

# A form-active reclaimed timber system for multi-story construction shaped by stock variability and grain orientation

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## Abstract

The growing demand for timber construction contrasts sharply with the continued downcycling, incineration, or disposal of reclaimed wood that rarely enters structural applications. A central obstacle is that reclaimed timber typically appears as warped, defect-ridden elements and uncertain mechanical behavior, making it incompatible with prescriptive design paradigms. In response, this paper investigates a structural typology that can work with irregular stock rather than against it, and explores how longer spans can emerge from short salvaged material. Through the research demonstrator, the study develops a point-supported funicular slab composed of short reclaimed timber elements organized into a compression-dominant load path, with secondary bracing promoting shell action and steel cables containing horizontal thrust. The resulting topology deliberately minimizes reliance on bending, the behavior most compromised in the reclaimed stock material, and instead exploits the relative predictability of compression parallel-to-grain. Simultaneously, because irregular geometries are difficult to orient, reference, and machine within robotic fabrication workflows, the principal-stress-informed spatial arrangement simplifies fabrication by favoring contact end-to-end connections and reducing the number of joints requiring precise milling. Backed by a digital timber upcycling framework, the demonstrator shows how computational engineering and digital fabrication can accommodate warping, variable cross-sections with mechanical variability and defect-free machinable regions while allowing disassembly and future reuse. The paper proposes a structural system for multi-story construction in reclaimed timber by positioning irregularities not as defects to be eliminated, but as a driver of structural robustness and circular construction.

**Keywords:** computational design, reuse, timber engineering, timber construction, robotic fabrication, digital fabrication, circular economy, upcycling

## 1. Introduction

The increasing use of timber in construction is motivated by the need to reduce the material and carbon intensity of the built environment, yet it also exposes a growing tension between timber demand and the sustainable availability of primary wood. Recent material-flow projections for Germany indicate that future wood consumption may increase substantially under climate-action scenarios, particularly when residential renovation and timber construction are considered together, while domestic forest supply is

unlikely to satisfy peak demand without either increased imports or changes in wood-use strategies [1]. At the same time, Germany already consumes timber at a level above the global average and remains dependent on imports, with domestic roundwood production considered close to the limit of sustainable harvest potential [2]. In this context, timber from existing buildings can no longer be regarded only as waste, but as a strategic material reservoir for extending carbon storage, reducing pressure on forests, and maintaining wood in higher-value material cycles.

However, this potential remains weakly activated in current waste-wood chains. Under German conditions, recovered wood is still positioned primarily as an energy resource: material use accounts for only about 20% of the stream, while roughly 80% is used energetically [3]. These shares have been supported by a context in which waste-wood combustion can substitute fossil-based heat and electricity; yet this scenario shall likely change with efforts towards a net greenhouse-gas neutrality. Although the availability of secondary wood shall increase, this stock does not automatically become construction-grade material without assessment and allocation routes [4]. Uncertain supply quality and quantity, contamination, insufficient classification, and fragmented regulatory frameworks still prevent secondary timber from entering stable construction markets [1]. Secondary timber is therefore not scarce in principle, but still unavailable in the form required by timber construction.

In contrast, the contemporary timber industry is optimized around serial manufacturing, dimensional stability and standardization, aspects fundamentally different from salvaged timber. It is often found in short, warped, locally damaged, contaminated by fasteners, marked by holes and cracks, and characterized by uncertain provenance and irregular mechanical behavior. Forcing this material back into conventional industrial formats requires extensive cleaning, cutting, planning and rejection, which can reduce both material yield and circular value. The limitation is therefore not only a question of assessment or certification, but also a typological mismatch. Existing timber systems generally assume dimensional regularity and span continuity, while secondary timber requires structural systems that can tolerate short lengths, variable geometry and element-wise uncertainty.

On the material level, current grading standards for structural timber are primarily developed for new timber and focus on naturally grown features such as knots and density to determine mechanical properties. In salvaged timber, however, pre-used elements are additionally characterized by a history of use and loading, which introduces a much more complex set of geometrical features and greater uncertainty regarding structural performance. Although standards and guidelines for reclaimed timber assessment exist, such as the Italian UNI 11119 and the Norwegian NS 3691-3, they can lead to significant deviations in both strength and stiffness [7].

This paper addresses this gap by investigating a grain-oriented, form-active slab system that works with the limitations of reclaimed timber rather than treating them only as defects to be eliminated. Instead of trying to reprocess all elements into homogeneous boards or lamellae, the system uses short reclaimed members as discrete structural components arranged along compression-dominant load paths. The proposed topology reduces reliance on bending, which is particularly sensitive to defects, holes and local grain deviations, and instead exploits the more predictable behavior of timber in compression parallel to grain as well as the capacity of contact joints and the ease of fabrication and the performance of contact-based timber joints between elements. The resulting point-supported funicular slab is braced to promote shell action, while a tension system contains horizontal thrust. By combining stock-aware allocation, principal-stress-informed member orientation and defect-aware fabrication constraints, the system seeks to transform material irregularity into a driver of structural organization.

### **1.3 Scope**

This paper focuses on aspects related to the engineering design of reclaimed timber through digitally upcycling of found objects in the proposed Grain-Oriented structural system. Section 2 examines the design research development of the system covering the data collection process and processing required for the design methodology with variable and uncertain material. Section 3 showcases how the generated

data is employed in the development of the building system and evaluates how material uncertainties are mitigated by investigating alternate load paths. Section 4 presents the system employed and evaluates its global performance metrics, together with a set of details developed specifically for this project.

The research demonstrator also embodies other topics which are not covered in this paper, namely, a method for the mechanical characterization of reclaimed pieces by defect-aware visual grading, digital fabrication methods for the cyber-physical interface of warped elements, the general computational framework upon the digital upcycling of elements and the data framework developed over a reclaimed timber ontology.

## 2. Data Collection and Processing

Within the scope of this paper, reclaimed timber elements are mainly distinguished between offcuts from production processes and pre-used elements recovered from disassembled structures. For offcut-elements, geometric and mechanical properties are either known or can be characterized using established industry standards. In contrast, pre-used elements embed uncertain material properties and a history of previous loading and weathering. Besides naturally occurring timber defects such as knots, these elements often contain carpentry holes and notches, embedded metal fasteners, cracks, warping and rounded edges. Besides introducing a higher uncertainty regarding mechanical properties, processing these elements into planar and machinable surfaces to common carpentry tools and regular cross-sections is impractical due to remaining metal fasteners and associated extensive labor.

The aim of this research was to source a stock of timber elements with a broad range of geometric and mechanical features to develop more generalizable methods and to enable advanced tailoring to local requirements of the building system. Based on availability and in line with the building systems design scope, the sourcing was focused on beam-type elements.

Table 1: Summary of stock types A – E with main characteristics.

| Stock | No. elements | Total volume [m <sup>3</sup> ] | Length [mm] | Width [mm] | Height [mm] | defect types |       |        |         | Pre-Used (PU) / Offcut (OC) |
|-------|--------------|--------------------------------|-------------|------------|-------------|--------------|-------|--------|---------|-----------------------------|
|       |              |                                |             |            |             | knots        | nails | cracks | warping |                             |
| A     | 48           | 1.2                            | 2835 - 4900 | 90 - 180   | 40 - 55     | ✓            | ✓     | ✓      | ✓       | PU                          |
| B     | 112          | 0.29                           | 538 - 1201  | 46 - 90    | 45 - 64     | ✓            |       |        |         | OC                          |
| C     | 56           | 0.2                            | 517 - 1005  | 45 - 104   | 45 - 94     | ✓            |       |        |         | OC                          |
| D     | 35           | 0.39                           | 1173 - 2502 | 48 - 155   | 45 - 145    | ✓            |       | ✓      |         | OC                          |
| E     | 40           | 1.14                           | 1099 - 2800 | 70 - 320   | 70 - 152    | ✓            | ✓     | ✓      | ✓       | PU                          |



Figure 1: Stock Types from A – E (left – right).

The collected stock is summarized in Table 1. It includes boards originating from a barn in Finland of unknown age (stock A), rectangular offcuts with comparatively small cross-sections and lengths (stock B-D) and beams recovered from a deconstructed, 120-year-old residential building in rural Germany

(stock E) (see Figure 1). While stock A clearly exhibits large defects such as cracks and holes and irregular cross-sections, stocks B-D appear largely homogeneous in shape and defect-free.

Small-sized specimens were extracted from the stock elements and digitized using the above-described process. Destructive bending and compression tests were performed according to DIN EN 408 to determine MoE, bending strength, and compression strength. In total, 92 bending tests and 74 compression tests were carried out. A machine-learning model was subsequently used to correlate fracture locations and defect patterns with the measured mechanical properties to predict the structural capacities of the remaining stock. Additional strength parameters, such as shear and tensile strength, were estimated using correlations based on MoE, density, and bending strength. Overall, the findings show moderate correlation between non-destructive measurements on parallel-to-grain compression strength, yet bending strength still remains highly influenced by the presence of defects on the salvaged material and often leading to non-conservative assessments via visual grading, in agreement with previous studies [8], [9].

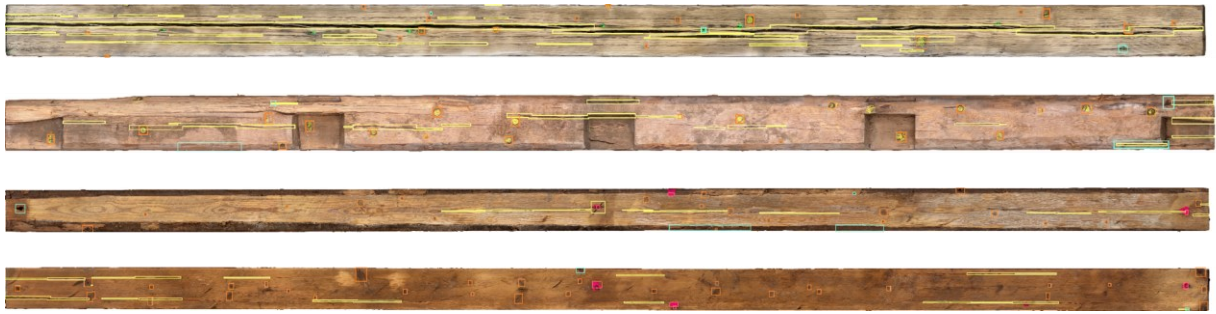


Figure 2: Example of a digitalized timber beam from stock E with defect markings.

### 3. Methodology

Computational design methods for upcycling found objects have emerged to address a central limitation of circular construction: reclaimed elements are available as non-standard inventories whose geometry, quantity, and quality cannot be assumed in advance. As Sun et al. note, these methods “automate the assignment of objects based on their shapes to approximate a target design”, allowing non-uniform material stocks to become active inputs to design rather than obstacles to standardization [10]. For reclaimed timber, however, this assignment problem is not only geometric. Each element also carries structural uncertainty, defects, and fabrication constraints. The methodology developed therefore extends the typical inventory–design–materialization workflow identified in the literature by coupling material clustering, structural feedback, robustness evaluation, and defect-aware cutting into one allocation framework. Starting from the feature extraction described in Section 2, the workflow first assigns target elements to material clusters during design exploration, and then resolves the accepted design through one-to-one allocation of physical stock elements and cutting positions.

In this context, the reclaimed timber stock is not treated as a passive resource to be fitted into a predetermined design, but as an active constraint that redirects the design process. In particular, it reframes material variability as a reciprocal design condition: the designer defines the structural intent and evaluation criteria, while the material stock limits, redirects, and sometimes expands the possible design space through its lengths, defects, grain orientation and mechanical uncertainty.

Material co-agency is first implemented at the level of the design model. The model does not define a fixed geometry to be populated with reclaimed timber afterward; instead, it defines a constrained design syntax within which the stock can redirect the structural configuration. The number and spacing of main arches, the density of bracing members, the subdivision of primary elements, and the overall slab geometry can be adjusted according to the capacities and lengths available in the reclaimed stock. At the same time, this adaptability is bounded by the structural grammar of the system and by its load-

bearing requirements. The geometry syntax defines valid relationships between arches, bracing members, supports, cable lines, and decking substructure, while the load requirements define the minimum structural performance that each configuration must satisfy. In this way, the material inventory acts as a co-designer by narrowing or expanding the feasible design space, but only within a rule set that preserves the intended form-active behavior of the slab.

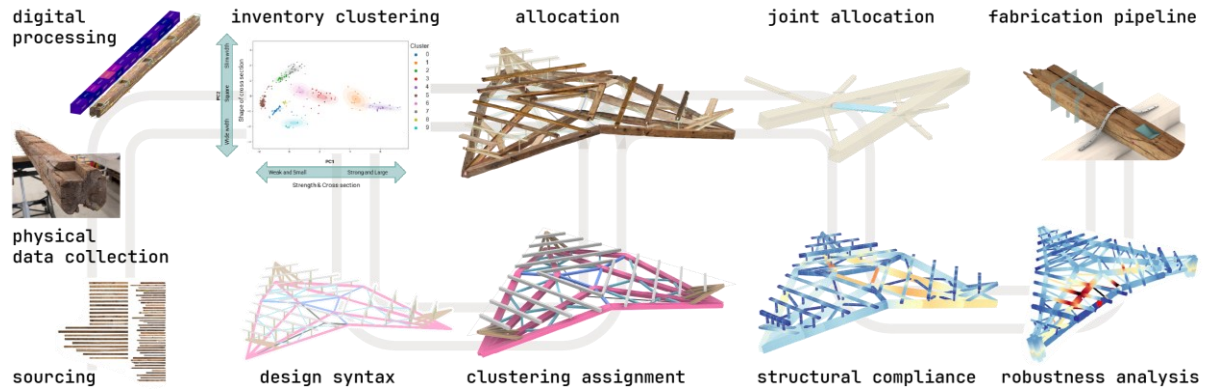


Figure 3: Design process for digitally upcycled reclaimed timber

### 3.1. Design Intent

Rather than classifying reclaimed elements according to material properties alone, the clustering is structured by the member types required by the pavilion geometry. Primary arches, bracing members, decking supports, and column-related elements impose different combinations of length, cross-section, member-wise allowable stresses, material uncertainty, and defect-free connection zones. These anticipated structural roles define which extracted features are relevant for grouping the stock into usable material families. The resulting clusters therefore operate as a bridge between the inventory and the design syntax: they describe not only similarities within the reclaimed stock, but also the types of structural positions that the stock can plausibly occupy.

From a fabrication perspective, this clustered representation also introduces a degree of contingency. If a selected stock element proves unsuitable to machining because of unexpected defects, they can in principle be replaced by another element from the same cluster without restarting the global design process. Clustering therefore supports both design allocation and fabrication robustness, by preserving a pool of structurally and geometrically comparable alternatives.

The relation between design syntax and clustering is therefore bidirectional. While the syntax defines which material features are relevant for clustering, the resulting clusters also feed back into the design model by indicating which structural configurations are materially plausible. The available distribution of cluster capacities and lengths can influence the number of main arches, the spacing between them, the subdivision of primary members, and the density of bracing. In this inverted operation, the design model is not only checked against the stock after it has been generated; rather, the stock clusters participate in defining the design intent itself. A stock with many short but structurally reliable elements may favor a denser subdivision of arches and bracing, while a stock with fewer long or higher-capacity elements may support a more open configuration with fewer primary load paths. The resulting design intent is therefore not a fixed geometric target, but rather a material-informed structural proposal that already reflects the capacities, limits, and redundancies of the available inventory. This intent is then passed to the one-to-one assignment, where each target member is matched to a specific stock element and cutting position.

### 3.2. Design model

The transition from cluster assignment to one-to-one allocation introduces a second feedback loop. At the cluster level, each target element is associated with a material family whose members have similar capacities; however, individual stock elements within the same cluster still differ in cross-section, length, stiffness, defect distribution, and predicted mechanical properties. Once a specific stock element is assigned to a target member, these element-specific properties must be written back into the global structural model. The one-to-one allocation is therefore evaluated iteratively: stock elements are assigned, their actual stiffnesses are updated in the finite element model, member forces and utilization ratios are recalculated, and unsuitable assignments are replaced or re-ranked until a convergence is reached.



Figure 4: Feasible design options for an equilateral 7-meter span in reclaimed timber

This step can again lead to a combinatorial optimization problem, because many stock elements may be feasible candidates for a given target member and each local assignment can affect the global force distribution. A purely exhaustive search would be impractical depending on the size of the inventory and the number of design elements. The workflow therefore employs cluster assignment as a reduction of the search space. One-to-one allocation is performed only within the assigned cluster and length bin, and candidate elements are ranked according to structural fit, available cutting regions, fabrication clearance, predicted utilization, uncertainty, and remaining offcut length. Instead of searching all possible stock-to-target combinations, the method iteratively tests feasible candidates within constrained material families and updates the structural model after each allocation cycle.

In this sense, the one-to-one allocation acts as the point where material specificity fully enters the design model. The cluster label provides a feasible material family, but the final assignment depends on the actual geometry and defects of the selected stock element. The following cutting search is fast and low-dimensional and therefore resolves not only whether a stock element has sufficient capacity and length, but also where along the element the target member can be extracted without conflicting with defects or embedded fasteners on all joint regions.

### 3.3. Robustness evaluation

Given the exploratory nature of the methods developed in the research for the material characterization and the inherent uncertainty of the strength predictions, another layer of safety is introduced through an evaluation of robustness in the hyperstatic system. Two methodologies were employed and compared: a stiffness-based method proposed by Forster and Von Scheven [11] and a progressive collapse analysis using a Eurocode 5 per-element evaluation using Beaver [12]. The latter one consists on removing each element on the design model under characteristic loading, as an abstraction for the failure of that element, and the surrounding elements are checked against their Ultimate Limit State (ULS). The removed member is then assigned a robustness metric, where values less than 1 indicate a safe redistribution of forces on the global system. Each element on the structure goes through the same evaluation, mapping the overall relevance of elements in the redistribution of forces, rendering the images shown in Figure 5.

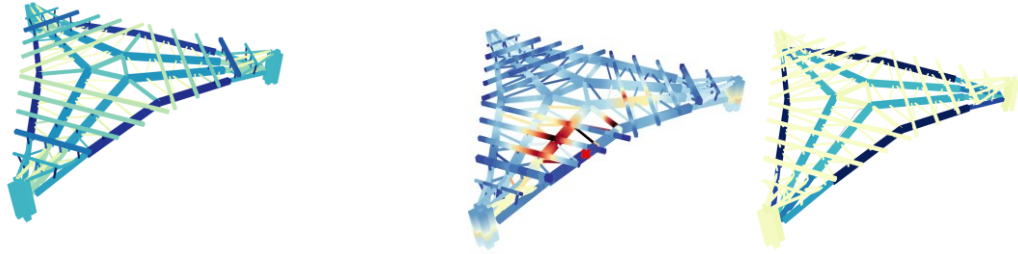


Figure 5: Comparison of robustness metrics using a stiffness-based evaluation (left) and a per-element progressive collapse analysis (right).

Overall, both methods agree on the relative importance of members but diverge when considering elements with low-importance: secondary members, such as the decking substructure, indicate a much higher metric in the stiffness-based method since they exhibit high local deformations under the stiffness-matrix approach.

## 4. Research Demonstrator

### 4.1. Grain-oriented form-active system

The structure behaves like funicular-like discretized shell, supported vertically by a point-supported slab spanning 7m between the supports and includes a cable element which connects all support points containing the horizontal thrust from the 3-dimensional arches. These main elements, denoted in rose at figure 1a, are oriented according to the direction of 1<sup>st</sup> principal stress lines on an isotropic continuous shell. The main elements are joined with a rotationally-stiff hinge with a behavior of 350 kNm/rad around their local-y direction, a value obtained experimentally from a specific end-to-end connection developed for this project. Secondary elements are arranged in a diagonal manner, so that the main elements are braced from horizontal forces and prevent out-of-plane buckling of the arches.

The vertical load-distribution happens through a decking of 25mm reclaimed timber lamellas, supported every 40cm by a substructure that spans between the arches. This substructure is also braced by the connection to the column node. To increase the performance of the system under asymmetric loadings, diagonals are introduced between the main elements and the upper column node at the level of the decking.

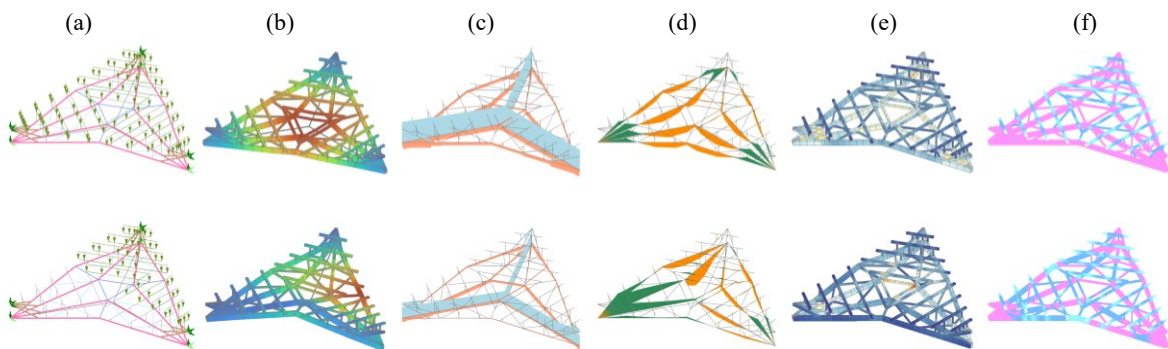


Figure 6: Structural response diagrams for characteristic symmetric (top) and asymmetric loadings (bottom). Applied loads on a wireframe model (a), deformations (b), normal forces (c), bending moments (d), ULS utilizations (e) and governing EN 1995 check (f)

The structure was designed as an equilateral triangle to showcase the bi-directionality of the system, which is uncommon for linear timber structures. Three-point supports were chosen over the typical rectangular layout to reduce total number of elements to be fabricated. Loads are applied directly on the decking substructure, with a live load of 2.5 kN/m<sup>2</sup> and snow load of 1.2 kN/m<sup>2</sup>, with only self-weight

as permanent loading. In a realistic scenario, an additional weight from the floor build-up and ceiling should be considered to improve acoustics, fire proofing and vibrations, which would in turn improve the performance of the funicular slab under asymmetric loads.

Adopting a prescriptive design approach, the structural system would be verified with a ratio of  $0.065 \text{ m}^3/\text{m}^2$  of timber take-off using a C24 strength class and show that the combination of a form-active structure with the correct timber grain orientations sustain a competitive structural system among timber alternatives for that same span. When adopting a non-prescriptive approach with the allocated material, the material take-off ranges from  $0.120$  to  $0.150 \text{ m}^3/\text{m}^2$ , which is still considered a lightweight structural floor for the proposed layout. The final configuration for the demonstrator was chosen to reduce the number of primary elements, which require robotic manufacturing operations.

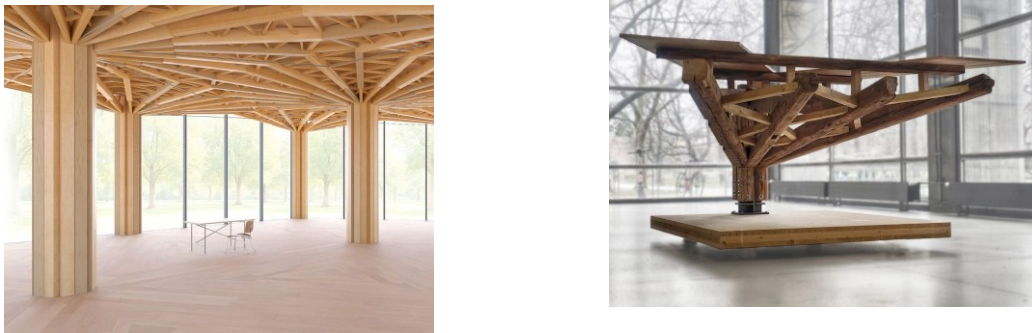


Figure 7: Speculatory application of the system and physical prototype at 1:1 scale

#### 4.2 Speculatory grain-oriented joint details

The structure relies heavily in the capacity of transferring compression between members while maintaining a small rotational stiffness. From these requirements, a novel dowelled timber connection was developed to maintain this force-transfer by exploiting parallel-to-grain stiffness. The detail concept is a mix between carpentry joints and fasteners with disassembly principles in mind: By orienting beech dowels vertically generating more shear area to transfer forces from one member to the other, as well as loading the timber exclusively their parallel-to-grain direction.

The connection coined by master students as the “Crocodile Joint” works just like a shear-notched connection: it must be locked by fasteners perpendicular to the notch, absorbing the perpendicular-to-grain movements due to the change in the angle of forces. Maintaining a high stiffness perpendicular to grain is therefore required to maintain contact on the timber dowels, leading to screws being preferred over bolted connections. If the screw diameters are sufficiently small, their shear stiffness will not contribute to the bending-stiff behavior and shall be loaded mostly in tension, which in turn can be easily disassembled after de-loading.



Figure 8: Compression-dominant joint using beech dowels and parallel-to-grain contact tested under compression and bending

Two different prototypes were tested simulating the transfer of bending and axial compression between members. The first specimen was built with 8x 8mm x 100mm beech dowels with a 8mm bolt with a washer per connecting member. The specimen, with a 10cm x 10cm cross-section reached a 1.6 kNm ultimate load and a small rotational stiffness of 34 kNm/rad and significant initial slip with failure both on the beech dowels and also compression perpendicular to grain near the washers. The second specimen, consisting of 4x18mm x 120mm beech dowels disposed in a symmetric manner and a 6mmx120mm screw at the center of stiffness between the dowels reached a maximum compression load of 42kN, roughly 21x stronger than just the screw loaded in the same way according to verifications according to code without safety factors. The material used was a reclaimed timber element with longitudinal cracks present before the test and the failure mode observed was a pull-through of the screw, indicating the possibility of further capacity. Although these findings show some promising results, further studies with larger sample sizes are needed to draw robust conclusions.

Another key connection detail of the system lies on containing the horizontal thrust from the arches. The ends of the compression elements are connected by a steel plate that transfer the forces to a threaded rod, where the axial force travels through cables connecting all supporting columns and closing the reaction system on the horizontal plane. The gravitational forces are taken by a notch in the column, minimizing the eccentricities on the support element and loading the timber exclusively at the along-grain direction, which also potentializes the use of reclaimed timber on the column. The main compression elements are tapered to fit into the column width and illustrate the possibility of maintaining continuity to adjacent funicular slabs of with the system logic.

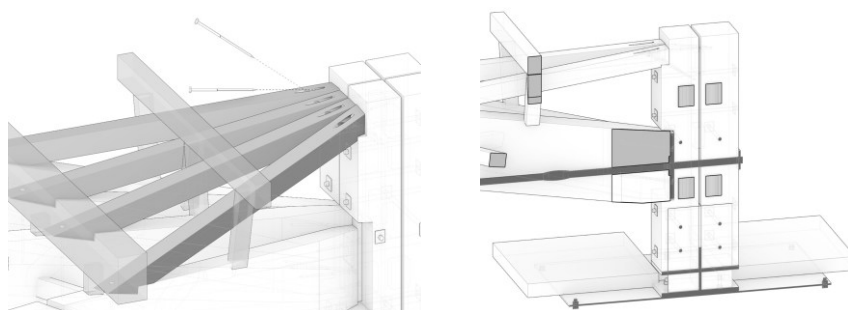


Figure 9: Connection details to the column support

## 5. Conclusion

The paper proposes a structural system for multi-story construction in reclaimed timber by positioning irregularities not as defects to be eliminated, but as a driver of structural robustness and circular construction. The authors pose that a data-driven approach enables designers to employ a minimal-processing fabrication which avoids cleaning and re-processing of elements and preserves the structural integrity of the reclaimed material while enables further reuse cycles. Embedding stochastic information into the engineering process enables a two-folded outcome: each element graded according to their unique properties instead of a probabilistic approach leads to a better resource-efficient design but reduce overall robustness due to the uncertainty on the material properties. A progressive collapse evaluation is added to the design workflow to evaluate the system robustness. The degree of uncertainty on the material level is also reduced by exploiting the relative predictability of compression perpendicular to grain while also harvests timber anisotropy by orienting the elements' timber grain orientation to the structure's natural load-path. Construction details for the reuse-based compression-dominant typology are proposed, although further testing is required to draw robust conclusions.

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