type is rather complex to manufacture but has a structural performance that matches the characteristic strength of the used CLT elements. This has been experimentally tested. Type B employs a similar

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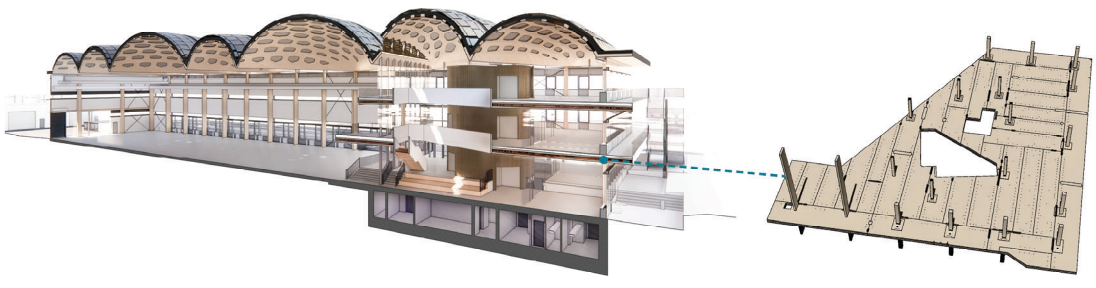

Figure 1. Section of the IntCDC Building (a) and isolated view of the MSTBS implementation (b).

finger joint connection in the bottom plate of the hollow slab, while the top plate is connected using a compression wedge. This joint type is particularly suitable for regions with positive bending (compression in the top plate). Type C connects the slab segments with cross screws, making it the simplest joint type in prefabrication and assembly.

2.1 DEMONSRATOR BUILDING

The *IntCDC Building* is a new building in planning located on the campus of the University of Stuttgart. It is designed to accommodate the research activities of the *EXC IntCDC*, featuring a robotic manufacturing hall and office spaces (see Figure 1 (a)). The *IntCDC Building* further serves as a demonstrator building, implementing the applied construction research developed over recent years at the *EXC IntCDC* and showcasing the development of resource-efficient building systems and innovative construction methods through computational design, digital fabrication, and cyber-physical on-site assemblies. Key features include a wide-span, segmented timber shell roof, ultra-lightweight natural fibre components, gradient concrete for the foundations, and the wide-span, point-supported *MSTBS* (see Figure 1 (b)).

The *MSTBS* is planned to be implemented in two office floors of the *IntCDC Building*, covering a total area of approximately 1,500 m². With an irregular column layout, spans up to 11.5 m, and balconies cantilevering up to 3.2 m, the slab system addresses key challenges in multi-story timber construction, demonstrating its potential in terms of structural performance and design flexibility.

3 – DESIGN PROCESS

The development of the *MSTBS* followed the co-design methodology as outlined by Knippers et al. (Figure 2) emphasizing reciprocal exchange and the integrative advancement of methods, processes, and systems [5]. The research findings are reflected in the *IntCDC Building*, which serves two primary purposes: first, the inductive development of the building system in synthesis with the associated methods, processes, and systems; and second, the validation of feasibility and overall performance.

This methodology facilitates an interdisciplinary collaboration across various research domains and establishes a foundation for knowledge transfer and common knowledge build-up between research institutions and stakeholders from the construction industry. Incorporating expertise from the construction sector into the building system development fostered the integration of practice-driven indicators and potentially will facilitate the long-term market adoption of the developed research methods and findings.

The co-development of the *MSTBS* was driven by a core research team operating within an extended network of collaborators. This network comprised the *MSTBS Research Network*, which enabled exchange with research teams working on related topics, and the *MSTBS Construction Industry Network*, which engaged industry stakeholders to address practical challenges in building system implementation (see Figure 3).

The core research team comprised researchers from the Institute for Computational Design and Construction (ICD), the Institute of Building Structures and Structural Design (ITKE), the Material Testing Institute (MPA), and the Institute for Building Physics and Acoustics (IABP), all affiliated with the University of Stuttgart and the *EXC IntCDC*. Their collaboration inherently fostered cross-domain knowledge synthesis, which led to the

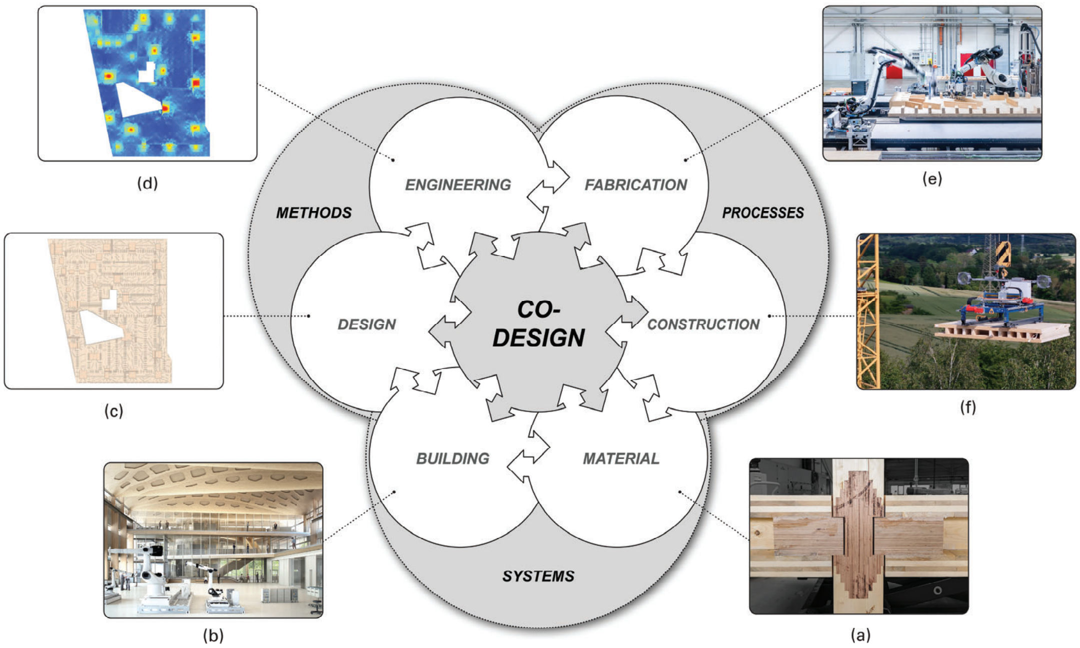

Figure 2. Co-design methodology.

development of integrated methods for design, engineering, and testing.

Beyond the core team, the extended research network facilitated interdisciplinary exchange with three additional research teams, which provided essential contributions to the advancement of the building system. Among the key collaborators was the *Cyber-Physical Wood Fabrication Platform Research Team*, which focuses on the development of transportable robotic platforms and corresponding end-effector tools that enable adaptive fabrication spaces for the fabrication of differentiated building systems, such as the *MSTBS*. The synthesis of adaptive fabrication and project-specific adaptable, lightweight timber building systems has been demonstrated on a smaller scale in previous projects, including the BUGA Wood Pavilion [8] and the livMatS Biomimetic Shell [9], and is ever since extending the machinic morphospace [10] and multi-actor fabrication [11]. Another important partner was the *Cyber-Physical Construction Platform Research Team*, which is developing a tower-crane-mounted end-effector capable of ensuring precise placement with minimal tolerances under challenging on-site assembly conditions [12]. Additionally, the *Multi-Perspective Co-Design Research Team* contributed by investigating visualization methods for design exploration in stakeholder negotiations within building design processes and researching architectural, historical, and social science perspectives in timber construction [4, 13].

The *MSTBS Construction Industry Network* provided an organizational framework that enabled a feedback-driven exchange between the core research team, the lead consultant, specialist planners, timber engineers, and the construction company. The lead consultant, in collaboration with specialist planners, was responsible for the overall building design, ensuring the integration of the developed building system while maintaining compliance with normative and regulatory standards specific to the *IntCDC Building*. Requirements from the building standards served as critical inputs for the core research team and, if relevant for systemic implementation, were incorporated into the building system development and computational co-design framework. Specialist planners contributed on a topic-specific basis in collaboration with the the lead consultant, and the core research team. The construction company provided expertise in fabrication and construction process optimization, offering key insights that contributed to the refinement of the building system.

In addition to establishing the stakeholder network, the sequential coordination of development phases and their respective feedback interfaces was essential for an inductive co-development process. Accordingly, the concurrent development and knowledge synthesis of the *MSTBS* and the *IntCDC Building* followed a structured process, divided into four main phases: (1) Pre-Development, (2) Development Phase A,

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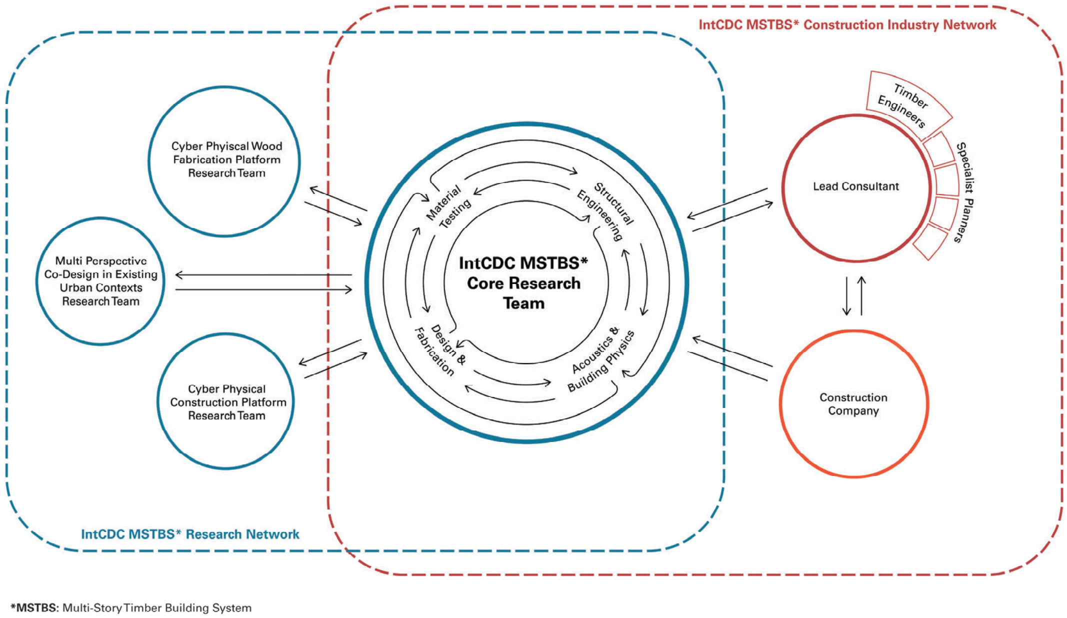

Figure 3. Stakeholder network in the co-design process of the IntCDC multi-story timber building system.

(3) Pre-Construction Phase, and (4) Development Phase B (see Figure 4).

In the Pre-Development Phase, the primary objective was to define the requirements of both the *IntCDC Building* and the building system, initially considering them independently. While the *IntCDC Building* focused on requirement analysis, program definition, and site selection, the *MSTBS* aimed to identify research gaps through a literature review and the definition of key performance objectives (as outlined in section 1) to inform the subsequent development phases.

The Development Phase A marked the beginning of the conceptual development of both the *IntCDC Building* and the *MSTBS*. The building systems research in this phase focused on the initial conceptualization of the tectonic scheme, the hierarchy of building elements, and the investigation of key system details – such as column-to-slab connection and slab segment connection – as well as the exploration of simplified integrative modelling methods, and the validation of hypotheses through simulations and physical prototypes. Towards the end of Development Phase A, the core system characteristics were defined and consolidated into a functional design specification. This specification served as the basis for a comprehensive system review and an initial feasibility assessment evaluating the system's integration potential within the *IntCDC Building* in collaboration with the entire stakeholder network.

The Pre-Construction Phase focused on evaluating the feasibility and cost implications of the MSTBS in its specific application within the *IntCDC Building*, while collaboratively identifying optimization potentials. A central aspect of this phase was the integration of in-depth process criteria from prefabrication and on-site assembly, which informed refinements to the *MSTBS* as well as adjustments to the architectural design of the IntCDC Building. At this stage, newly established optimization concepts were validated and systematically incorporated into the building system development, enhancing prefabrication time and material usage. The Pre-Construction Phase provided the basis for further refinement and detailed elaboration in Development Phase B through the core research team.

A key focus of the detailed development process (Development Phase B) was the advancement of schematic details into a comprehensive and robust set of building system details. These not only had to meet the process criteria established in the pre-construction phase but also had to accommodate a wide range of detail configurations, varying in geometry and service integration requirements. This was achieved through iterative, collaborative feedback loops.

A particularly important element of this process was the establishment of regular data exchange, where all *IntCDC Building* design stakeholders uploaded their respective planning statuses at defined intervals in a

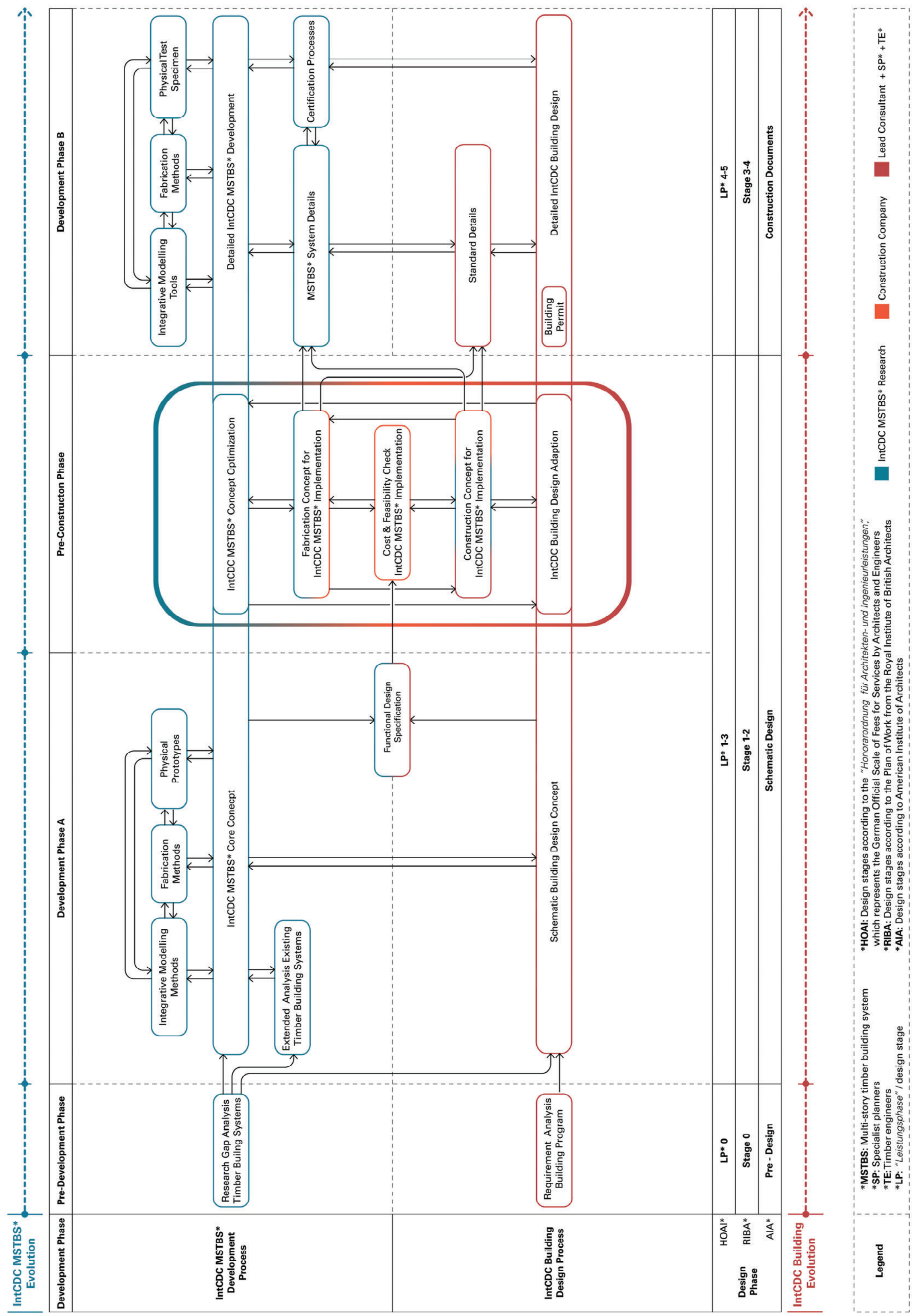

Figure 4. Inductive co-design method: The IntCDC Building planning process as a development catalyst and evaluation object for the IntCDC multi-story timber building system.

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common model space. This served as a central mechanism for coordinating interface clarifications and iteratively addressing evolving service integration requirements. For the *MSTBS*, this approach was especially valuable as it fostered a deeper understanding of service integration within the architectural design process. In turn, it enabled the systematic incorporation of these requirements into the building system development and enhanced the adaptability of integrative computational design tools, broadening their applicability to diverse architectural scenarios while increasing their overall robustness.

Each iteration of building system adaptation underwent detailed structural performance assessments, manufacturability evaluations, and assembly feasibility studies. Furthermore, the continuous refinement of computational generation methods played a fundamental role in this phase. The integration of these methods into a comprehensive computational framework, along with the synthesis of cross-domain knowledge into a coherent design application for *MSTBS*, formed a methodological cornerstone for structured knowledge development and archiving within the interdisciplinary co-design process.

Furthermore, system details were evaluated through destructive and non-destructive material testing within the core research team, while external testing institutes conducted certification procedures for critical construction details. This ensured the safety of the building design for details not explicitly regulated by building codes, in their application in the *IntCDC Building*. The results of these evaluations provided essential empirical validation, offering further crucial feedback for the continuous refinement of the building system. Moreover, this process represented a critical step towards project-specific regulatory approval, paving the way for the integration of the *MSTBS* within the *IntCDC Building*.

3.1 CASE STUDY FOR INTEGRATIVE DEVELOPMENT: SEGMENT EDGE CONNECTION TYPE A

The evolution of the edge connection detail exemplifies a highly integrative development process. As essential part of the slab system, the joint detail was conceptualized and optimized progressively throughout the development phases outlined in Figure 4. Along with its advancement, the primary focus was placed on balancing structural performance with efforts in prefabrication and on-site assembly.

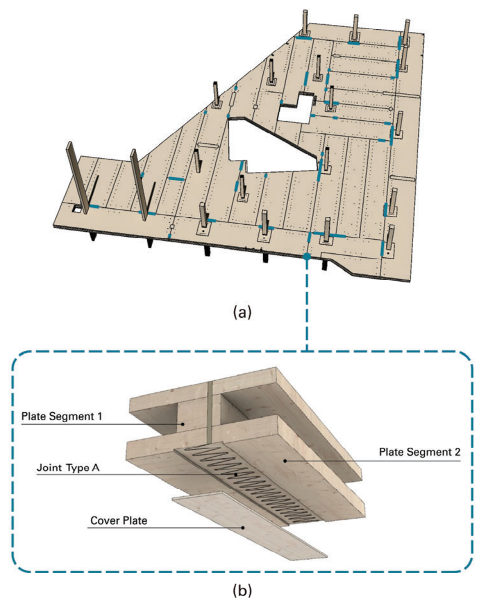

Figure 5. (a) Locations of segment edge connection type A within the first-floor slab of the IntCDC Building. (b) Isolated view of the edge connection type A detail.

In Development Phase A (see Figure 4), the objective was to establish a single segment joint detail that fulfills the structural requirements for all positions within the floor plan. A wide range of joint details was conceptualized, some of which were prototypically tested for their fabrication process and structural capacity. Intermediate joint details of this phase included concepts based on stepped, overlapping tabs [14] and tap connections with maximized shear interface areas [15]. While these designs showed promising structural performance, they have disadvantages in terms of prefabrication and assembly, including the need for flipping the workpieces, which leads to a complex fabrication process and extended fabrication time. The resulting segment joint geometry of Development Phase A is a mega-finger joint connection, with the fingers spanning throughout the entire cross-section of the timber slab, enabled by a CLT plate glued into the hollow space (see Figure 5). Mega-finger joints exceed the dimensions of large finger joints, that have a maximal finger length of about 50 mm, and are commonly used in e.g. portal frames. These were initially investigated in [16]. In this development phase, the finger joint geometry was planned to be sawn from the prefabricated slab segments. A steep angle between the side walls and a thin gluing gap enhances the structural capacity of the joint detail. The finger joint geometry concluded in Development Phase A (see Figure 6, (a)) demonstrates a structurally driven solution, based on shape optimization procedures shown in [17, 18].

In the subsequent Pre-Construction Phase (see Figure 4), a rationalization of the segment joint detail was conducted in a reciprocal process between the *IntCDC Research Network* and the *IntCDC Building Design Network*, reducing fabrication complexity and production costs. As one part of the rationalization process, two additional segment joint details were developed, that are aligned with typical stress situations within point-supported slabs (see chapter 2). The detailed planning of the *IntCDC Building* showed, that only 6 % of the total segment edge length is structurally required to be joined with segment edge connection type A, demonstrating a significant optimization in production costs. Another aspect of rationalizing the segment joints involved revising the finger joint geometry of segment edge connection type A. Sawing of the mega-finger joints proved to be an elaborate fabrication technique, as it requires multiple rotations of the tool head at low speeds. Consequently, the construction company of the *IntCDC Building* proposed milling as an alternative method for fabricating the finger joints (see Figure 6, (b)). Milling introduced a rounded finger joint tip, which reduces the proportion of structurally effective bonding surfaces. A flat angle between the side surfaces and the low depth of the fingers reduces the milling path length and therefore increases the production speed. Furthermore, the gluing gap needed to be widened to accommodate on-site tolerances. The finger joint geometry (b) in Figure 6, therefore, demonstrates a mainly fabrication-optimized option. However, to meet the required structural capacity as stipulated in [17, 18], the percentage of the structural effective bonding area was increased by reducing the radius of the tip to a manufacturable minimum and increasing the depth of the fingers in the concluding finger joint geometry of the Pre-Construction Phase (see Figure 6, (c)).

In Development Phase B, detailed refinements were made, including the specification of assembly tolerances to be accommodated by the finger joints and the selection of an appropriate adhesive product. Test specimens of the agreed finger joint geometry (see Figure 6, (c)) were fabricated and subjected to destructive testing. The evaluation, reported in pending publications by the authors, demonstrates high joint strength. However, complications were encountered during adhesive application, as the nozzle diameter exceeded the gluing gap. In coordination with the structural engineers from the research team, an extension of the rounded finger joint base was defined (see Figure 6, (d)) to locally widen the tip gap. Since the bonding at the tip of the finger joint has negligible involvement in load transfer, and the reduction of the net cross-section is minor, its impact on the structural capacity is minimal.

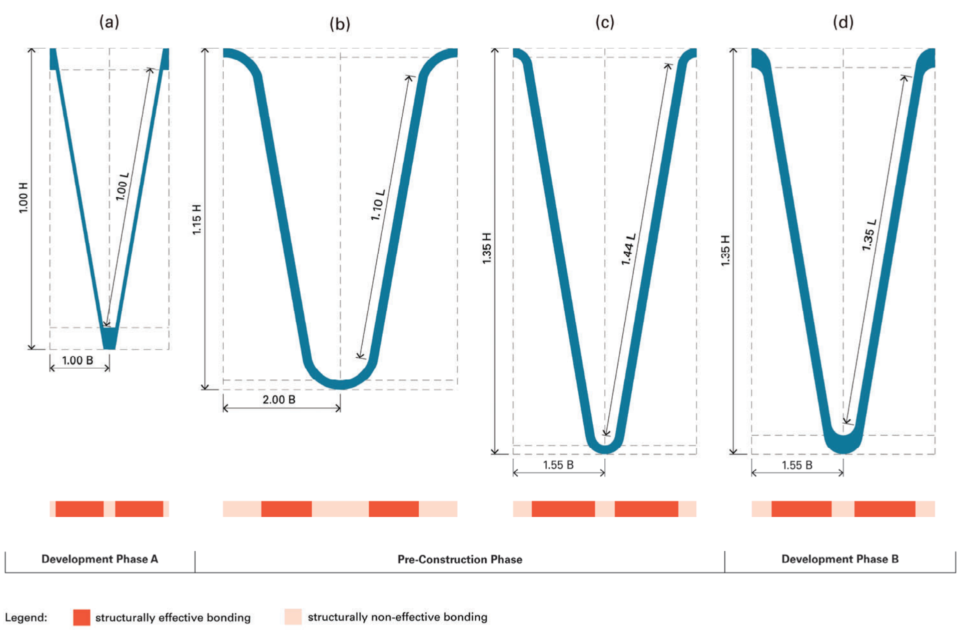

Figure 6. Evolution of the mega-finger joint detail in the IntCDC multi-story timber building system throughout its development phases in the co-design process.

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The integrative co-design process described in this paper is exemplified through the development of the mega-finger joint connection of segment edge connection type A. The *IntCDC Research Network*, in collaboration with the *IntCDC Construction Industry Network*, collectively developed the detailed finger joint geometry throughout the development phases described in Figure 4. Initially, the research team proposed a mega-finger joint design, which was subsequently refined within the planning context of the *IntCDC Building* to reduce cost and processing time and accommodate on-site assembly requirements.

4 – OUTCOMES AND REFLECTIONS

This paper presents an organizational co-design framework for the integrative development of a point-supported, long-span multi-story timber system with flat slabs - referred to as the *MSTBS*. The methodology particularly facilitates a close interconnection between the integrative planning of the *IntCDC Building* and the inductive development process of the *MSTBS*. A core research team comprising researchers from four distinct disciplines had been established to lead the co-design development process from multiple perspectives. This team operated within an extended research network of the *EXC IntCDC* while also engaging with a construction industry network embedded in the planning process of the *IntCDC Building*.

First, the consolidation of collaboration among various stakeholders is examined alongside the parallel development of the *IntCDC Building* and the *MSTBS*. The resulting synthesis emerging throughout the entire planning process is systematically structured into four main phases. Second, the impact of interdisciplinary co-design and the inductive research approach within the building system development process is demonstrated through the example of the advancement of a specific slab segment joint. This case study highlights the synergy effects enabled by the integrated development framework, illustrating how iterative, cross-disciplinary interactions contribute to the refinement and optimization of key system components and methods.

5 – CONCLUSION

The overarching objective – expanding timber construction typologies to include point-supported flat slab systems with flexible column arrangements – has been achieved through synthesis and iterative evolution, enabled by continuous feedback loops between the core research team and stakeholders of research and construction industry networks. This was facilitated by the foundational structure of an interdisciplinary research environment, allowing for the establishment of a comprehensive database of system details, the development of integrative computational design and engineering methods, and validation through physical prototypes. Furthermore, the integration of planning processes to ensure compliance with technical, regulatory, and normative requirements has contributed to the consolidation of the system for implementation in a multi-story building.

The development of the *MSTBS* within a co-design network illustrates how cross-disciplinary research and collaboration between academia and industry stakeholders can facilitate the advancement of innovative building systems. The presented methodology serves as a foundational structure for developing novel computational design and construction methods while ensuring their feasibility at a full-scale implementation, in compliance with technical, regulatory, and normative requirements. The continuous collaboration between research and the construction industry throughout the development process enabled direct knowledge transfer in both directions, potentially fostering the long-term market adoption of the developed methods and processes, and contributing to the transition towards more sustainable construction practices.

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