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Timber Structures for Circularity: Reinterpreting Lessons from the Past

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Abstract

Recurring resource scarcity has created a long record of ingenious systems for optimizing use of available wood. Reciprocal frames, Delorme arches and laminated timber trusses exemplify the use of small elements for large-span systems. As the current environmental urgency necessitates addressing circularity with surplus and reclaimed materials, revisiting ingenious ideas from these systems can inform optimal resource reuse by future professionals. This paper shows how considering successful precedents aided in generating circular designs in two courses, guided by the principles of “Design for Reuse” and Design from Reuse”. Through the development of a reciprocal frame arch using small plywood components and of a spatial laminated truss crafted from waste lumber, it showcases both opportunities and challenges inherent in reinterpreting historical lessons to create contemporary sustainable spatial timber structures.

Keywords: Circular economy, reciprocal frame, laminated spatial truss, Design for Reuse, Design from Reuse

1. Introduction

Availability of materials and fabrication processes have shaped past as well as current building approaches. Reciprocal frame (RF) systems, comprised of short members supporting each other to form expansive structures, have a historical lineage spanning centuries and cultures. Examples can be found in both Eastern and Western traditions. For instance, in Europe, Villard de Honnecourt proposed planar grillage for timber floors in the 13th century, a concept later revisited by Sebastiano Serlio four centuries later. Similarly, some of Leonardo da Vinci's designs for bridges employed the principles of reciprocal frames to address the challenge of spanning large distances with small beams (Larsen, O.P. 2007 [1]). Zollinger revived the concept of the reciprocal frame in the early 20th century with timber arched roofs, using short timbers called 'lamellas.' These varied in thickness and depth but were consistent for each span, with curved top edges and beveled, radial ends. Bolted together on edge with the curved side facing up, they formed a rhomboid network of framing timbers (Allen, 1999 [2]).

In 1561, French architect Philibert de l'Orme [3] outlined a construction technique using short, thin wooden boards arranged vertically and laminated together with wooden pegs. His innovative approach was extensively utilized in constructing lath vaults supported by ribs made of the laminated elements. In more recent times, in the 20th century, on-site laminated timber trusses, constructed using wooden boards and nails, have been employed for large-span roofs in hangars and industrial halls. These historical examples highlight the inventive use of limited-dimensional wood elements to construct larger systems, showcasing resourcefulness in timber tectonics. They offer inspiration for modern building practices grappling with novel challenges in minimizing the environmental impact of construction. These challenges encompass efficient resource utilization, minimal raw material consumption, and waste reduction in the construction process to embrace circular economy strategies. In wood construction, upstream strategies can facilitate the future reuse of wood elements in new buildings (i.e., Design for Reuse), while downstream strategies focus on repurposing wood elements from demolished or disassembled buildings (i.e., Design from Reuse). This paper presents two educational experiences detailing upstream and downstream strategies adopted in designing spatial wooden systems inspired by historical precedents. The first case in the U.S. and the second in Europe both teach architecture, engineering and construction principles through small group design, detailing and building activities.

2. Reinterpreting Reciprocal Frames: "Design for Reuse" of Engineered Wood Panels

2.1. Why Reciprocal Frames?

Reciprocal frames (RF) are popular for demonstration pavilions because they can efficiently span long distances with aggregations of lightweight elements. They can be composed of rod, planar or volumetric elements. When individual elements support each other without notches or butt connections, the connections create a slope. Different types of reciprocal frame systems can be achieved by varying parameters such as the number per unit and length of the elements, eccentricity between the members, and configurations of the members within the structure. Common approaches are a standardized kit-of- parts designed for use in multiple configurations or customized elements to create non-standard geometry. Design for Reuse is facilitated through the smart design of toolkit with enough standardized elements to provide geometric flexibility and few enough elements to be easily organized and used.

Our efforts focused on planar components that could be cut perpendicular to the panel surface due to previous challenges in cutting reciprocal frame elements for triangular and hexagonal tessellations. This constraint that supports 90-degree connections in plan simplifies and expedites prototyping via laser cutters and CNC. While the program focused on the reusability of the kit's parts, the potential use of wood manufacturing waste was also considered. This includes offcuts from engineered wood products like plywood, laminated veneer lumber, and mass ply panels. 23/32" Douglas Fir plywood was donated by industry partners and used for the demonstration pavilion.

2.2 From planar to spatial

Preliminary experiments in Summer 2023 (Figure 1) showed that surfaces with single curvature (cylindrical) or bends are simple to create with standardized curved or angled members. In contrast, because surfaces with double curvatures require diverging or converging members, they require custom pieces. Systems generally require a specific order of assembly according to joint geometry. For example, our notched systems require rotating a slotted element first to around one slot to connect a second slot and then locking the member when its third slot is connected. The 4-fold rotational system requires beginning in the center and gradually expanding locked elements, increasing the system stability. Its elements can be stabilized against wracking with stiffening plates.

Figure 1: Single-direction RF curved surfaces created with three notch members with special members in clue.

For quickly assembly and disassembly, we considered breaking our pavilion into framed modules with reversible metal fasteners as recommended by Pozzi, 2019 [4]. While they would expose students to up to date hardware, they would require using or piecing together longer members for the framework, breaking the RF continuity and increasing the carbon footprint. We instead decided to rely on carpentry joints to connect modules of our RF system into a continuous frame.

2.2. The course and the program

The Timber Tectonics in the Digital Age (http://timbertectonics.com) studio jointly teaches undergraduate and graduate students enrolled in Oregon State University's Wood Science and Engineering department and University of Oregon's Architecture department. The 11-week hybrid course focuses on timber structures, physical prototyping and digital workflows.

For the Fall 2023 class, students were asked to design a kit of parts for a seasonal pavilion that could be disassembled and deployed elsewhere. 23/32" plywood was donated for the class project and was chosen for its suitability for normal CNC cutting and its light weight. Working with light elements allows easy handling by a wider range of people. Students were encouraged to explore formal opportunities by using planar materials instead of linear members, diverging from the classic reciprocal frame constructed with beams. The problem limited the number of component types, so that standard elements could be interchangeably deployed for reuse in different configurations.

Teams of mixed backgrounds selected precedent examples of reciprocal frames to develop their initial proposal. They adopted a bottom-up approach, beginning with the development of a concept for a kit-of-parts. This involved considering material, fabrication, and connection constraints before proceeding to formulate an overall design for the reciprocal frame structural system. Constraining to perpendicular cuts kept the design explorations more similar, facilitating peer sharing and easier consolidation into one concerted effort. Participants studied how 4-fold rotational patterns could create curvatures over multiple connections by offsetting notch endpoints on elements. Their experiments with notched elements (deep half-laps) revealed the best notch profiles for enabling the rotational attachments.

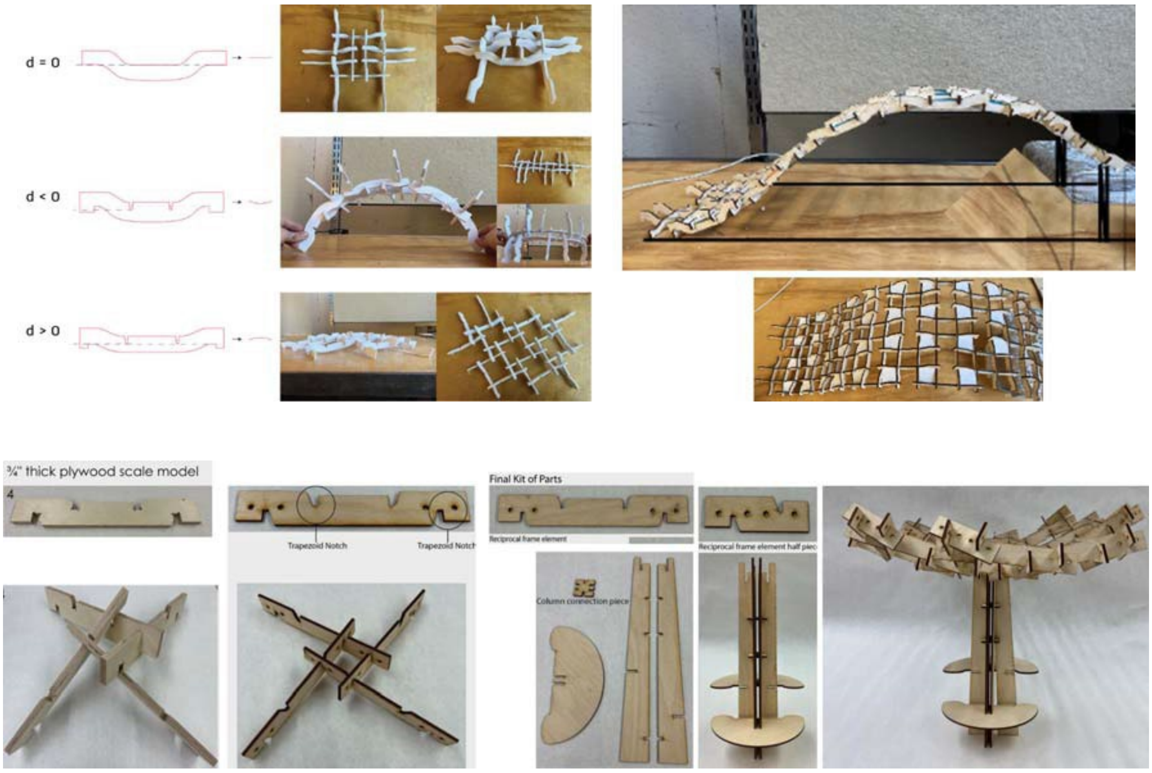

Figure 2: Shape experiments for curvature and constructability. Curved member studies by Sage Fetkenhour and Seunghyeon Park (top) based on Pizzagoni [4]. Lower studies by Jin-wei Jerry Chu.

A proposal that built on a Kengo Kuma & Architects (KKAA) 2013 project for the Kyushu Geibun Kan Museum was chosen for further development. In KKAA's project, a roof consisting in a planar reciprocal frame is composed of notched triangular cedar members "2.5 m long, 20 kg, combinations of which can expand or shrink with no limit" [5]. After creating a small-scale model of the project, which uses a modified hexagonal grid, the students adapted the triangles to a 90- degree planning pattern that employs 4-fold rotational symmetry so it could be more easily cut and assembled. The rectilinear plan pattern (Figure 3) echoes a structure from a 2007 Cecil Balmond exhibit at the Louisiana Museum of Modern Art in Copenhagen (Pizzagoni, 2009 [5])

2.3 Canopy Support and Reciprocal Frame Continuity

We found continuous wall to canopy solutions to be more graceful than column roof supports. Point supports require deeper canopy members near the columns, disrupting our goal of standardized reciprocal frame elements. We found few strong examples. An Aalto University Wood Program Project featured layered cantilevers similar to the Chinese and Japanese traditional bracket system, and dendriform members that touch the canopy at multiple locations [7]. A Shigeru Ban experimental pavilion for Forest Park in St. Louis (Godthelp 2019 [8]) employed a twisted bundle of small members so that each would hit a different intersection of the roof network. Both situations show that integrating periodic vertical roof supports is an aesthetic and technical challenge.

KKAA may have chosen a triangular-shaped member to brace from occasional slender columns and heavy wood plate supports to the horizontal roof, as well as for aesthetic effect. The students realized that the triangle could be rotated to create a convex corner, bending the surface in a visually integral way (Figure 3). Due to its continuity, this curving surface that turns from a canopy into a vertical support wall was more graceful than column-based proposals.

2.4 Connections and Structural Behavior

For module stability, the joint notches are located on a top flat edge of the triangular pieces, which means individual elements are resting on the symmetrical corner of the isosceles triangle. The advantage of half-lap notches is that they allow higher tolerances compared to other types of wood-to-wood joints. One critical disadvantage is that the notch weakens the element, and depending on their location within the triangular element, their depth was exceeding the recommended ratio (Figure 3 left, and Figure 4 top). Another disadvantage is that with few pieces, the partially constructed system resting on the triangular corners is not very stable and only acquires stiffness progressively by the expanding network. The instability is exacerbated because each piece has only two slot connections – in systems with more connections per member, destabilizing rotation is prevented when a third point connected. In modifying the reciprocal frame tessellation from a triangular to an orthogonal one, the reciprocal frame also lost any stabilization from triangulation and had smaller surfaces whose friction could reduce slippage. To increase stability, inspiration was found in the Siza-Souta de Moura-Balmond 2005 Serpentine Pavilion (Gouw, 2011 [9]) which used mortise with pegged double tenon joints for sturdy and reversible connections. In the pinwheel pavilion, a pegged mortise and tenon joint locks the edge components, which secures the internal notched connections.

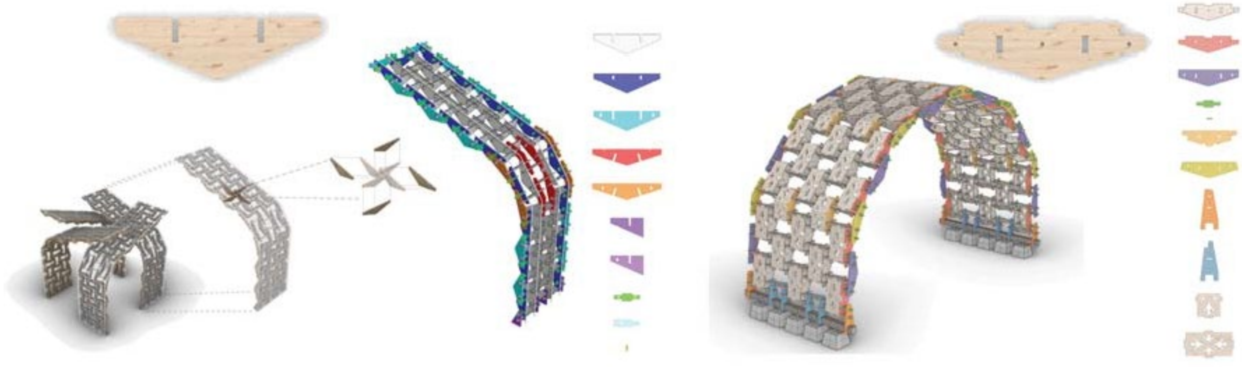

Figure 3. Notched pieces (left) and modification into mortise and tenon connections (right)

This system of triangular elements system was adopted to create a segmented arch which could address the site's directionality. When the structural analysis revealed the need to stabilize the canopy against wind uplift, mortise and tenon joints were adopted throughout the system, not just at the edges. To further reduce the uplift action, perforated rectilinear stiffening plates were added to create a “permeable” roofing surface. (Figure 3 right). Structural movements were recorded during construction and after the completion of the assembly. In the as-built structure, differential deflections were observed between the arch planes across its width. The center plane, located at half the arch's width, experienced a deflection of about 2.3 cm more inward at the first corner near the ground compared to the outer planes. At the crown, the center plane had a deflection of about 4.6 cm more outward (upward) than the outer planes. This indicates that the stiffest load path under self-weight formed an "X" from one end of the arch to the other. (Figure 4 lower right)

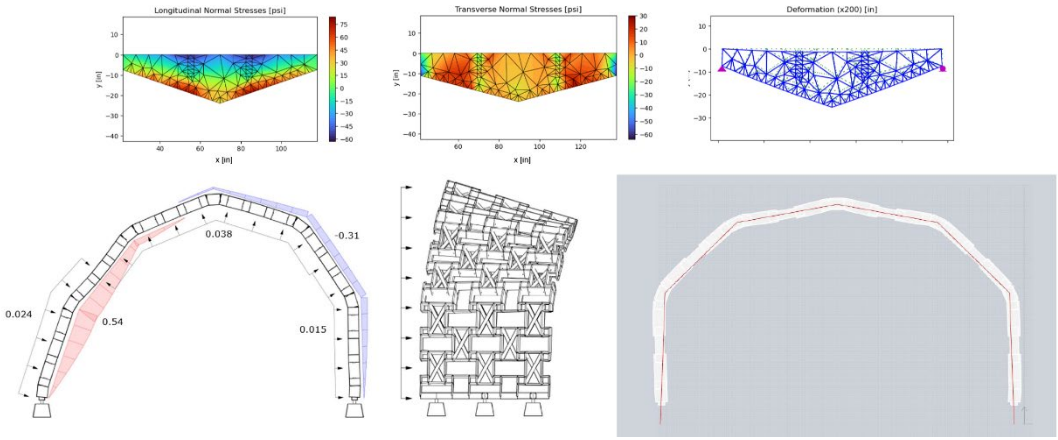

Figure 4. FEM modeling (top) by Nicholas Thielsen (top) revealed original notched member weaknesses, wind load vulnerability (lower left) and on-site deformation (lower right) images by Lara Diehm

2.5 Construction and Reuse of the kit-of-parts

The full-scale arched pavilion was constructed and deconstructed twice in December 2023 and February 2024. The small, lightweight components are easily transported and assembled by untrained students (Figure 5). The arch was installed with telescoping struts, ladders and required a scissors lift or crane for the keystone section.

During the deconstruction phase, to disassemble the mortise and tenon joints, a mallet was used to tap the tenon out of the mortise. However, in a few instances, this caused localized damage, such as crushing of the tenon ends or small areas of plywood delamination. Preassembling the reciprocal frame into modular sections not only facilitated construction and disassembly but also promoted reusability by minimizing the disassembly to joints between modules. This approach effectively reduced material damage.

Figure 5. Module construction with concurrent sliding notches (l), first assembly (m) and second assembly (r)

After the two installations of the arched pavilion, the components became part of a reusable building kit. Alternative corners were cut to create 90 and 120 degree corners that were used in small demonstration installations, and additional designs were created for Y-shaped or L-shaped components to support three plane connections. Physically manipulating small scale or full-scale components made it much easier for participants to understand the construction process and design opportunities, thus facilitating further digital variations.

The variability of the plywood thickness did not allow precise fitting of the carpentry joints. Shims were needed for slightly large slots and components exposed to moisture had to be sanded to fit precise slots cut in new components from wood stored in low humidity. Connections which can adapt to slight material thickness variations (i.e. bolting, clamping, lashing, pegging) can make the use of irregular reclaimed wood more feasible.

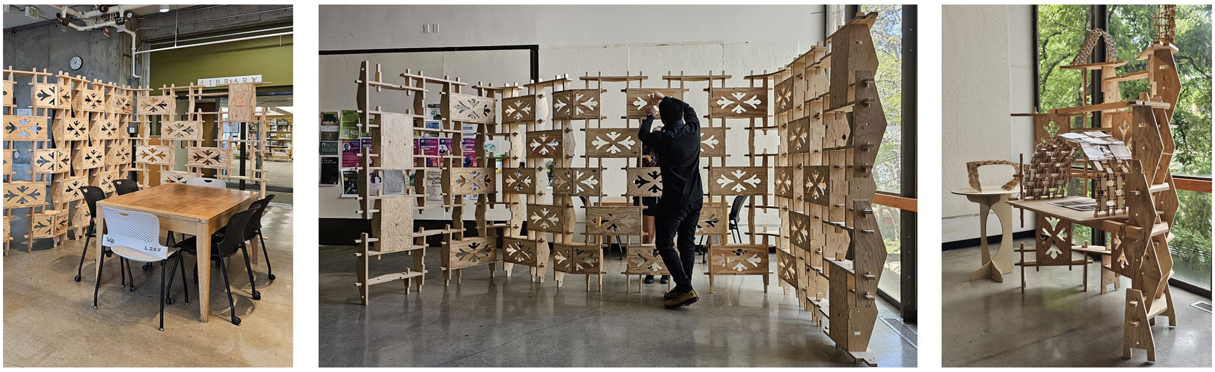

Figure 6. Pavilion components became a toolkit for a sculptural partition wall and a display stand.

3 Reinterpreting Laminated Timber Trusses: "Design from Reuse" of Reclaimed Lumber

3.1 Project Context

In the second educational setting, post-professional architects from all around the world study and work together intensively over 9+ months on building sustainably with local reclaimed materials. In this case, the reclaimed timber complements locally harvested and produced building materials such as compressed earth blocks and earthen plasters. It unfolds in a one-year (30 weeks) postgraduate program in Belgium, open to graduates and professionals in architecture and related disciplines who wish to explore regenerative and distributive ways of building. Each edition of the program culminates in a small-scale design/build project that represents the discussions and knowledge generated over the year. To reach this point, students build their knowledge and skills through theoretical classes, hands-on workshops, research studios, and a four-week design/build internship. Of the 16 students from 13 different nationalities enrolled in the 2023-24 program, five chose the Circular Wood Construction research track, starting at week 11 and offered along with Participatory Design, Urban Harvesting, and Earth Blocks.

(https://www.buildingbeyondborders.be/platform/postgraduate-certificate/pg-structure-ed-23-34)

The project goal was to design and build an outdoor gathering space using circularity principles in the garden space of a former vicarage in a Flemish village to be renovated and adapted as a public community center, providing a new gathering place for villagers. The outdoor gathering space will complement the vicarage building renovation led by a local architectural firm.

The program challenges students to design and construct a covered outdoor gathering space for a minimum of ten people. A maximum footprint of 40 square meters and a height of four meters avoids the need for a building permit. The space should provide shelter from the rain but can be opened on the sides, which means it will not have mechanical cooling or heating systems. A primary timber load-bearing structure was envisioned for the canopy, with possible earth-based partitions as needed.

3.2. Design from Reuse with reclaimed timber

To support circularity, local reclaimed wood was selected for the load-bearing structure. Initially, a local interior contractor agreed to donate scrap wood from their production line. The large variability in sections and lengths of the donated pieces created design constraints. The design of the canopy structure had to be considered from the smallest sections and lengths available (about 40x90x1000 mm), which meant that mechanical lamination was needed to join pieces into longer structural elements for a sufficiently generous covered space.

To develop the students' knowledge, skills and experience for the design/build project, the Circular Wood research track had the following research question: How can a canopy structure be designed/built using short-length timbers? To answer the question, the research track proposed three sequential phases: 1) reference projects, 2) connection prototyping, and 3) canopy concept design. In Phase 1 (Week 11), students individually researched references for wooden pavilions designed with short timbers, beginning with references shared by the U.S. students and their reciprocal frame proposals. These were presented to the whole group in week 12.

The program's overall low-tech approach directed the selection of precedents toward more handcrafted solutions. Students were particularly interested in using traditional wood joinery to overcome the design problem of building with short-length timbers. Therefore, the initial selection of precedents included sophisticated carpentry joint references such as dovetails and mortises and tenons, as well as simpler options such as lap joints with wooden dowels. Understanding historical precedents using carpentry joints in Phase 1 was a critical step in building up the students' repertoire of conceptual solutions for the following applied phases of the assignment.

In Phase 2 (weeks 12 to 13), students iterated different proposals for reversible connections to laminate and extend the length of short timbers through hands-on prototyping. Following the instructor's advice, the students first attempted to replicate the more complex carpentry joints. The students' lack of advanced woodworking skills made the production of dovetails and mortises and tenons very time consuming and resulted in relatively low-quality samples. This led the students to focus on simpler ways of joining the short timbers using wooden dowels and developing spatial trusses (Figure 7). These provided the basic building blocks (or modules) for the final phase of the assignment.

Figure 7. Phase 2 prototypes: 1:2 models exploring lamination with wooden dowels to create truss elements.

Finally, in Phase 3 (weeks 14 to 15), students synthesized their acquired knowledge to develop a holistic concept for the design brief individually. Students started from the same answer to the research question of mechanically laminating shorting timber with dowels, but proposed different modular spatial truss systems that could respond to the design problem of building a canopy with short timbers. Despite the simplicity and relative homogeneity of the joinery solution, the canopy solutions iterated by the students were diverse, ranging from more rigid shapes to organic.

Figure 8. Phase 3 proposals: Canopy design possibilities using Phase 2 technical solutions.

Design from Reuse requires agile adaptation to changing possibilities. While the students investigated how long span structures could be created from the donated short members and tested building with material reclaimed from houses slated for demolition, these pathways were not possible due to scheduling and liability reasons. In the end, they changed the form of the final pavilion to fit wood that came from several sources. Spruce dimensional lumber donated by a contractor allowed creation of an A-frame structure braced by seating. For the sill pieces, they used reclaimed oak from a dealer that could offer nail-free, consistent lengths and sections of a known species. For the shingles, students bought eight chestnut trees from a local plantation forest. The chestnut logs were cut to length and divided into quarters still in the forest. Then they were transported to the site, where students took around 16 weeks to split them into shakes.

Figure 9. Final pavilion design and build: physical model and framing in progress.

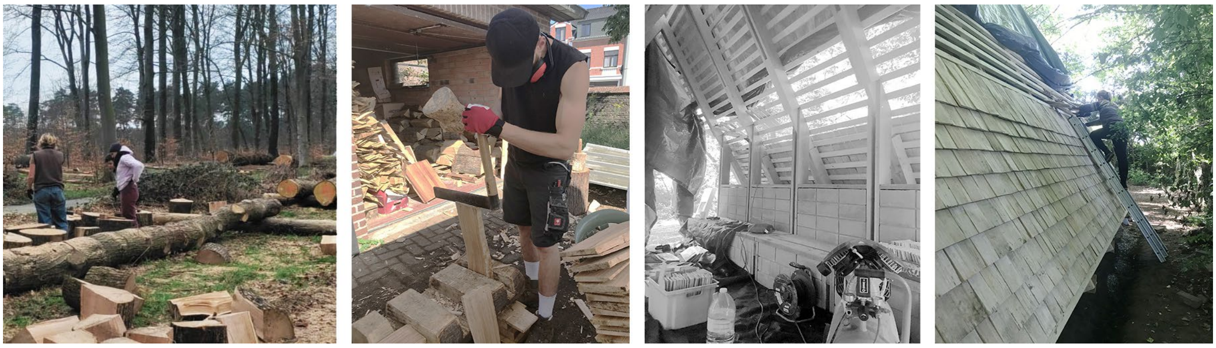

Figure 10. Chestnut log harvesting, splitting shingles and applying them to the framing

4. Discussion

4.1 Takeaways for Design for Reuse

The design of a flexible and expandable kit-of-parts enabled us not only to explore alternative designs for the canopy, ultimately settling on a segmented arched pavilion, but also to establish the foundational set to create very different structures: decorative display walls. These secondary projects necessitated only two additional corner components. This bottom-up approach not only stimulated creativity in conceptualizing different structures but also established a foundation for future reuse and adaptation. It promotes an iterative design culture, enabling structures to evolve and respond to evolving needs and contexts over time. Flexibility is partly achieved by selecting small elemental components, yet this approach leads to a greater number of joints. While this enhances adaptability, stability depends on the aggregate performance of many joints and repeated disassembly of these joints can gradually cause damage, potentially impeding future reuse. To address this issue, opting to retain larger sections during disassembly speeds up the deconstruction process and reduces damage, thereby facilitating the reuse of materials in future projects.

4.2 Material, labor and technology in Design from Reuse

In Design from Reuse, Form follows Material. The use of reclaimed materials requires a reverse approach compared to the conventional design process, where designers usually start by pursuing a holistic formal and functional concept from an endless pool of options to answer the design problem, for which a given materiality and detailing is specified and developed. In this case, however, the students were initially confronted with a limited materiality (small-section short timbers), which created a specific and strict set of formal and functional design constraints from the very start. More specifically, the one-off nature of the reclaimed short-length timbers defined joinery techniques as one of the key challenges for the project, reiterating the observations of Asa et al. (2024). Therefore, the students had to start their design answer by iterating technical detail solutions acknowledging the great variability of the reclaimed material available (Huuhka, 2018) and then use them to extrapolate the design into a holistic answer to the design problem.

The second project's change in direction allowed by donation of longer members shows that designers must have an opportunistic mindset to make the best possible of the available material (Macdonald and Schumann, 2021). In this context, the use of historical precedents for artisan joinery, analyzed under the lens of circularity and a hands-on approach to architectural education, was found to be beneficial to the process. From a repertoire of validated solutions, the students were able to curate those that seemed more promising within their constraints. A critical factor in this exercise was the prior level of woodworking skills in the cohort. An initial lack of familiarity with woodworking techniques determined the range of solutions that could be applied in subsequent design phases. Therefore, a different cohort with a more advanced level of woodworking skills could potentially result in a very different set of design solutions. Nevertheless, it is worth noting the great variety within the proposed solutions, despite the limited range of technical solutions to laminate the short timbers. A possible reason for this variety was the use of very light, easy-to-process sawn lumber. The use of more robust engineered wood products, such as glulam, CLT, or LVL, would present a different set of challenges and limitations in terms of material reprocessing and would require more well-equipped facilities than a wood shop in an architectural school. Consequently, as well as the initial level of woodworking skills, the choice of which materials to reclaim and reuse was another critical factor in the second case study. Overall, when designing and building according to circular principles, the initial choice of inputs will have repercussions that define the possible outcomes.

5 Conclusion

This paper highlights two educational endeavors that push students to design spatial structures using small timber elements following circular economy approaches. In one instance, the focus was on planning for future reuse, optimizing components for easy assembly, deconstruction, and adaptable design. The aim was to craft a limited set of components capable of accommodating multiple and flexible configurations. By contrast in the second situation, students were tasked with repurposing available materials to construct a permanent structure. They were initially challenged to manage a large variety of elements with limited lengths to create standardized components of larger sizes. Throughout both experiences, bottom-up approaches, beginning with material and fabrication constraints and leading to overall system design, played a pivotal role. In both educational experiences, students were given the opportunity to devise non-standard solutions for spatial structures, guided by principles of sustainable design rooted in the circular economy. This challenge encouraged experimentation with structural systems validated by both historical and contemporary precedents.

While the path to integrating circular economy principles into mainstream design practices may still be long, these educational experiences serve as sources of inspiration, driving innovation and sustainability within the field.

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