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LOADBEARING STRUCTURES FROM RECLAIMED WOOD – STRATEGIES, DESIGN PARAMETERS AND REFLECTIONS

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ABSTRACT

It is a well-known fact that the building sector is one of the largest polluting and CO2 emission-contributing sectors. In addition, what nature has created over millennia as material resources is being used up very quickly, with some materials already becoming scarce. The climate emergency we are facing calls for better and more sustainable approaches for the building sector.
This is the motivation and starting point for this paper, which presents three different strategies for building load-bearing structures in wood. Through three full-scale prototypes, we put forward strategies, design parameters, and reflections about the opportunities and challenges of utilizing second-hand wood for load-bearing structures. The three projects all seek to investigate the viability of wood cascading, giving wood a longer life in its solid form by offering a load-bearing structural design that can be reused several times. Furthermore, ReciPlyWood, Waste Wood Canopy, and Wood ReFramed test different strategies for structural safety through robustness as well as simple connection systems. Optimizing usability, buildability, and aesthetics and waying them out has been important in all three projects. The paper ends with a reflection of the process and results and points to steps needed for wood to be accepted as a multigenerational material for load-bearing structures.

Key words: wood cascading, reclaimed wood loadbearing structures, full-scale prototypes

1. INTRODUCTION

In response to major environmental challenges, wood is regaining attention as a material that can solve some of our climate-damaging practices. Once known as a material that made up a significant portion of our material culture, its use in building design has been subsided by the rapid development of other materials over the last centuries, such as steel and concrete.

The procurement of timber invokes complex challenges surrounding availability and biodiversity; both parameters have created strong critiques of different types of forestry practices. Optimum stand rotation, diversity of species, and cutting methods are topics that struggle to find consensus (Liu et al., 2018). As well as this, a changing climate leads to uncertainties in how prediction models calculate wood availability due to forest vulnerability to fire and insect attack, both of which are expected to increase with a changing climate (Seidl et al., 2017).

The majority of timber today experiences a short lifespan, and where longer lifespans are made possible, such as timber used in buildings, most material is single-use (Husgafvel et al., 2018). Energy recovery is typically the most common second application for timber, and where timber is reused, it is most often downcycled into particle-based products (Cristescu et al., 2020). Extending the lifetime of wood can have many benefits. The most significant is the increased availability of timber, which reduces pressure on virgin wood sources. Furthermore, extended timber lifetimes offer increased anthropogenic carbon storage, where the reuse of timber is essential for this to be most effective

(Churkina et al., n.d.). As well as this, aesthetic opportunities emerge from the layers of exposure captured by used timber. In addition, material reclaimed from old existing buildings was harvested during a period when forests grew more slowly, creating timber of a higher density, often an indicator suggesting longevity and higher quality.

A key framework for conceptualizing extended uses of wood is biomass cascading. It is a system of material flows that, instead of focusing on product lifetimes, focuses on material lifetimes (Vis et al., 2016). For effective cascading, a series of sequential applications of timber are required, each utilizing the highest proportion of material possible. Current challenges for scaling cascading strategies in the building sector include knowledge gaps and issues surrounding quality criteria, where contaminants such as fastenings inhibit secondary timber's use in current production methods (Sakaguchi et al., 2017). Furthermore, timber has been neglected during the development of legislation and building regulations, leaving reclaimed timber further ostracized from legal building practice (Niu et al., 2021).

The paper investigates some of the emergent challenges of effective timber utilization as well as realizing theoretical material flow strategies, or in this case, biomass cascading, by finding opportunities in unusual material forms. Each project asks how design can work towards extended timber lifetimes by investigating symbioses between the vast library of structural typologies and emergent parameters describing timber less commonly used in building design. The three projects, ReciPlyWood, Waste Wood Canopy, and Wood ReFramed, each offer optimal utilization of timber, albeit in different ways. They have been developed with their own strategies for extending the lifetime of the wood into multiple uses. Also, all three projects focus on material optimization as well as novel approaches to designing for disassembly. The projects aim to motivate alternatives to current wasteful material flows and explore the structural potential of timber that is today regarded as waste. As demonstrators, they are each developed as design projects that lead to mature, full-scale, inhabitable structures.

2. RECIPLYDOME – BENDING ACTIVE PLYWOOD MODULAR KIT OF PARTS

ReciPlyDome is a prototype of a minimal structure designed for disassembly as a kit of parts. It is a spherical gridshell consisting of 45 double-layered beam members based on reciprocal frame principles.

Figure 1: *The ReciPlyDome pavilion*

The minimal plywood beam members form a grid – a self-supporting load-bearing structure that spans 5 meters using plywood of only 12 mm thickness. The double beam members are curved, providing the required rigidity and stiffness.

2.1 Strategy

The ReciPlyDome is a spherical gridshell consisting of 45 double-layered beam members. As a starting point, the ReciPlywood pavilion was designed as a structure from new-virgin material. The approach was to design a minimal, optimized-by-weight structure spanning a long distance that, after its first use, could be dismantled, possibly reconfigured, and re-erected for a new application. Thus, the two main strategies were: 1. material optimization; and 2. design for disassembly (DfD) and reuse.

In order to minimize wood use by weight, a decision was taken to utilize plywood for the loadbearing system, a considerably lighter alternative to solid wood that required a design approach to accommodate the challenges of working with a thin plate or sheet material (instead of the common longitudinal wood beam members) and also establish and embrace the opportunities that it could offer.

2.2 Design approach: Reciprocal Frame principles and bending active beam members

The ReciPlyDome as a design was developed as a kit of parts based on reciprocal frame (RF) principles (Popovic Larsen, 2008) using bending active beam members. RF structures are three-dimensional grid structures consisting of mutually supporting beams, forming closed, stable circuits of closed polygons with mutually supporting beams. The connections between the beams are made so that no more than two beams are attached at a time, adding to the simplicity of both design and construction. A decision was made that all members and all connections should be designed as geometrically identical, offering further uniformity. This also enabled the development of simple connections utilizing a single bolt, forming the connection between two beam members. The identical single-bolt connections further promoted the reversibility of the structure.

Figure 2: *The ReciPlyDome pavilion was built with bending active plywood beams*

Working with plywood sheet material posed challenges as well as opportunities. The thin sheets of plywood with only 12 mm thickness offered a truly materially minimal structure. However, load-bearing structures such as beams that resist bending stresses require structural depth. Thus, a double-bending active beam member was developed that could efficiently resist the combination of axial forces and bending that the structure was subjected to. The lightweight plywood kit-of-parts dome was created by overlaying the RF configuration onto a dome, resulting in a kit of parts with a high level of repetition, further enhancing the ease of construction. One of the main drivers for this project was the *handling of complexity through uniformity*.

2.3 Construction aspects

The ReciPlyDome structure was a fully reversible design made for DFD. It could be fully reconfigured and re-erected in a new form (within the geometrical boundaries). Actually, a design with "universal" beams was also designed so that domes of different member density and size could be built in the subsequent material lives of the structure.

The construction was intended for untrained individuals who, with a set of instructions, could fabricate and erect the structure themselves. The Domes of Transition study investigated the potential for an emergency shelter application where untrained people could both fabricate and construct temporary structures out of local materials. Research suggests that involving the disaster-affected people in rebuilding their homes and communities helps the healing process. (Larsen, 2019)

The overall dome design, geometry definition, and detail design required teamwork and specialist knowledge, while the fabrication, assembly, and disassembly, apart from a set of instructions, did not require any special skills. The ReciPlyDome was fabricated out of plywood sheet plates that were first cut into strips and then prefabricated into the prefabricated bending active beams. The kit of parts required only a few days to fabricate and a few hours to assemble for 3–4 laypeople. Because of the lightness of the members, no specialized equipment was required.

2.4 Reflections

The ReciPlyWood project investigated the implementation of bending-active components in reciprocal grids. The project demonstrated that the mutually supporting RF beam structures, with their weave-like patterns that in each node connect only two beams, despite the large number of connections, are simple to fabricate, construct, reconfigure, and utilize in multiple further applications. The plywood beam members in this project were utilized for several exhibitions, concerts, and workshops and they clearly demonstrated that the plywood had the potential for multiple applications.

The integrated connections, made by cut-outs or simple bolts, can, however, be complicated by the different beam inclinations. Moreover, the curvature of the grids depends on the eccentricity of the connections and, thus, the cross-sectional height of the members. This, along with the bending forces that are imposed through the intermediate connections along the beams, often requires large cross-sections. Using bending-active components allows for the flexibility of the components to overcome the difference in beam inclinations and produce the cross-sectional height. While the flexibility of the components allows further reducing the technical complexity of the structure, it is often more challenging to produce adequate load-bearing behavior in the bending-active case. (Brancart et al. 2019).

Perhaps the biggest challenge for *ReciPlyDome* was developing a cladding system that is prefabricated and as high-performing as the structure yet low-tech in fabrication and construction. One development in that direction was *ReciPlySkin,* a fully enclosed structure with a lightweight membrane. This was a waterproof solution that offered speed and simplicity of construction; however, it was not insulated. Further design and development need to be carried out to find alternatives to inexpensive, insulated façade systems. (Larsen, 2022).

From the point of view of wood cascading and investing in the potential for multiple applications of reclaimed wood in loadbearing structures, the *ReciPlyDome* structure reconfirmed that wood offers the potential for minimal, material-optimized structures that can be reused several times.

3. WASTEWOOD CANOPY – RECIPROCAL FRAME (RF) GRID STRUCTURE FROM SHORT LENGTHS

WasteWood Canopy is a small, grid-shell, inhabitable structure. It is a shelter and has been conceived as a demonstrator testing the viability of utilizing reclaimed timber for an inhabitable load-bearing structure.

3.1 Strategy

The strategy for making a case for wood as a material that can have multiple uses and reuse potentials was done in testing the viability of designing a load-bearing structure out of short-length reclaimed wood. The technical and safety-related aspects of the loadbearing structure were not the only requirements. Usability (architecture and aesthetic aspects) as well as buildability (ease of construction) were tested in parallel. By waying out the different objectives and developing a design that achieved the best of the combined criteria through an iterative multi-objective criteria optimization (instead of the usual single-objective optimization), the canopy was usable, safe, and easy to build. By achieving a highly optimized holistic design, this project presents the holistic potential for wood cascading in building design.

3.2 Design principles - geometry and structural configuration

The structure is shaped like a vault, open at both ends. The ends provide access for visitors to the interior of the structure. The structure acts as a gridshell, carrying the load via arch action.

The canopy's geometry is based on a reciprocal frame geometry with offset joints between the beam members. The members are all identical and are arranged in diamond shapes in a repeated pattern. They are connected at four-member nodes via a specially developed connector plate. This plate clamps the four members together and prevents them from sliding in the connection. The structure is assembled from prefabricated beams and connectors.

The structure can be either supported directly on an existing concrete floor or on a wooden floor.

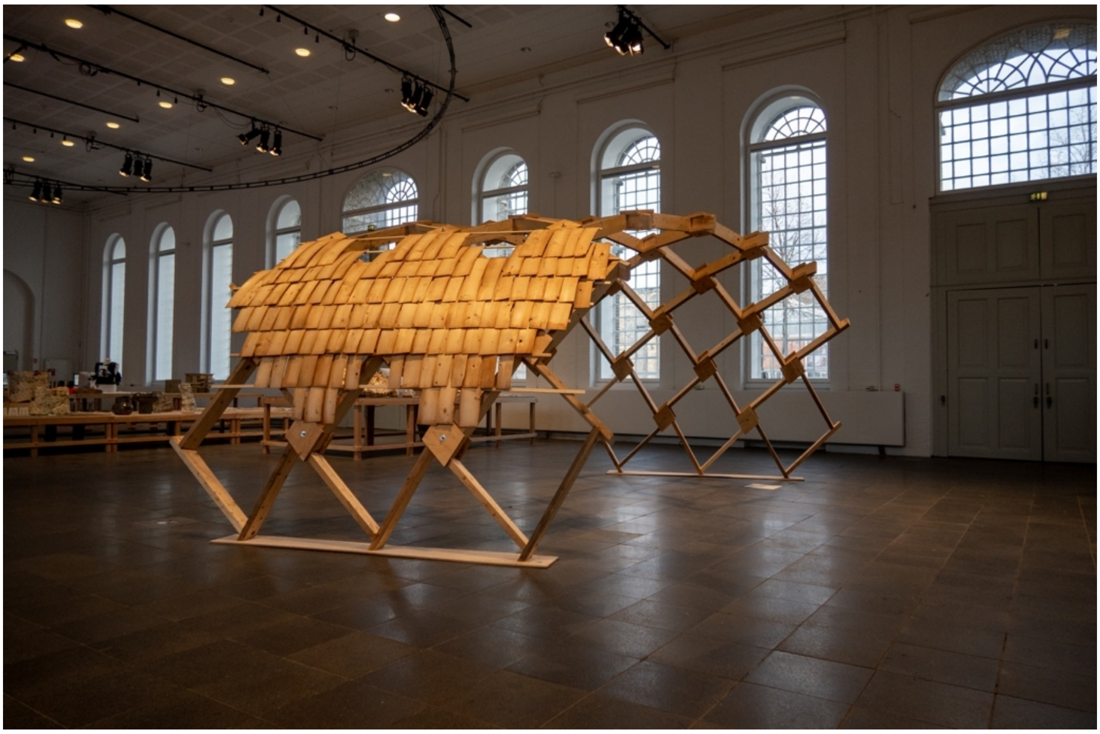

Figure 3: *WasteWood Canopy, exhibition at the Royal Danish Academy 2020*

3.3 Members, connections, and construction aspects

When building with reclaimed wood, typically we are confronted with using shorter lengths of wood members than in conventional structures. That also means that we have many connections.

The timber members are 100x50 mm in cross section and are made of reclaimed (waste) wood. The clamp connection developed for this project with plates that connect the main members is made from plywood that is CNC carved to fit the shape and angles of the incoming four members. The clamp plates are held together with a steel bolt and nut. This considerably reduces the number of connections and simplifies the construction. Due to the tight fit of the members in the clamp plates and the bolts, the connections have high stiffness and safety against failure. The assembly was simple and did not require any specialist equipment.

3.4 Reflections

The overall stability of the structure is secured via the vault shape in the transverse direction and via the stiff connectors in the longitudinal direction. The structure is highly statically indeterminate, which means that there are alternate load paths taking the self-weight down to the floor. Removing one or more timber members will not cause the whole structure to fail. Likewise, the failure of a single clamp plate or bolt will not lead to the overall failure of the structure. This ensures a safe and robust design secured against disproportional collapse.

Figure 4: *The WasteWood Canopy's clamp connections rely on a single bolt connection.*

Designing robust structures is one good way to work with reclaimed materials where there is a level of uncertainty about the material quality. The structure has been constructed and taken down several times and can still be used many more times, showing that wood can be a multi-generational material. Further work, especially in the connection design using high-strength materials, will enable longer spans and greater longevity of the structure.

4. WOOD REFRAMED

Wood ReFramed is a pavilion that investigates the potential of utilizing reclaimed timber of different origins in structural applications. The design is based on a series of portal frames made up of trusses that each integrates a variety of tones and geometries. These frames' structural capacity is demonstrated by a hanging amphitheater where the public is invited to interact with the structure.

4.1 Strategy

The *Wood ReFramed* pavilion project, developed from concept to completion over a 6-month period, had the primary aim of demonstrating the structural potential of reclaimed timber at scale. The project departs from the idea of a building segment, featuring genuine loads, a relatable form, and components that could be integrated into buildings today. This strategy was to create a project that the many stakeholders in the building industry could relate to, whether they were craftspeople, urban planners, contractors, demolition workers, or policymakers. In short, the project aims to convince, mediate between the current disregard for reclaimed timber, and propose a future alternative for timber structures. Exhibited during the World Architectural Congress (UIA) 2023, the pavilion also served to kick-start discussion around how we might (re)frame timber construction, as well as drawing upon the verb ‘framing’ - an activity associated with the assembly of timber buildings.

Figure 5: *Complete pavilion structure with 5 frames and a hanging amphitheater*

A core challenge regarding the effective utilization of timber is yield, a metric that determines the quantity of source material ending up in a component. If the quantity that is included is larger, it reduces the overall material footprint and therefore the burden on resource availability. Recent research has highlighted the significant variation in yield across component types and how effectively they can utilize reclaimed timber streams. Based on this, a truss-like component typology was selected that also succeeds in exposing the surfaces of reclaimed timber. Many common timber components today rely on planning timber surfaces, leading to relatively homogeneous timber surfaces compared to the varied aesthetics present in timber. In this project, the traits that have emerged as a result of the timber’s origins remain exposed, leading to new relations between new building components and the material origins they rely on.

The trusses offer a unique opportunity to assimilate the many forms inherited from timber waste streams into components of standard rectilinear geometries. This works to mediate between the diversity inherent in reclaimed timber and the construction industry’s preference for standards. Furthermore, material can be allocated within the trusses to create optimized topologies for specific load conditions, enabling an efficient distribution of material within a repeatable, rigid boundary.

Many of the previously mentioned barriers to using reclaimed timber, such as contaminants (nails, screws, paints, and treatments) and geometric deficiencies (cupping, wane, and twist), lead to the material being rejected from production. *Wood ReFramed* works towards utilizing materials with these traits, where the typical barriers associated with reclaimed timber are incorporated as a key part of the structural design.

4.2 Design

Wood ReFramed comprises two main parts: a series of five frames and a suspended amphitheater. Each of the frames consists of three trusses, all uniform in exterior geometry, with a varied distribution of material according to the loads of the amphitheater. The amphitheater, constructed from glulam beams, is the central interactive component of the structure, where members of the public can sit. It also initiates the main design challenge, requiring the frames to demonstrate their load-bearing performance.

The arrangement of the glulam elements in the amphitheater at 45 degrees creates an intimate space for hosting talks and for visitors to experience the load-bearing capacity of the trusses. The bottom step floats just a few centimeters above the floor, and the entire amphitheater oscillates gently, limited only by three wires in the floor to prevent it from swinging uncontrollably. The dimensions of the glulam beams vary, creating unequal intersection points between the center line of the glulam beams and the center lines of the trusses. Their varied cross-section dimensions and length also create highly varied self-weight, resulting in a range of loads on the beams.

The trusses have a uniform exterior geometry of 5x0.6m and a varying allocation of material within this boundary. Figure x (main photo) describes the core components of the structure and the connections between them. The location of the amphitheater creates a gradient from one end of the structure to the other, where frame 5 is subject to the smallest loads and frame 1 the highest.

The full frame is modeled in Rhinoceros 3D, Grasshopper, and plug-in Karamba 3D as a wireframe with supports and point loads based on the intersection with the glulam beams. At first, the frames are filled completely with web elements that can be progressively removed based on the axial stress reported by the calculation.

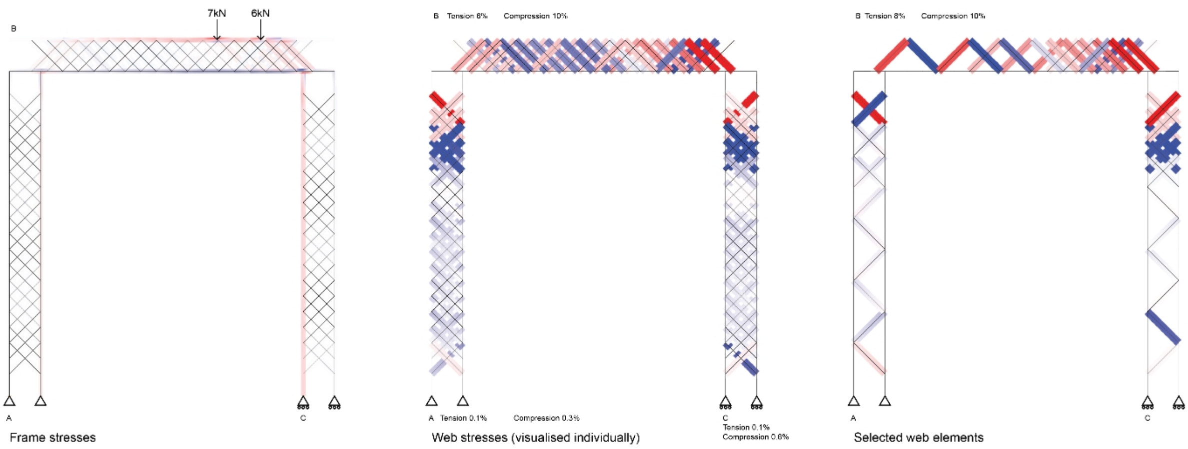

Figure 6: *Process of calculating the material allocation for frame 3. The frame on the right shows the final material allocation*

Frames x and x are designed using the same method; however, the material quantity is arguably overallocated in the horizontal elements. This is due to the load distribution being relatively uniform, leading to symmetrical allocation and presenting an opportunity to integrate structural redundancy. Structural redundancy is typically applied to the design of a global structure to avoid progressive collapse and has been implemented in the design of spatial structures that utilize reclaimed materials, including the *ReciPlyDome* and *Waste Wood Canopy* presented previously. Wood ReFramed applies redundancy at a component level, aiming to inhibit the progressive collapse of the truss if one of the web elements were to fail. An overallocation of web elements also has an impact on failure modes.

Failure modes are one of the most important considerations when designing load-bearing structures (ref. DOTS). Ductile failures are considered optimal over brittle failures, which are often achieved using steel connections, a material that is highly ductile. The shear connections between the web and chords are made with birch timber dowels. This brittle connection makes redundancy more relevant, as a component would progressively deflect via a series of brittle failures, mimicking the performance of a ductile failure. Mechanical joints also offer effective material utilization, as the uneven surfaces of reclaimed timber would otherwise need to be processed in order to create the accurate interfaces required by glued connections.

4.3 Construction - Material sourcing and fabrication

The project strived to be fabricated from only reclaimed timber materials and therefore was developed in close collaboration with a demolition contractor. The demolition sector is not a traditional source of material for construction projects, and although many recent initiatives aim to change this, challenges remain in terms of material procurement. A major barrier is the unsynchronized material flows of demolition and new construction, leading to the mass discarding of resources that do not have immediate value. While this can be attributed to flaws in our current value system and logistical challenges, the project aimed to solve this during the design process.

Already during the early design development of the pavilion, an evolving set of requirements for materials was being established. This culminated in a simple search criterion that could be distributed to all current demolition sites, and any material that met the criteria could be set aside for the pavilion with confidence that it could be used on a project. Very clear requirements were defined, stating a domain of permissible cross sections and minimum length, that metal fastenings and paint are allowed, and elements with signs of rotting or significant quantities of expanded foam should be avoided.

Figure 7: *Steel connections that support the hanging amphitheater*

Enough material for the pavilion was gathered in a short time that would otherwise have been discarded. A range of floorboards and beams from different demolition sites were delivered to the demolition contractor’s main warehouse, which was also the site of fabrication.

This method enabled comparatively short supply chains relative to the typical procurement methods for structural timber in Denmark today. All the material required for the project was sourced within a 30-kilometer radius, reducing transportation distances that can have a high impact on sourcing wood in global supply chains. Fabricating all the parts for the entire pavilion took two people four weeks, using no specialist tools or digital fabrication technology. The fast production time is achieved due to the minimal processing of reclaimed feedstock and the uniform external geometries of the trusses. This meant that a single assembly jig could be used for all 15 trusses. The structure was assembled on site in a single day, a short period achieved due to the simplicity of connections and relatively lightweight structural frames.

4.4 Reflections

The project is successful in demonstrating the load-bearing potential of reclaimed timber and offers a clear reference point for developing the strategies further. Both the design and construction methods are novel, offering an alternative to the current practices of material allocation and construction. These methods initiate a close dialogue between material availability and material allocation, alongside new constellations of industry stakeholders. *Wood ReFramed* demanded significant design time relative to the project's scale. However, the methods could be adapted to the building scale by optimizing groups of components rather than individuals. And developing projects in closer collaboration with demolition contractors would enable better utilization of materials that are imminently available.

5. CONCLUSIONS

The paper presented three different projects investigating the viability of building load-bearing structures from reclaimed wood. *The ReciPlyWood*, *Waste Wood Canopy*, and *Wood ReFramed* through full-scale demonstrators all tested different strategies for structural safety through robustness as well as simple connection systems. The projects have in common that they all show that there is great potential for using reclaimed timber for loadbearing structures. For all three projects, optimizing usability, buildability, and aesthetics and waying them out was important; however, they all presented different approaches for achieving them. Each project offered reflections about the opportunities as well as challenges of each approach. Perhaps more projects with full-scale demonstrators should continue the investigations and continue making the case for reclaimed wood. It is hoped that the presented learning from *ReciPlyWood*, *Waste Wood Canopy*, and *Wood ReFramed*, together with new studies, will impact further research and building regulations to enable reclaimed wood to become a common occurrence in building design. This will be a huge step in resource optimization and help in addressing the climate crisis. It will also give rise to new ways of creating architecture through material agency.

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