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Embraced Wood: Circular construction method for composite long-span beams from unprocessed reclaimed timber, fibers and clay

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ABSTRACT

This paper presents a method to expand the availability of wood in construction by establishing a computational design and robotic fabrication workflow. Digital tools enable the evaluation of the structural, material and geometric properties of pieces of unknown origin to create beams from unprocessed reclaimed timber using clay and natural fibers. Methods to overcome challenges such as material irregularities, embedded fasteners, size variation, and surface toxins allow for timber that would otherwise only be downcycled to serve a structural high-value use. A full-scale prototype beam was fabricated to test the fabrication process, and structural testing was conducted to demonstrate design specific span and loading performance.

1. Introduction and relevance

Germany produces over almost 8 million tons of waste wood annually [1]. Currently, most of this wood is burned for energy, which is the least sustainable method in the waste hierarchy pyramid (Fig. 1). With the recent EU directive of September 2022, burning of wood for energy is not recommended as it is no longer considered a renewable fuel and higher value reuse is encouraged [2]. In June 2023, the Ministry of Housing, Urban Development and Construction in Germany set as an aim to develop and promote the circularity of timber construction in the further development of timber construction methods and the potentials of waste wood recycling [3].

At the same time, timber as a sustainable building material is gaining interest in the construction world. In France, construction materials for new public buildings are to be at least half timber and other natural materials by 2022 [4]. In the United States, the International Building Code (IBC) included sections for timber construction for the first time in 2021 [5]. Lastly, in Germany, the most recent coalition agreement stated that a national timber construction strategy would be established [6]. Yet, while the demand in timber resources is increasing, forests in Germany are getting sick, rendering some of the timber unsuitable for high-value applications. In fact, out of a total of 80 million m^3 of timber logged in Germany in 2020, almost half was damaged by insects [7]. As an alternative timber source, urban mining has a huge potential. Germany has 220 million tons of timber in the built environment, almost 4 times more than what is annually logged [8,9]. Both the volume of timber from the building stock and from demolished houses are expected to increase [10].

With the continuing need for new construction especially in urban areas [11] and growing interest in timber as a building material, identifying alternatives for virgin timber and waste wood processing can create economic opportunities and help to mitigate an expensive and environmentally sensitive problem [12]. Each upcycled application of timber leads to a delay of carbon release into the atmosphere. Unlike virgin lumber, which is sent to sawmills to be processed into standardized timber, it may be possible to prevent energy-intensive processes by reuse, as the material already comes in transportable dimensions. This research shows how timber from old buildings slated for demolition can

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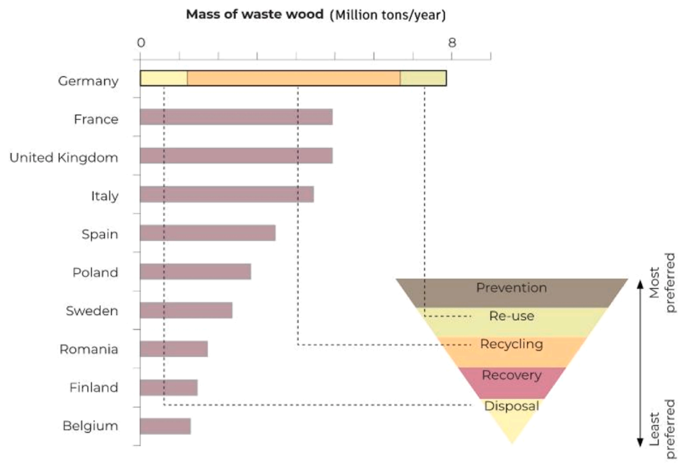


Fig. 1. EU countries with the highest annual mass of waste wood. Division of how waste wood is used in Germany relative to the waste hierarchy pyramid (Data: Privat, 2019 [1]).

be reused in structural applications, and how typical challenges for such reuse can be overcome through digital analysis, a computational building system and novel fabrication processes.

1.1. Context

Despite the fact that there is a high availability of reclaimed timber and that the stock would contribute to lower environmental impact, reclaimed timber is seldom used in construction. In this section, four main reasons that inhibit the reuse of timber are outlined: Design limitations (1.2.1), Fabrication limitations (1.2.2), Uncertainty for safe reuse (1.2.3), Material procurement (1.2.4).

1.1.1. Design limitations

Materials from demolition sites or old houses no longer have standardized dimensions [13,14]. As building codes are revised over the years, many codes become more stringent. This means that beams used to span a specific distance may not meet the criteria to do so again when repurposed for the same structural application without a design or fabrication strategy. Designers are then left to keep the spans of their designs short to ensure that the reclaimed material can be used [15] or devise combinatorial methods with short elements based on the material stock [13,16]. Macdonald and Schumann note that when using a standard material, designers can predetermine fabrication techniques to yield irregular resultant forms, but when beginning with found materials, a designer should strive for opportunistic outcomes that make the best of the material at their disposal [17]. An opportunistic design attitude has inherent drawbacks to meet client needs, designer ambitions, and builder procurement. Furthermore, besides consisting of short lengths, reclaimed timber stock material is often permeated with dimensional irregularities (Fig. 2). Without strategies for joinery, the one-off nature of the material will introduce difficulty in joinery and building system integration.

Fig. 2. Variability of cross sections and sizes among reclaimed timber pieces.

1.1.2. Fabrication limitations

Reclaimed timber often includes embedded nails, bolts, paint, and surface contamination [13,18]. These factors influence whether the timber can be reused or not. The presence of metal fasteners makes it challenging to use subtractive machining processes and recent reuse applications depend on total cleaning of the fasteners from salvaged timber [18–20].

1.1.3. Uncertainty for safe reuse

Reclaimed wood is often avoided in design and construction because of its structural uncertainties [20]. In unison with visual grading, non-destructive tests need to be conducted to estimate the modulus of elasticity, moisture content, and density of the material. Contrary to the belief that old timber may be structurally weaker, most studies show no or little difference in the mechanical properties of salvaged timber compared to new timber of the same species. A literature review by Cavalli et al. indicates no significant reduction of modulus of elasticity (MOE) and rupture (MOR) due to aging [21]. Sonderegger et al. also found little difference in MOE and MOR of old timber sourced from deconstructed buildings, with some old timber having higher values due to higher density [22]. Falk et al. demonstrated that age has a minimal effect on the properties of timber and that timber has high potential for reuse even after decades of service [23]. Analyzing reclaimed lumber from four different military buildings around the US, they identified that grade reduction was mainly caused by nail holes. They concluded that in order to recover higher grade lumber from buildings, deconstruction should be done more carefully, thus increasing the potential of timber reuse. The German Waste Wood Ordinance does not permit reused timber with coatings to be used in habitable spaces and states that they should be incinerated due to the possible presence of lead or other heavy metals found in these waste wood classes [24]. Even if coatings were permissible, visual regrading cannot be easily achieved. The obstructive coating would need to be removed.

1.1.4. Material procurement

Lastly, lack and inconsistencies in the availability of desired cross sections and sizes makes reclaimed wood hard to use for construction [25]. From a sourcing perspective, a design can only be built with available reclaimed material or adjusted based on available material stock [26]. Furthermore, sourcing can have an economic impact on a project and the feasibility of material reuse [27]. Wuyts et al. state that material stock information needs to be consistent and up-to-date to assist circular economies [28]. For instance, in order to design with reclaimed materials, one must know the amount of the materials and their dimensions. Besides the geometric information, Kühlen et al. note that due to the challenges of analyzing the properties of reclaimed material, engineers might be opposed to using them [29]. This means that the material most likely needs to be procured early in the design phase of a project. Two paths for this procurement have been outlined. In the first, the material is inventoried from an existing operating building. Byers and De Wolf proposed using digital material passports to assist in this process and the reuse of the materials [30]. The demolition and subsequent reuse can then be planned to be repurposed as quickly as possible. Some shortcomings of this approach are that the material may be damaged in demolition or other unknowns may be exposed upon disassembly and should be tracked and matched with these material passports. The second approach is to procure the material and store it early on in the design phase. With this approach, storage fees will need to be considered while the design and permitting phases are being completed. From a reuse perspective, Huuhka states that architects will need to account for the variability in member lengths when sourcing reclaimed timber [15]. She informs the reader that designing roofs with many hips and non-symmetric ridges lends itself better for a structure built from reclaimed timber.

1.1.5. Reclaimed timber homogenization

In order to overcome all of these challenges, wood requires high processing time and energy. Conventionally, reclaimed timber would undergo some level of standardization where most of the material is lost (Fig. 3) [31]. For example, the study “Feasibility of Producing Value-Added Wood Products from Reclaimed Hemlock Lumber” found that two-thirds of reclaimed Hemlock lumber was lost in standardization processes such as cutting to length and embedded metal removal [25]. During this process any part with defects and irregularities is cut out, wood pieces are trimmed to standardized dimensions and cleaned from nails, dowels and joints in many projects using salvaged timber [18,19,32]. Similarly, the fabrication of CLT from reclaimed hardwood timber by Llana et al. resulted in approximately 44% material loss from each reclaimed element before planing for CLT boards [33]. The removal of construction joints is not only accompanied by material loss but also by structural loss. Once the reclaimed material is finished being homogenized and cleaned, the material typically undergoes conventional fabrication processes yet again, embedding nails, introducing notches, and adding coatings.

1.2. State of the art

In recent years, investigations into timber upcycling have been well documented. Most of the research in this field stops short of providing a holistic workflow from sourcing to construction that can be implemented in an industrial setting. The state of the art includes four different sections:

1.2.1. Reclaiming timber

Several research projects investigated the reuse of wood [34–37], but typically the focus is on either (1) a cascading reuse process with a limited set of reuse cycles (i.e. each time more timber is lost due to offcuts) or (2) the design for disassembly via mechanical fasteners.

One example is the Cross-Laminated Secondary Timber (CLST) project by Rose et al. which presents a product that can feasibly substitute new growth cross laminated timber for many applications [32]. This study collects and analyzes timber boards from construction and demolition sites to make industry applicable cross-laminated timber. Compared to a cross-Laminated timber (CLT) of primary timber made under the same conditions and with the same process, cross-laminated secondary timber prototype did not have a significant reduction in compression stiffness and strength and minor defects only had a slight impact on compression and bending stiffness, thus concluding that the use of secondary timber could be viable for CLT applications. Although this research provides a method for upcycle of timber in construction, secondary timber still undergoes heavy processing in terms of cleaning the reclaimed material for reuse by trimming pieces to uniform size and cutting out irregularly shaped parts.

Another project is by Wibranek, who introduces a construction framework that utilizes computational design and augmented reality to facilitate the reuse and salvage of waste lumber in industrial prefabrication [16]. By incorporating existing materials and automation, the framework enables the design and assembly of wood columns using cut-off lumber blocks, promoting resource efficiency and simplifying assembly instructions.

Giordano et al. investigated fabrication of dowel-Laminated timber panels from a mix of reclaimed timber with new timber boards [14]. Short salvaged pieces were used in between the long new timber layers and salvaged plywood tenons as connectors. This approach shows that design choices can lead to higher material reuse and less processing. Bergsagel and Heisel also constructed a demonstrator project using reclaimed timber [18]. Their design procedure allows for dimensional irregularities and unknown mechanical properties by using parametric design for the former and wood species identification for the latter.

1.2.2. Computational design with reclaimed materials

Research by Huang et al. uses an algorithmic approach to match linear pieces of timber elements from a digital model of a house to create geodesic dome design iterations [38]. Although this research is important to show how various designs can be created from available stock material, they assume the reclaimed timber elements still have regular geometries after their initial use, can be easily processed to cut into the same cross-sections, and have the same structural properties.

Parigi also studied multi-objective optimization for reuse of salvaged timber elements with non-standard sizes in floor or wall layouts for minimal waste and maximum use of the material [13]. While this approach greatly expands the usable stock, it limits the designer to work within the current properties of the material.

Besides timber, several studies looked at optimized use of other deconstruction materials. Brütting et al. presents an algorithmic method for the design of truss structures from a given stock of steel components to minimize waste [39]. However, steel reuse mainly considers linear elements with the same geometrical section and properties, and therefore evades the idiosyncrasies of old wood.

1.2.3. Composite biomaterials

“Timber-Clay Composite Slabs” by Trummer brings together clay and timber to form a floor slab [40]. The timber offers structural performance to the slab while the clay loam adds mass reducing sound

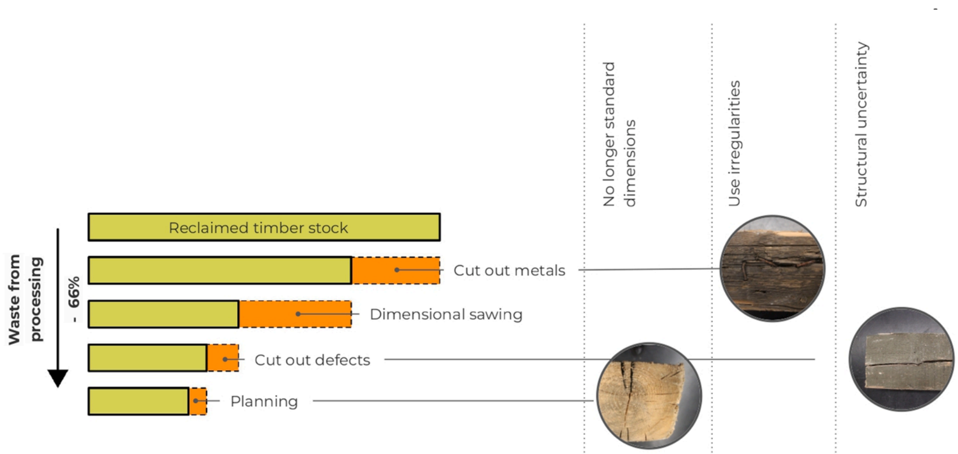


Fig. 3. Off-cuts that occur in the homogenization of reclaimed timber (Data: Irle et al., 2018 [31]).

transmission through the slab. Additionally, the clay loam offers fire and moisture protection to the timber. The thesis is supported by demonstrators which show that clay does not crack or fall off of the timber design when loaded.

Mutis and Polanski studied alternative fabrication methods for assembly of wood laminates using filaments made of bioplastic and different fiber additives as binding material [41]. As this process does not involve gluing it can simplify the future disassembly and reuse of the material. However, as it includes subtractive manufacturing methods and combines same-size, regular timber layers, this method cannot be applied to uncleaned reclaimed timber.

1.2.4. Designing with timber for disassembly

The People's Pavilion showcased at the 2017 Dutch Design Week in Eindhoven is a temporary structure designed to minimize its ecological footprint in materiality, construction, and disassembly [42]. The primary structure of the pavilion is constructed of borrowed timber, which needed to be returned undamaged to the owner at the end of the exhibition. The use of non-invasive and disassemblable fasteners was required. For this, the design team specified steel straps. Additionally, the borrowed timber had standardized dimensions.

The Robotic Reversible Timber Beam project demonstrates the integration of material reuse considerations in the design process through the construction of a beam made from short timber elements [43]. The connections using mechanical fasteners are reversible and the pieces can be reconfigured in a finite amount of variation. The reversible and reconfigurable logic of the beam serves as a technique to a circular economy.

Interlocking Cross-Laminated Timber (ICLT) developed by Euclid Timber uses pine wood damaged by beetles to create CLT-like wall panels [44]. As opposed to the glued connections of CLT, ICLT joins the lamellae through interlocking dovetail joints that can be more easily disassembled [45]. However, such complex interlocking patterns can only be made with cleaned timber and would not be feasible for reclaimed timber with embedded fasteners.

1.3. Aim

This research investigates how unprocessed stock timber can be worked without the need for homogenization as a way to save on energy, time, cost, and material. To prevent processing, embedded materials found in reclaimed timber are left as is, and therefore a non-invasive lamination method is presented to prevent the risk of damaging tools. To allow for disassembly and subsequent reuse of the material, alternative material compositions and fabrication techniques are explored.

Variable dimensions bundled together to form beams allows for a greater intake of reclaimed wood, furthering the potential of upcycling. By creating reinforced long-span beams from reclaimed elements, Embraced Wood provides components that can be adjusted to any design, instead of adjusting the design to the material stock.

1.4. Scope

1.4.1. Non-destructive regrading

Through non-destructive re-grading, extracted material data will be used to make predictions on material properties. Each evaluated timber piece will be added to a digital inventory and face marked for identification.

1.4.2. Informed lay-up algorithm

By using computational data of the material properties of reclaimed timber, one can make performance driven design choices. Through a custom encoded combinatorial algorithm, beam lay-up compositions are generated through informed selection of timber pieces from stock availability, then using a rule-based approach to bundle them together to meet a design scenario.

1.4.3. Long span structures

Through the design of multi-lamellar composite beams with spans longer than the sum of their timber pieces, the limitations imposed when reusing material such as span limits and structural capacity are overcome. Proof of component performance will be tested through physical structural testing, FEA simulation, and full-scale prototyping.

1.4.4. Fire/ moisture/ toxin protection

To expand the ability to reuse more waste wood this research will use clay as an encapsulation technique to reuse wood waste categories A III and A IV, which may contain toxic coatings such as lead based paints. Testing was conducted to check the level of protection offered by clay encapsulation. However, moisture and fire resistance testing has not been conducted.

1.4.5. Non-destructive lamination for continuous reuse

The use of natural fibers will be proven as an effective non-invasive fastening technique that can be disassembled.

1.4.6. Informed fabrication

Analysis to fabrication specific workflows will be demonstrated that furnish prefabricated beams that can be designed for specific conditions using adaptive fabrication processes. The integration of prefabricated beams into other building systems will be touched on as well as how prefabrication can be upscaled and implemented into industrial production lines.

Although integration of prefabricated beams into primary structural systems is outlined, detailed joint structural analysis for the integration of composite reclaimed beams will not be conducted. This research offers bio-composite material specifications for reusing reclaimed timber safely. However, meeting code compliance was not a criterion of this research. Four-point bending tests were conducted using scaled prototypes and a full-size, 1:1 scale demonstrator beam was constructed as a proof-of-concept of the workflow.

2. Methods

When working with reclaimed timber, material irregularities such as embedded nails limit deductive manufacturing methods. This research establishes a workflow that integrates digital and physical processes to facilitate the structural reuse of timber without processing (Fig. 4). This workflow is divided into three areas: evaluation, design and fabrication. In evaluation; sourcing, digitization of the geometry, and the non-destructive methods used for regrading sourced timber are discussed. In design, a combinatorial algorithm is introduced to produce optimal beam lay-ups and material composition of the beams is explained. In fabrication, a robotic end effector design for fiber wrapping and beam construction methods are presented.

2.1. Evaluation

2.1.1. Timber sourcing

Two main criteria were considered for the selection of timber pieces. First, the selected timber had to be linear as this study focused on creating beams. Elements such as old beams, columns and framing members were taken. Boards, doors and trims were not salvaged. The second criterion focused on rot. Timber that had evidence of rot or severe insect damage was purged. Most of the timber sourced was from a demolished oak half-timber (Fachwerkhaus) building. In addition to oak, other timber stock of unknown origin was sourced. The sourced material for this research was a combination of hard and softwoods of various cross sections, lengths and levels of man- made defects.

2.1.2. Regrading

Each sourced piece then goes through non-destructive regrading. First, moisture levels are recorded using a hygrometer, which according

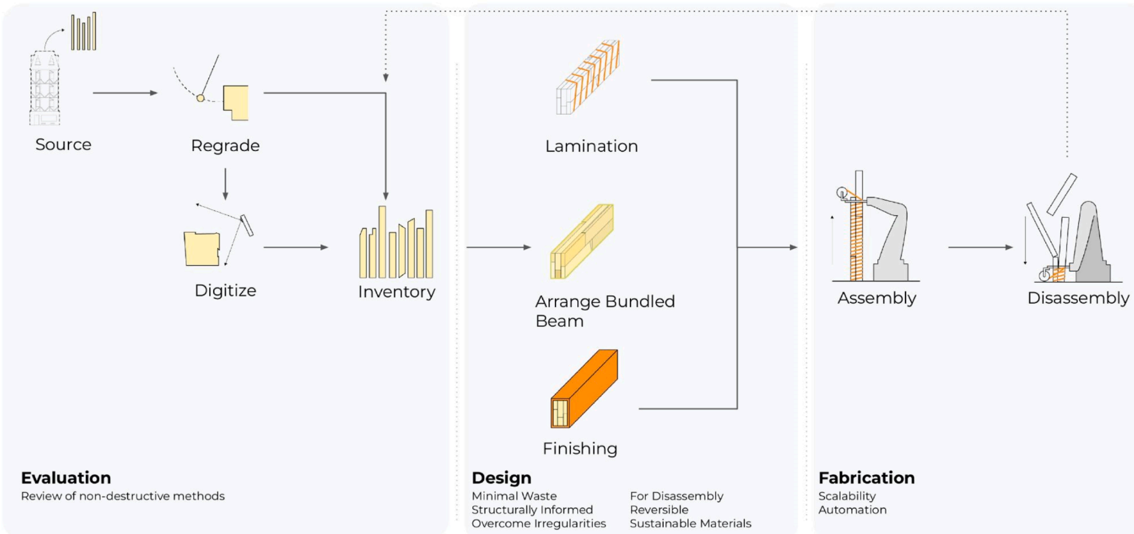


Fig. 4. Reclaimed timber composite beam workflow.

to EN 15497:2014 should be below 12% for structural applications [46]. Then, the dynamic modulus of elasticity is measured using a laser vibrometer (Fig. 5), which is a non-destructive method of evaluating the inner voids and density of the materials, thus giving a predictive measure of its stiffness.

Arriaga et al. developed a model that combines dynamic modulus of elasticity values obtained from ultrasound testing and visual grading of old timber pieces into an equation to predict modulus of elasticity (MOE) and rupture (MOR) more accurately [47]. They conclude that the visual grading parameters with the most influence were edge knots and slope of grain. However, visual grading standards only specify the assessment of new timber according to natural defects. Falk et al. state that the nail holes were added up and considered as an equivalent knot size [48] as nail holes act as small knots [32]. Moreover, several sourced pieces had large fractures that went deep through the width of the material. Therefore, besides knots and slope of grain, nail holes and fractures are also analyzed during the visual grading.

Knot coefficient is calculated by dividing the knot diameter with the length of the associated edge according to DIN 4074 "Strength grading of wood" [49] (Fig. 5). The knot with the biggest coefficient has the decisive defect. If there are nail holes larger than the knots, they are measured in the same way. For measuring slope of grain, the fiber with the largest inclination is chosen and the inclination angle is recorded as a percentage for a length of 300 mm [47]. As fractures in reclaimed timber can expand with loading, deep fissures are considered instead of slope of grain if their inclination angle is steeper.

Knot diameter ratio (d/b) and slope of grain (sg) percentage are then put into Equations 1 and 2 to determine MOE and MOR. The parameters A, B, C and D had the specific values shown in Equations 1 and 2 as dynamic MOE was determined using a surface excitation tool based on Arriaga et al. [47]. With the MOE and MOR values evaluated, pieces were assigned into strength classes based on EN338 Structural Timber Strength Classes [50]. It should be noted that the determination coefficients of the referenced models for MOE and MOR were 66–68% and 51–52% [47] and require further testing to improve the prediction accuracies.

$$MOE = A + B*MOE_{dyn} + C*(d/b) + D*sg = 5056 + 0{\cdot}5111*MOE_{dyn} - 4286*(d/b) - 94*sg \quad (1)$$

[47].

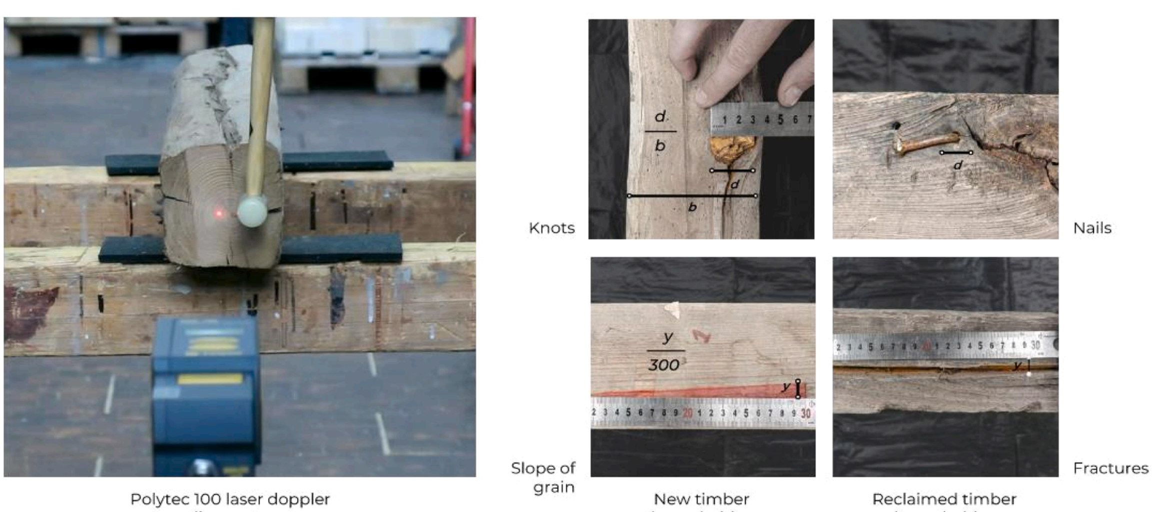


Fig. 5. Left: Laser vibrometer measurement setup. Right: Visual grading measurements. Photos edited to highlight the features.

$$MOR = A + B^* MOE_{dyn} + C^*(d/b) + D^*sg = 9{\cdot}86 + 0{\cdot}0023^* MOE_{dyn} - 22{\cdot}47^*(d/b) - 0{\cdot}52^*sg \quad (2)$$

[47].

Each sourced timber member determined to be structurally adequate is 3D scanned using a smartphone application [51]. Geometric mesh and mapped photogrammetry texture are exported into Rhinoceros 3D [52], where any parts external to the timber mesh are cleaned and simplified using Grasshopper 3D [53]. Each cleaned mesh is digitally inventoried along with extracted re-grading data such as grade, MOE, MOR and moisture content.

2.2. Design

2.2.1. Combinatorial algorithm

Using a custom GHPython script and Kangaroo Physics 2 plugin [54], an algorithm was developed in Grasshopper 3D to generate rule-based beam lay-ups to meet design inputs such as span and loading conditions. The clean mesh list acquired at the end of the 3D scanning process coupled with grade information is fed to the algorithm. To generate beams longer than any one timber element, a composite beam consisting of three lamellae ensures that any discontinuity can be reinforced by the other layers.

With a search operation, high grade and larger timber pieces are selected for the lowest lamella where shear forces are the highest. Within this layer, the search engine is also asked to fetch longer timber members to reduce discontinuities. Additionally, all timber pieces within the lamella are within an equal cross section of one another. The algorithm continues to place timber along the lower layer until the desired span of the beam is met. Then, the algorithm moves on to the uppermost one. The same process of finding higher strength timber is repeated with the remaining pieces. Lastly, the algorithm continues to place timber in the middle lamella. Here only offcut is relevant in the search criteria, otherwise lower grade timber is specified.

Once beam selection is complete, the Kangaroo Physics plugin within Grasshopper 3D is used to place the elements within their layer with the goal of resolving local weaknesses. For faster processing, each timber element is discretized into a line and populated with circles that have the diameter of the depth of the timber element. These elements are coded to follow a set of conditions (Fig. 6):

1. **Pulling of circle packed curves toward each other while maintaining a circle pack repellent distance:** The circles will be used to repel each representation line from one another to assure the timber does not collide into other members.
2. **Extremity repelling logic to force staggering of joints:** On top of the circle repellents, additional circles with larger radius are introduced at the extremities of each line that repel only each other.
3. **Butt joint attractor logic to maintain continuity:** To maintain the order of the timber pieces in each lamella, a spring with a set length maintains continuity within a fixed distance to its neighbor.

Using a surrogate logic, at the end of each simulation the mesh representation of each beam is brought back to replace the line representation. These meshes can then be used for finite element analysis (FEA) to compare their structural performance. Each Kangaroo physics simulation output is recorded and fed to the Karamba 3D FEA solver [55]. To input into the solver as shells, vertical middle surfaces of the bounding box of each mesh are extracted (Fig. 7). The inner edges of the surfaces are divided to be connected to the points on the next layer surfaces. These connecting lines are input as springs to simulate the fiber connections. Widths of the bounding boxes are checked against the initial input list to determine the height and grade of each piece to feed in specific material properties. Maximum displacement and material utilization of the combinations are compared to select the most optimal ones and a satisfactory combination with minimum offcuts is chosen to be evaluated in more detail with the SOFISTIK FEA plug-in in Grasshopper [56], further detailed in Section 3.1.4.

2.2.2. Material system

Once a combinatorial lay-up is output, the beam can be fabricated according to the irregularities of reclaimed timber. The composite beam build-up developed in this study addresses the challenges of working with unprocessed timber. The first of these are the irregular surfaces, which create voids between the layers. Furthermore, these irregularities require a lamination method that will transfer shear and provide surface contact without damaging the pieces.

Most timber sourced for this study contained several protruding nails and steel embedments (Fig. 8). In most projects that work with reclaimed timber, nails are taken out one by one or parts with embedded materials are totally cut out, leading to extra labor or material loss as otherwise they might damage the tools. This study strived to avoid processing to maximize material intake, however if the nails are left in place, steps should be taken so they would not be a danger during fabrication or in use.

To accommodate the voids in the lamination, a clay plaster and

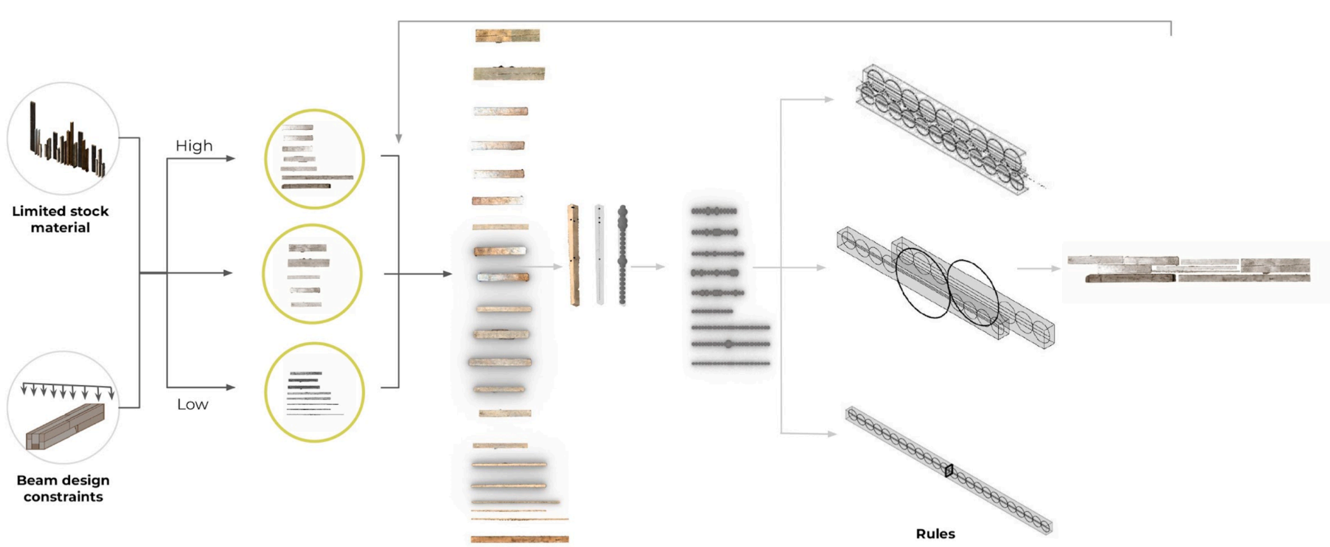


Fig. 6. Combinatorial algorithm steps.

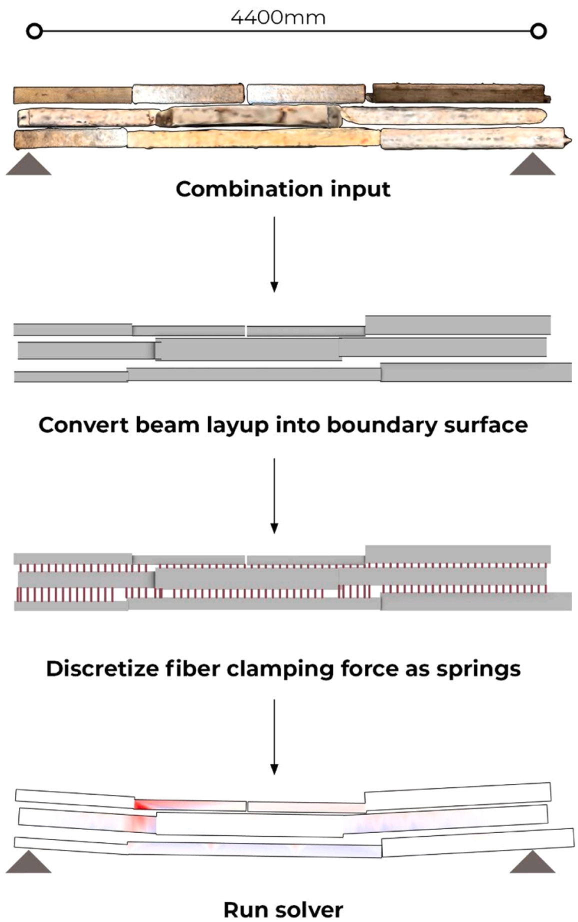


Fig. 7. Structural analysis steps.

Fig. 8. A steel plate embedded in one of the sourced pieces.

mortar mixture was used as its malleable state can easily conform to the surface irregularities of reclaimed timber (Fig. 9). Clay mortar used in this mixture provides adhesion between the layers for shear resistance at the lamella interface. Jute fiber is specified to be wrapped around the bundled timber pieces to provide clamping force against transverse shear forces. Prior to wrapping fiber around the timber beam, a thin layer of clay plaster is first applied along the entire surface of the beam to act as a gripping surface for the fibers to stay in place, allowing for wrapping patterns that would otherwise not be possible without the presence of clay.

After the fiber wrapping is complete the entire beam is encapsulated in a second, thicker coat of clay plaster. The first purpose of the layer is to protect the user from the surface contaminants of the unprocessed timber such as toxic coatings and nails. Secondly, it prevents moisture damage to timber as clay is a hygroscopic material and absorbs moisture from its environment. With these properties, clay also helps regulate the relative humidity [57]. Additionally, this clay layer fire proofs both the fibers and timber [58]. Lastly, as shown with volatile organic compound tests in Section 3.2, clay can mitigate the emission of toxins on the reclaimed timber.

2.3. Fabrication

2.3.1. Tools

Material choices presented in Section 2.2.2 accommodate high tolerances found in irregular timber and lead to fabrication methods designed to precisely lay-up and wrap the beams. Considering automation prospects for composite beam manufacturing, both robotic and analog fabrication methods were investigated with the implication for introduction in an industrial setting. Scenario-specific designs, which call for adaptive rather than mass production, can be achieved with robotic fabrication.

For full scale demonstration of beam fabrication, a robotic process is established to achieve accuracy of wrapping and accommodate scenario-specific designs. For fiber wrapping, a custom end effector mounted on an industrial robotic arm wraps fiber around bundled timber elements through a series of gears and a post tensioning configuration (Fig. 10). The method of fiber wrapping overcomes high tolerances as irregular surfaces and cross sections of the timber do not hinder this process. For this research, a clay sprayer was used to apply clay to the timber. Although not demonstrated on an industrial robot, the use of such a process can allow for differential spraying of the clay.

2.3.2. Process

For the physical beam lay-up and bundling process, first, the selected timber stock material is identified to match the digital beam output. Starting from one end of the beam, the initial pieces are laid up to match the digital algorithmic output. As the pieces are stacked, clay mortar is applied between the lamellae. After all three lamellae are built up, the outside surface of the beam is applied with a base coat of clay plaster. The clay plaster is applied with a compressed air spray gun similar to that in gypsum application. A custom spinning end effector mounted on the robot is positioned so that the timber is within the spinning ring. Starting from the extremity of the beam, the robot attaches the fiber to the beam and moves the end effector across the portion of beam covered in clay, wrapping fiber to bundle the pieces together. As the next pieces are placed, the same process is repeated until the entire length of the beam is laid up, covered in clay plaster, and fiber wrapped. Once the entire assembly is laid up, the fiber is secured to the timber and cut loose so that the end effector could exit out of the beam. Afterwards, the finish coat of clay plaster is applied with a clay sprayer over the entire beam. The beam is then left to dry for approximately 48 h, but the time is contingent on humidity and temperature.

2.3.3. Material-informed fabrication paths

Considering specificity in fabrication, wrapping patterns responsive to timber beam build-up and overall beam stress analysis are converted into tool paths for the robotic arm to execute in tandem with the spinning end effector. Variable wrapping patterns are controlled by the speed and direction of the robotic arm. For example, if the speed of the robot executing the tool path is increased while the end effector rotating speed stays constant, the wrapping pattern will be more spaced apart, but the angle of the fibers will be more parallel with the beam. For a tighter spacing, the speed that the end effector moves along the beam is slowed down. Although tighter spacing is achieved, the fiber is more perpendicular to the force flows. Guided by material and global design intent parameters, an inventory of informed tool paths was investigated.

To begin, the baseline standard wrapping pattern gives the

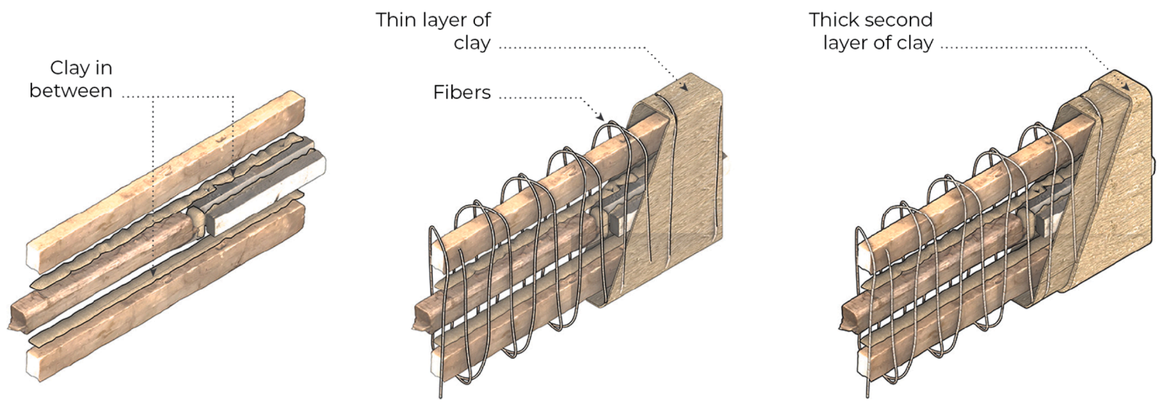


Fig. 9. Material layers.

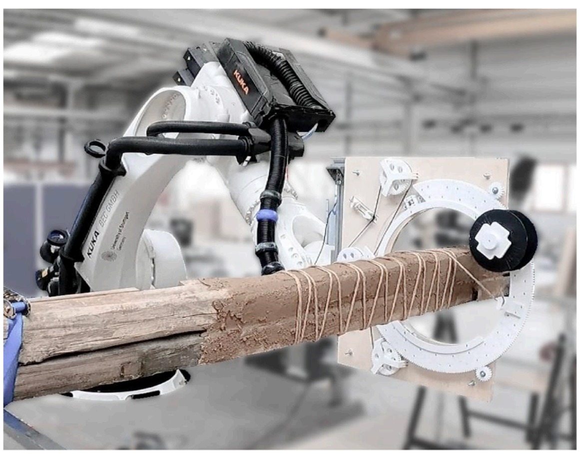


Fig. 10. End effector on a 6-axis robot. Background blurred to highlight the end effector.

appearance of an "X" in the directionality and spacing of the fibers along the composite beam face. The symmetry offers force line transfer to half the fibers in either direction while all the fibers aid in clamping force. The advantage of this pattern is that the robot and end effector can operate at a constant speed. An increased gradient in speed of the end effector along stretches of the beam will lead to elongated "X" syntax and may be beneficial in transferring shear forces.

To reinforce the localized weakness areas around the discontinuities additional fiber is wrapped at these locations. A reduced robotic tool path speed coupled with constant wrapping reinforces localized weakness at the linear joints. Additionally, the robot doubles back over the discontinuity to further create reinforcement (Fig. 11).

When generating force flow optimized patterns (Fig. 12), the robot path is non-linear and the end effector moves back and forth with variable timing. The speed of the program considers the timing of one-half revolution of the fiber end effector to execute the proper winding pattern.

One advantage offered by the clay is the ability to change direction in such force flow patterns without sacrificing tension strength due to increased surface friction. On a smooth surface, if the fiber wrapping pattern doubles back, changing direction in wrapping, the fibers would easily loosen and the tension would be lost. With the introduction of clay however, the grit in the wet clay allows the fiber syntax to double back while maintaining the tension force at which the fiber was applied. As the beam dries, the fibers are locked in place, this advantage offers a wrapping syntax that is both contributing to clamping force as well as force flow transfer.

3. Results

3.1. Structural

Three sets of four-point bending tests were conducted with Zwick Z100 testing machine [59] according to DIN EN 408 [60] to determine the optimal material composition and structural performance for: 1. clay type, 2. fiber type, 3. wrapping patterns. All the samples in these tests were manually wrapped using a tensioner system to ensure consistent pre-tension using the same type of pine laths and a 3-lamella lay-up and had a final size of approximately 350×80×44 mm. Bending strength was calculated with 95% of the maximum loading and the bending and shear performance evaluations were based on these initial tests. Due to limited access to the testing equipment, the results were not corroborated over

Fig. 11. Joint reinforcement pattern. Background blurred.

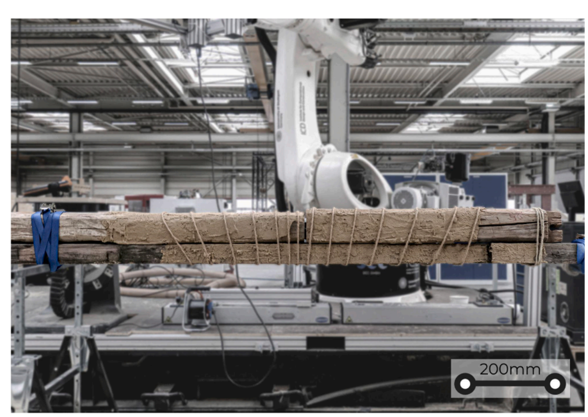


Fig. 12. Tension stress line aligned pattern. Background blurred.

several samples. Structural performance analysis requires further investigations as discussed in 4.2. Reduced Carbon Footprint and Comparison to GLT.

3.1.1. Clay types

For this research clay adhesive and reinforcing mortar and clay plaster SanReMo provided by CLAYTEC in Germany were used [61,62]. The first set of tests looked at how to increase friction between the layers by experimenting with different clay types. Three samples were compared: 1. 100% clay plaster with straw, 2. 100% adhesive mortar clay, 3. 1:1 blend of the two. The samples were wrapped with a common pattern.

The results of the tests are shown in Graph 1 and Table 1. The 100% clay plaster with straw sample had the highest bending strength, which may have been caused by the larger grains increasing friction. On the other hand, adhesive properties of the clay mortar facilitated fabrication and caused less displacement of the layers and fibers during wrapping. Considering the higher force-deformation slope of the 1:1 mixture sample and the fabrication advantage of clay mortar addition, all forthcoming samples to test fiber type and wrapping pattern used the 1:1 blend of clay plaster and clay mortar.

3.1.2. Fiber types

The second set of tests compared different natural fibers with three samples: 1. flax, 2. sisal, 3. jute. Flax and sisal were straight fibers whereas jute had twisted rovings. The results are shown in Graph 2 and Table 2. Although the flax fiber sample had considerably higher bending strength, it has been observed that the flax and sisal fibers started breaking due to tear around the corners. The jute twisted rovings did not exhibit tears in the fibers at corners. Moreover, while unwrapping, the flax and sisal straight fibers disbanded, making them not possible to reuse. Although rovings made into a rope do not exhibit the same direct stress transfer in the direction of the fibers, the rope-laminated sample also showed comparable structural performance. As jute, though not as strong in bending as flax, did not fail before the timber and was more accessible, the rest of the test samples were produced with jute fibers to further develop its performance.

3.1.3. Wrapping patterns

Using the chosen 1:1 clay plaster-mortar mixture and twisted jute fibers, three wrapping patterns were tested with one sample each: 1. tension stress line aligned, 2. “X” cross, 3. hybrid (Fig. 13). Wrapping following the tension stress lines provides resistance against shear. However, this pattern is prone to fiber slipping, and the tension can be lost resulting in slack fibers. Therefore, although with higher angles, a crossed “X” pattern resulting in double wrapping was tested to compare its clamping force and to prevent slipping of the fibers during loading. The third sample had a non-uniform “X” pattern, where the X’s sloped with lower angles the ends where the shear forces were higher. The results are shown in Graph 3 and Table 3. Wrapping that follows the stress lines helped fibers overcome shear and the results showed that they also improved the clamping force. During fabrication, the adhesion of the mixed plaster around the outer surface kept the fibers from slipping despite the pattern that was prone to lose tension.

It has been observed that in the stress line pattern sample the failure continues through the middle layer, showing the layers were working as a composite, which was not observed in the other samples. As the jute rope laminated sample with the stress line pattern showed a comparable bending strength to that of the flax fiber sample with the aforementioned advantages, it has been decided that the final demonstrator would be built with 1:1 clay adhesive mortar and plaster mixture and jute ropes that follow the tension stress line pattern of the beam design. The bending strength of this sample was 29% higher compared to an earlier sample tested as a proof-of-concept study with a more favorable lay-up with only a discontinuity in the middle layer.

Table 1
Clay composition tests bending strength (σ_b), max. moment (M) and max. shear stress (τ_{max}) results.

Sample	σ_b (MPa)	M at failure (N.m)	τ_{max} (MPa)
100% adhesive mortar (AM)	12.6	594.1	2.2
100% clay plaster (CP)	14.6	721.7	2.6
1:1 mixture (AM_CP blend)	14.9	647.6	2.5

Table 2
Fiber type tests bending strength (σ_b), max. moment (M) and max. shear stress (τ_{max}) results.

Sample	σ_b (MPa)	M at failure (N.m)	τ_{max} (MPa)
Flax (FF)	19.3	954.5	3.4
Sisal (SF)	12.5	619.7	2.2
Jute (JF)	14.9	647.6	2.5

3.1.4. Physically-informed digital models

The results of the bending tests were replicated in SOFISTIK finite element analysis Grasshopper plug-in in Rhino 3D [56] to estimate the connection stiffness values of coefficient measure between clay, jute and timber. The pieces were only modeled as their vertical surfaces and connected with elastic couplings corresponding to the sample wrapping. As input geometry into the solver as shells, vertical middle surfaces of the bounding box of each mesh were extracted. The inner edges of the surfaces were divided to be connected to the points on the next layer surfaces. These connecting lines were input as springs to simulate the fiber connections. Widths of the bounding boxes were checked against the initial input list to determine the shell height and grade of each piece to feed in specific material properties. The extracted vertical surfaces were meshed according to the spacing of the wrapping pattern to be applied. By replicating the displacement and stress results at F_{max}, the axial and rotational stiffness values that should be used to analyze the full-scale samples were determined. Connecting edges of the surfaces were adjusted to be simulated according to clay and fiber connections with an axial stiffness of 5000 kN/m^2 and lateral stiffness of 1×10^6 kN/m^2. Due to the analysis and material unpredictability based on different lay-ups, performance should be further corroborated through more tests to improve the accuracy of the digital simulations.

Graphs 1–3 and Tables 1–3. Four-point bending test load-deformation graphs and bending strength (σb), max. moment (M) and max. shear stress (τmax) results. Selected performances highlighted in burgundy.

3.2. Toxin tests

Material testing has been conducted to test if clay can be a viable option to use timber clad with paint or coatings by encapsulating the toxins. First, using a Niton™XL3t XRF Analyzer [63], instantaneous readings of chemical composition of reclaimed timber samples were conducted. Two samples from the same reclaimed timber beam, one exposed and one covered with 5 mm of clay and left to dry for 24 h, were studied. The exposed sample showed a reading of 15% lead, while the encapsulated sample did not, indicating the potential of clay encapsulation.

As these tools only provided instantaneous results, more testing was conducted to examine if such compounds would be emitted through the clay over time. A Fabry-P é rot interferometer detector was used to verify if volatile organic compounds (VOCs) naturally found in pine wood would be released from encapsulated samples over time. Three pine blocks of equal size were cut; one was left exposed while the other two were covered in 5 mm and 10 mm clay respectively and left to dry for 24 h. Each sample was separately placed in a sealed container where an air pump constantly cycled air to the interferometer that recorded results over 24 h (Fig. 14). Clay encapsulation substantially decreased

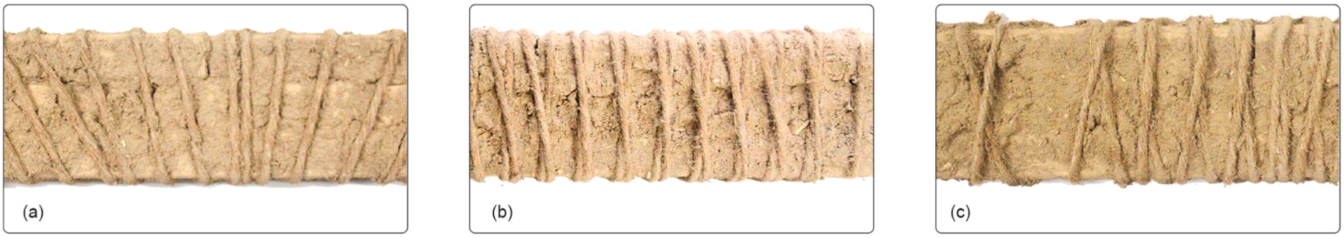


Fig. 13. Fiber wrapping pattern prototypes for four-point bending tests. (a) Tension stress line-oriented fiber wrapping pattern. (b) Uniform "X" wrapping pattern. (c) Hybrid "X" pattern with tension stress informed fiber inclination.

Table 3
Wrapping pattern tests bending strength (σ_b), max. moment (M) and max. shear stress (τ_{max}) results.

Sample	σ_b (MPa)	M at failure (N.m)	τ_{max} (MPa)
Crossed (CP)	14.1	694.2	2.5
Hybrid (P)	14.9	647.6	2.5
Stress line (SL)	17.9	885.6	3.2

pine organic compounds emission in the 10 mm clay covered sample over the exposed piece (Graph 4).

As some samples from the sourced stock material were shown to be contaminated with hazardous substances, the importance of toxic coating encapsulation has been proven to be necessary if the intake of reclaimed timber and their lifespans are to be increased in accordance with the current codes. Clay encapsulation was proven to prevent the readings of heavier chemicals such as lead. Although these tests did not prove that the clay plaster was completely encapsulating the toxic substances read by the sensors, the results showed that clay plaster slows the release of VOCs. Future tests should be done to attempt to completely encapsulate the substances and to study how the clay acts over the lifetime of a structural component. Additives to lower the porosity of the clay or a less permeable coating over the final clay layer to act as a vapor barrier can further improve the results.

3.3. Demonstrator beam

To prove the feasibility of the "Embraced Wood" method, a beam was fabricated as a demonstrator. It went through stages of design till disassembly (Fig. 15).

3.3.1. Design scenario

To meet urban migration needs a building extension was planned for Stuttgart Mitte. An additional two stories are to be placed on top of an existing three-story wood framed house. Aligning with the existing building structural grid, Embraced Wood beams need to span 4.4 m between bays. One of these beams was designed and fabricated using the methods established in this research.

3.3.2. House demolition & sourcing in recycling facility

The predominant amount of sourced timber came from a demolished barn in the summer of 2022. Most of the timber pieces had notches and flanges still intact with little sign of damage from demolition. The various demolition debris from the barn ended up at the Werner Recycling facility in Bad Langensalza, Germany. Besides the oak timber sourced, softwoods were reclaimed such as Douglas fir from unknown origins. In the selection process timber that did not show signs of rot was purposely selected.

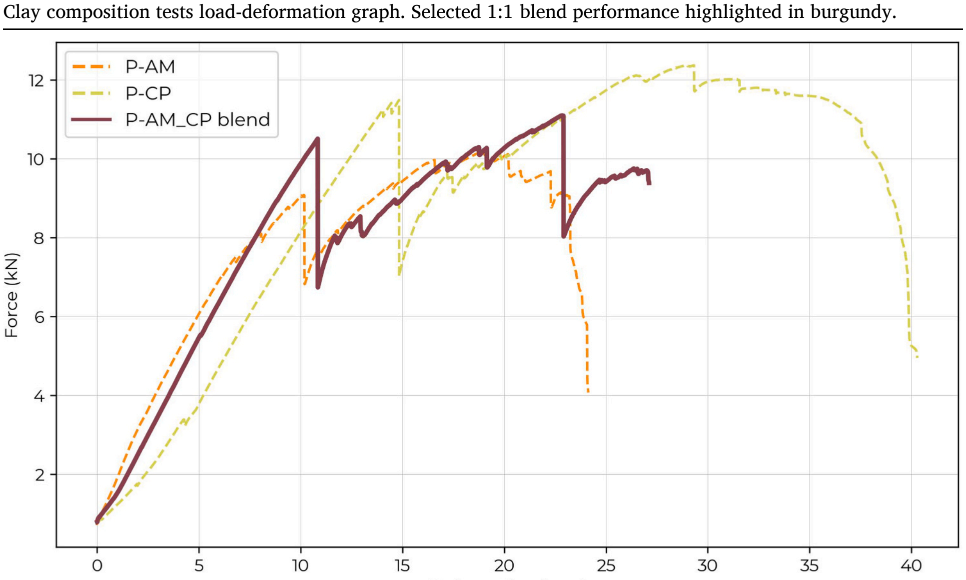
3.3.3. Assessment and grading

Moisture readings of all the pieces were all below 12% and regrading according to Section 2.1.2 proved that the timber had potential to be structurally reused.

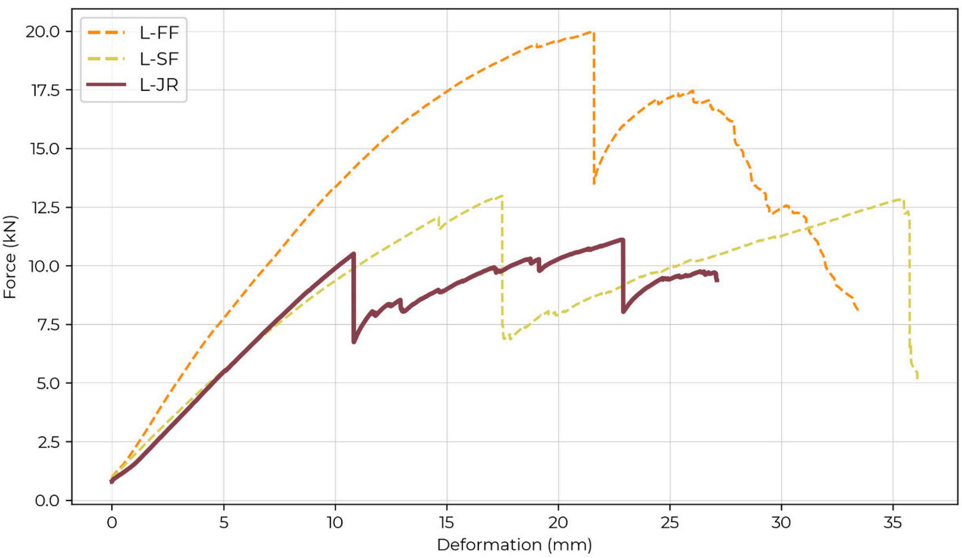
3.3.4. Scanning and digitization

In total 36 pieces of timber were 3D scanned and inventoried for this research. Within the demonstrator beam, 9 reclaimed timber pieces were used for the design scenario.

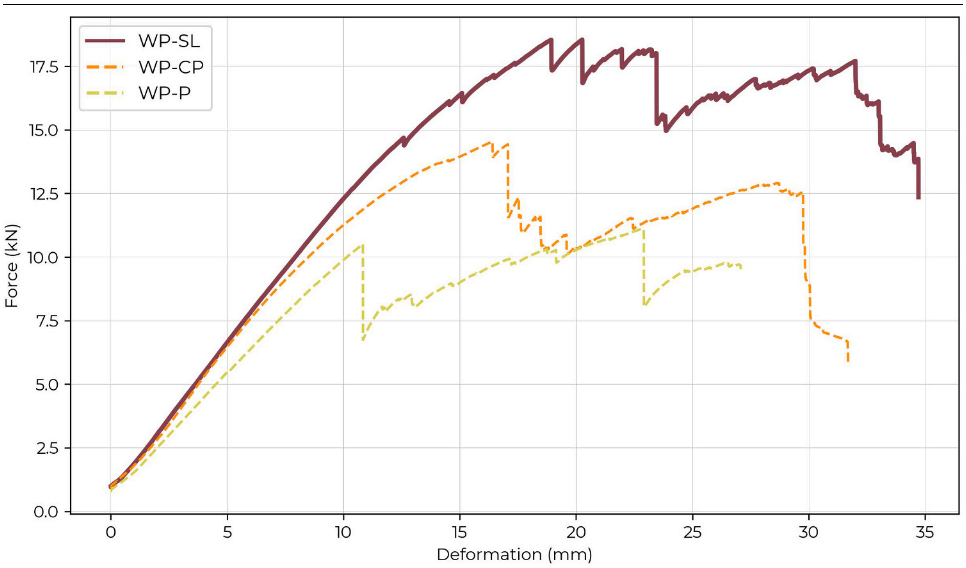
Graph 1
Clay composition tests load-deformation graph. Selected 1:1 blend performance highlighted in burgundy.



Graph 2
Fiber type tests load-deformation graph. Selected jute performance highlighted in burgundy.



Graph 3
Wrapping pattern tests load-deformation graph. Selected stress line pattern performance highlighted in burgundy.



3.3.5. Beam layup through combinatorial algorithm

In the overall beam layup generated by the algorithm, a discontinuity can be seen at the mid span of the bottom lamella. This area of the beam has the highest tension forces and intuitively a break in the lamella should not have been placed there. However, the FEA simulations ensured that the solution would work structurally. This non-optimization appears counter intuitive, however, the distribution of long and or strong timber elements should be rationed throughout the design scenario extension to ensure sufficient stock to meet structural requirements. Otherwise, if the algorithm was optimized to search for best results, all the high-grade timber would be used leaving only low-grade timber to create entire composite beams.

3.3.6. Structural analysis

Following the method described in Section 2.2.1, the selected beam configuration was analyzed structurally using finite element analysis software. The beam was found adequate for the span and loading conditions specified in the design. It can take a maximum load of 7 kN/m and supersede the design scenario loading and deflection requirement. Confirmed by the analysis, a 4.4 × 3.5 m design grid was achieved. The demonstrator beam had approximately 30 mm of displacement for a loading of approximately 560 kg. The deflection observed in the beam may be due to the middle portion being purposely incomplete to show the inner layers. Additionally, the clay was not completely dry when the demonstration was loaded.

3.3.7. Robotic fabrication and finishing

In the demonstrator beam, a flax mesh fiber from CLAYTEC [64] was wrapped with a close spacing to create a continuous substrate for the clay to be applied, while the jute fiber is more spaced apart to follow structurally informed wrapping paths. The last layer applied was a white YOSIMA clay plaster coat from CLAYTEC [65]. Its function was mainly aesthetic. As a design intent to show the inner workings of the beam, clay was incrementally omitted from the middle span outwards towards

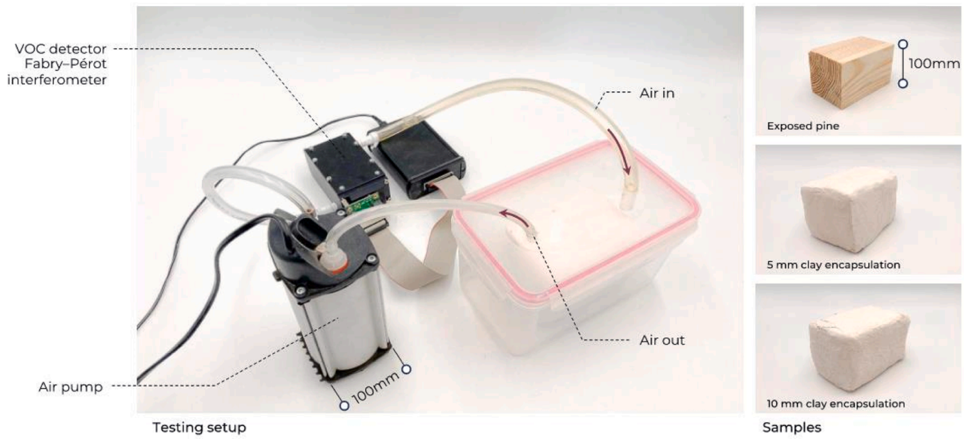


Fig. 14. Fabry-Pérot test setup for VOC testing.

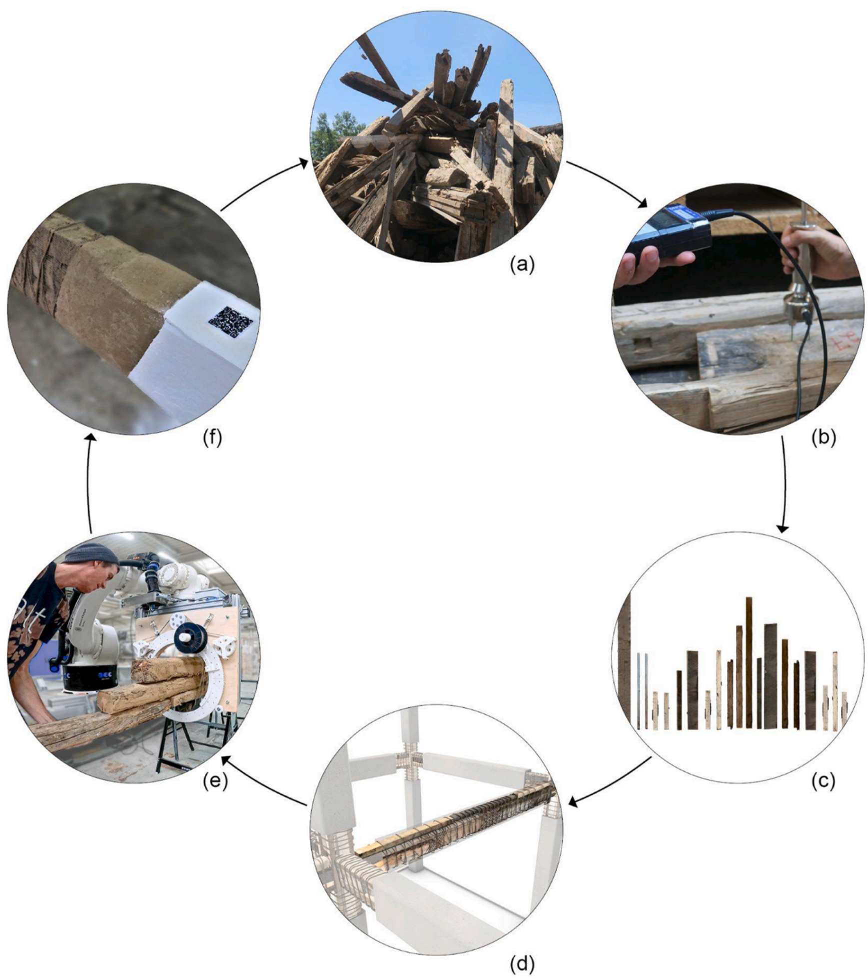


Fig. 15. Demonstrator beam sequence of steps from sourcing to construction. (a) waste wood pile photo taken from the Wagner recycling facility. (b) Assessment and regrading of the reclaimed timber. (c) Digital repository of regraded data using scanning and digitization methods. (d) Beam design for site specific scenarios using beam layup and fiber wrapping pattern algorithms. (e) Informed robotic fabrication using the custom fiber wrapping end-effector. (f) Furnished beam designed for disassembly.

both ends (Fig. 16). QR code embedded on a timber piece is left exposed for onlookers to be able to gain access to the history of the timber. Upon disassembly, the QR system can be used to understand the potential encapsulated hazards present on each unprocessed timber element entrapped in the clay and fiber. At the end of life of the structure, the components can be disassembled off-site for the continuous reuse of the timber, fiber, and clay (Fig. 17).

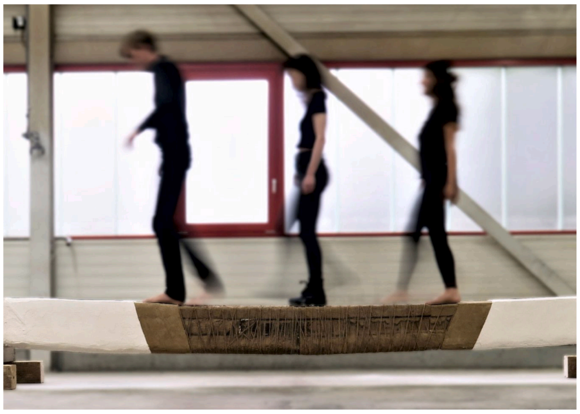


Fig. 16. Full-scale demonstrator beam with the inner layers exposed to show the material composition. In this image the background is blurred to put focus on the beam in the foreground.

3.4. Integration to other building components

Structural integration for timber post and beam construction typical of multi-story residential and vertical building extensions was considered. Since each element in a composite beam has a corresponding material ID containing information for reuse, the disassembly should go beyond the component and consider the disassembly of entire systems. To demonstrate non-destructive connection potential, a beam-to-column joint model was built and an embedded plate design for integration with secondary building systems was developed.

3.4.1. Primary structural connections

One of the main reasons sourced timber needs to be regraded is due to construction, use, and deconstruction damage inflicted due to improper planning. The joinery between reclaimed composite timber beams and columns should also be reversible and non-destructive in order to ensure the material can rely on its material passport for reuse.

Prefabrication and rapid construction offer methods to reduce the risk of timber damage. From a logistics perspective, prefabrication allows for the controlled conditions required for regrading, scanning, and finishing the composite beams. To this end, for prefabricated beams, two different assembly methods are outlined of how the components can be joined on site. A design with prefabricated members with connection on site was investigated. Timber lamellae were extended beyond the encapsulated area of the beams and columns. As seen in Fig. 18, these extensions can be used to slot into one another. Taking advantage of the availability of dense hardwoods from demolished half-timber buildings throughout Germany, this material can be placed in high compression areas of the joint. In the design of the joint, hardwood elements can be placed perpendicular to the column on center of its length with both ends fingering outwards. The extended timber lamella from the composite beam can be slotted to receive the hardwood. The same clay and wrapping technique is then used on-site to fix the joint in place. The ability of the clay to be rehydrated offers methods to seamlessly integrate off-site and on-site processes.

3.4.2. Secondary and non-structural connections

Besides primary structural connections, this research investigated methods for integrating reclaimed timber components with finishes, partitions, and services. The design of embedded plates mounted to the surface of the prefabricated beams allow for pre-planned connections to other building systems (Fig. 19). These embedded plates have flanges that extend between the timber and natural fiber wrapping syntax to help fix them in place. Toolpath planning in the wrapping process would need to be coordinated with the placement of these plates. Without the use of a system such as pre-planned embedded plates, the components would be modified by drilling through the surface clay. This would expose the encapsulated timber to the environment posing a health hazard. Additionally, the reuse of the material would not be feasible without once again regrading.

4. Discussion

4.1. Limitations

4.1.1. Interior use limitations

This research specifies clay plaster and clay mortar that is used for interior applications. The current material specifications are not adequate for exterior use due to precipitation and the effect of hydration on the clay. In the event of contact with water, the clay would become viscous and expose the timber and fiber within the composite structure, potentially causing fire and life safety hazards. Further studies would have to be conducted to add finish coats suitable for exterior applications. In “Rehabilitation of Half Timbered Houses with Clay Fillings in Denmark” a thin coat of lime mortar is added as a finish coat for exterior applications [66]. Despite not having investigated exterior applications, according to the manual of Multi-story Timber Construction, mass timber structures will require an exterior cladding based on building class

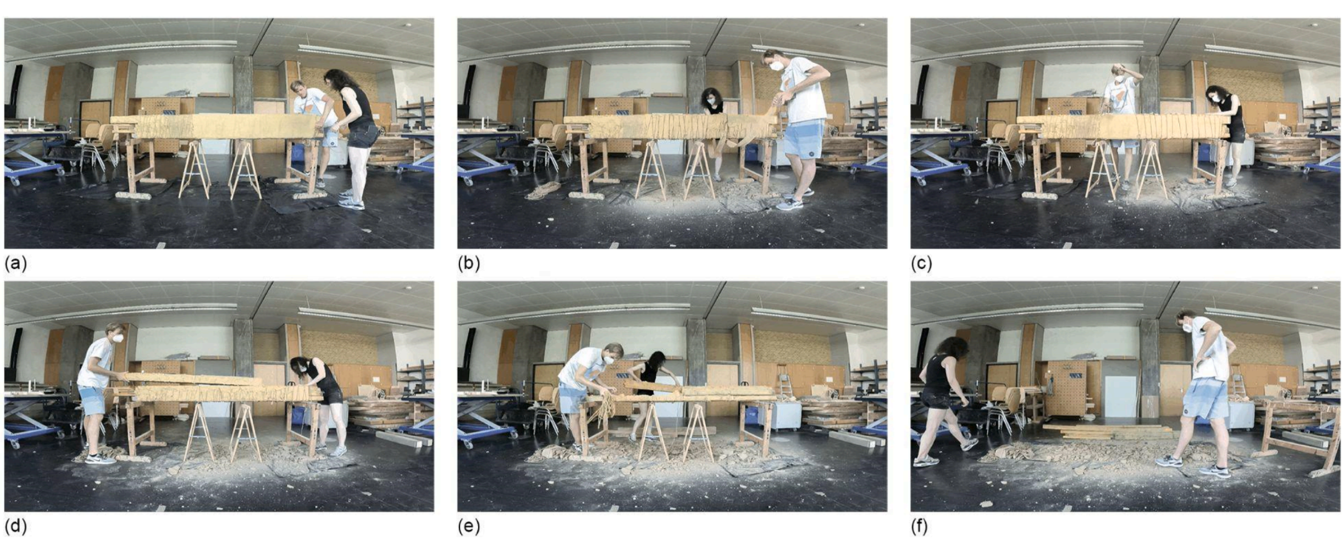


Fig. 17. Demonstrator beam sequence of disassembly.

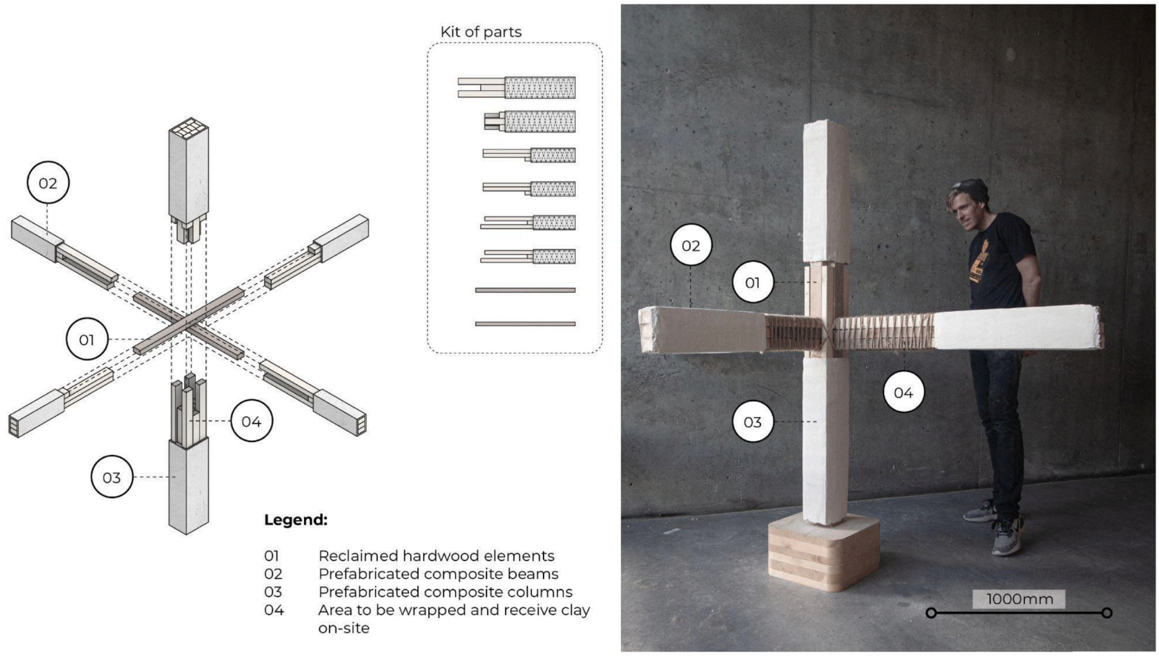


Fig. 18. Left: Prefabricated components coming together to form a cruciform joint. Right: Scaled demonstrator of cruciform joint.

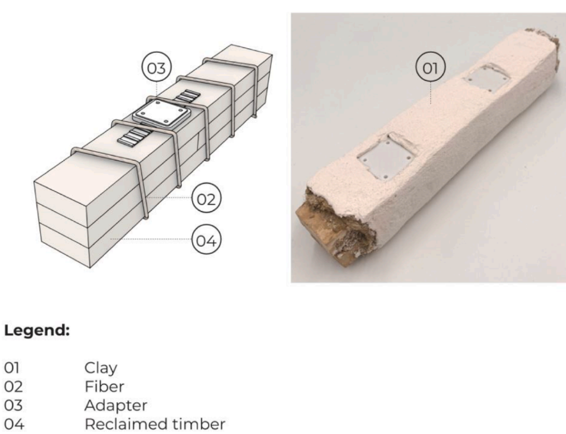


Fig. 19. Integrated embedded adapter ensures that the timber and clay are not damaged.

and height. Thus, this limitation does not have a detrimental effect on the immediate implementation of the method for construction [67].

4.1.2. Algorithmic limitations

The algorithm developed in this research is limited to outputting single width lamella build ups similar to LVL or GLT products. The algorithm seeks for similar cross section members per layer to ensure that our beams are straight and minimize the gaps between layers. However, multiple width aggregation in lay-up would lead to further inclusivity of timber members being used in a beam lay-up as the algorithm would not need to purge members based on cross section alone.

4.1.3. Building code limitations

This research overcomes the restriction of toxic coatings found on reclaimed timber by means of encapsulation using clay plaster. X-ray spectroscopy has proven to block the detection of lead when lead-painted timber is encapsulated in a thin layer of clay plaster. However, volatile organic component measurement devices gave readings that substances contained within the encapsulated timber slowly off-gassed at a slower rate than when exposed. In order to be able to assure reuse of the toxic materials without the need to use heavy processing to remove the coatings, further encapsulation testing needs to be investigated. Similar to concrete which is porous, additives in mixing or finish coat sealants should be studied for total encapsulation of toxic substances.

4.2. Reduced carbon footprint and comparison to GLT

The more processing a wood product undergoes the higher the embodied carbon impact. In fact, glulam timber and other engineered wood products emit more CO_2 than sawn lumber due to the added manufacturing processes [68]. This study not only eliminates processing steps, but also extends the carbon storage of timber. It is important to note here that there are different methods of accounting for biogenic carbon in wood construction. In fact, there can be significant variations in greenhouse gas emissions calculations, which highlight the need for further research and guidelines to standardize life cycle assessment methods for buildings with bio-based materials [69]. For this research, we considered that the carbon stored in the reused pieces of wood equaled the sum of carbon stored in the initial timber of the first building and that saved from potential burn.

In glued laminated timber (GLT), around 48% of the CO_2 equivalent emissions come from producing the glulam (i.e., gluing and lamination), 39% is usually attributed to lamstock production and 13% is assigned for forestry [68]. In lamstock production, the drying of the lumber pieces accounts for the step with the highest amount of energy needed. During the manufacturing process, dimensional lumber is joined into long lamella through finger joinery. This process involves milling and gluing. The lamellae are coated in glue, stacked, and pressed. The curing process uses a combination of pressure and heat. The process of making GLT especially with regards to pressing is energy intensive [68].

Fig. 20 shows that drying, producing resin and curing have the highest carbon footprint in glulam production. In the production of reclaimed wood beams, these processes and materials are absent. In fact, in the Embraced Wood beams, fabrication energy is primarily expended in the operation of running the robotic arm, the fiber wrapping machine, and clay sprayer compressors. The fiber is pretensioned and requires no additional pressing unlike that required in GLT production. Clay plaster

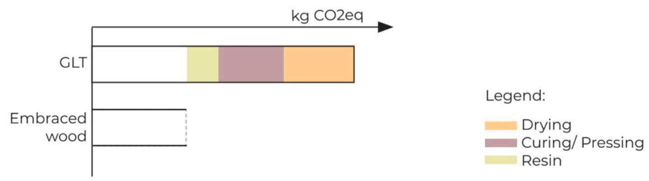


Fig. 20. CO_2 intensive processes omitted in the production of reclaimed timber beams.

air dries and requires no energy in hardening.

With regards to end-of-life treatment, the baseline scenario for GLT is taken to be burnt for energy. With legislation currently calling for the end of burning wood for fuel, new ways of recycling GLT will need to be considered as a means to keep the material from being sent to landfills. However, glue makes it hard to disassemble glulam pieces into discrete wood pieces that can be assembled differently. Embraced wood, however, offers methods for entirely disassembling a structure and being able to reclaim timber, fibers and clay separately. This ability to break down components into the individual timber pieces is not possible at the moment in other such composite beam technologies.

This research offers a competitive alternative to glued laminated engineered timber beams in lower loading scenarios, such as the storey addition case presented in Section 3. 3. Demonstrator Beam with a positive trade-off of reduced environmental impact for structural performance and weight. Comparing 1 m^3 of concrete to 1 m^3 of glulam and Embraced Wood, one notices that from a manufacturing process perspective the carbon footprint of Embraced Wood beams is at least 86.6% smaller than the carbon footprint of concrete and at least smaller than 65% than the carbon footprint of glulam (Fig. 21) [68]. Taking into account carbon sequestration of wood, Embraced Wood would have a carbon footprint 35% smaller than glulam.

Regarding the performance trade-off, structural testing and FEA analysis provided initial results that reclaimed timber beams laminated with fiber and clay can meet the structural performance required for certain loading situations, albeit with a larger cross section and weight than with other engineered timber systems. The partial omission of secondary construction build-up should be accounted for when comparing GLT to this technology with both regard to weight and overall cross section. Given that existing structures have proven to be able to take additional loading of up to two stories, this technology can be used for building extensions despite the added weight.

5. Outlook

Although this research has incorporated a combination of analog and bespoke fabrication techniques for reusing timber, this outlook incorporates these same processes into industrialized settings (Fig. 22). Having concluded that Germany has the suitable infrastructure for larger mass implementation (Section 5.1), the conceptualization of how the integration of reclaimed timber specific processes into existing engineered timber operations is done through schematic drawings and proposed workstations (Section 5.2).

5.1. Establishing a network

To support our claim that industrial integration of reclaimed timber beams can be feasible in Germany, a thorough study of sawmills and recycling plants within the country is conducted. For sawmills, facilities that demonstrated the potential to fabricate engineered beams on their websites were included (Fig. 23(a)). For recycling plants, only businesses that explicitly mentioned timber availability from construction waste on their websites were included (Fig. 23(b)). The qualifying businesses have been plotted on a map of the country to verify their proximity to major cities as well as to each other. For these maps, only cities in Germany with a population over half a million inhabitants are noted.

The study concludes that there are sufficient recycling plants and sawmills distributed throughout the country. The potential to source locally reclaimed material, reduce transportation, and contribute to local business can be achieved.

5.2. Industrial integration

Having established methods to build with a wide variety of linear typology reclaimed timber, the selection of the material only requires this geometric criterion. The linear timber is then transported from the recycling plant to the sawmill. Once at the mill, the integration of technology to support the processing for production of reclaimed unprocessed timber beams requires specific evaluation and fabrication machinery and software.

First, the timber needs to be evaluated and regraded. Most, if not all,

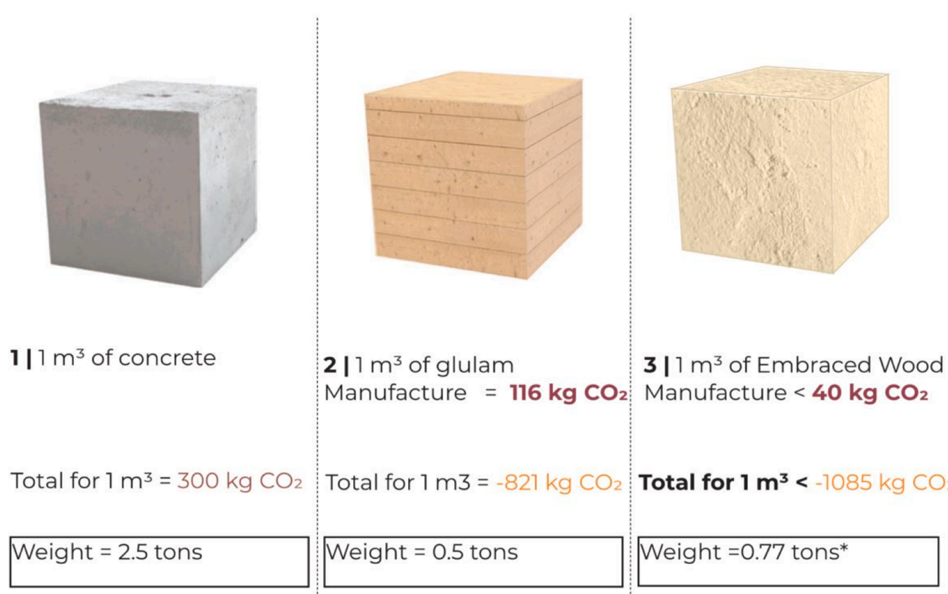


Fig. 21. Carbon footprint comparison for 1 m^3 of (1) concrete, (2) glulam, and (3) fiber wrapped reclaimed beams.

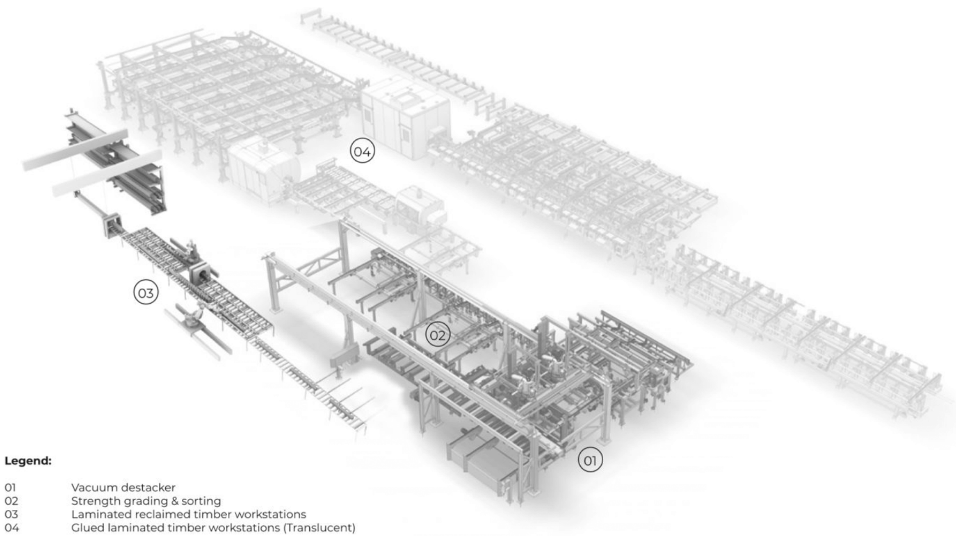


Fig. 22. Concept integration visual for reclaimed timber workstations adjacent to an existing glulam operation. Visual appropriates an image taken from ledinek.com which depicts a GLT manufacturing line located in Spytkowice, Poland [71].

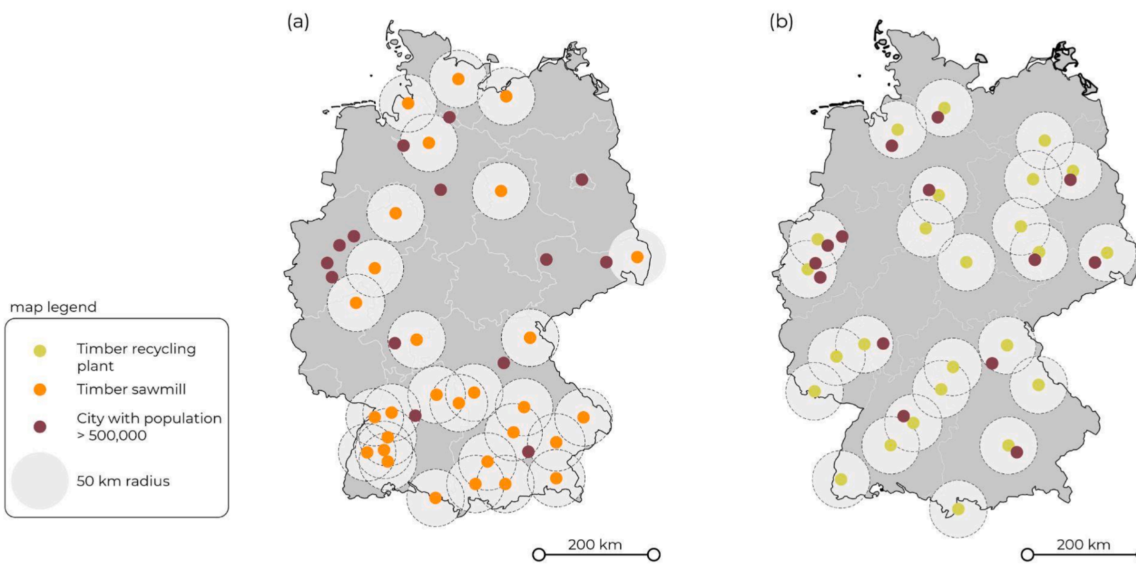


Fig. 23. (a) Country wide recycling plant distribution map of Germany. (b) Country wide sawmill distribution map of Germany.

of the tools needed for this process are already commonly found within sawmills. Following the methods for evaluation in this research, the reclaimed timber needs to undergo moisture detection, non-destructive regrading, visual scanning, and finally face marking (Fig. 24). To establish sorting and regrading, the timber pieces are fed on a conveyor across an automated evaluation configuration. The uncertainty of embedded metals in the material makes the use of X-ray radiation evaluation not possible. For this step, oscillation tools are then used similar to those used in the results of this research. For visual grading, AI-based scanning technology such as Finscan are used [70]. Several sawmills already use these exact machines in their virgin timber evaluation. However, unlike Finscan's default AI engine, tweaks to machine vision detection would have to be coded to recognize nails and first use evoked defections. This data would be coded to assimilate the results based on the research of Rose et al., which compares salvaged timber defects to natural defects [32]. Once data regarding oscillation and scanning are registered, the timber is marked with a custom QR code. The timber is then sorted based on evaluation results into stacks based on length, cross section, and grade.

Reclaimed wood production diverges from conventional GLT as there is no cutting or gluing required. The stations required for such production do, however, use many of the common tools already within the inventory at a sawmill, such as drying racks and conveyors (Fig. 25).

For production of reclaimed composite beams, the reclaimed timber is conveyed in a circular motion to be able to return to previous stations to extend the beams and add additional clay or recursive wrapping of laid up members. Reclaimed timber specific stations would consist of clay spraying using an industrial robotic arm, a pick and place beam lay-up industrial robotic arm, and an opposing rotation fiber wrapping machine. Per the illustration diagrammed in Fig. 25, at least two beams can be fabricated at one time. Lastly, the beams leave the circular motion undergone in spraying, lay-up, and wrapping and move on to a station where a finish coat is applied. Upon passing through the finish coat station, the beam is pushed through a rubber squeegee on all four sides, troweling the finish surface smooth. As the beam passes the squeegee, the beam is cantilevered off the conveyor. At this point, the coordination of ceiling mounted travel lifts needs to be implemented to move the beams from the finish station to drying racks without

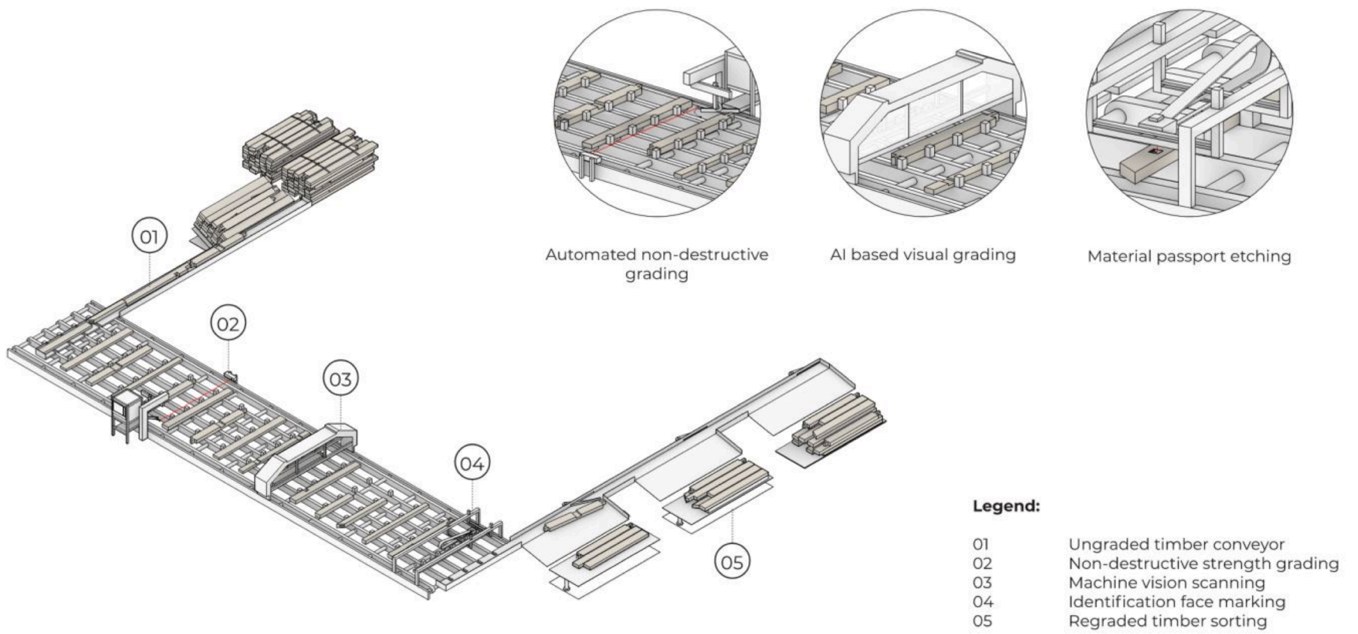


Fig. 24. Automation assessment and evaluation of reclaimed timber configuration.

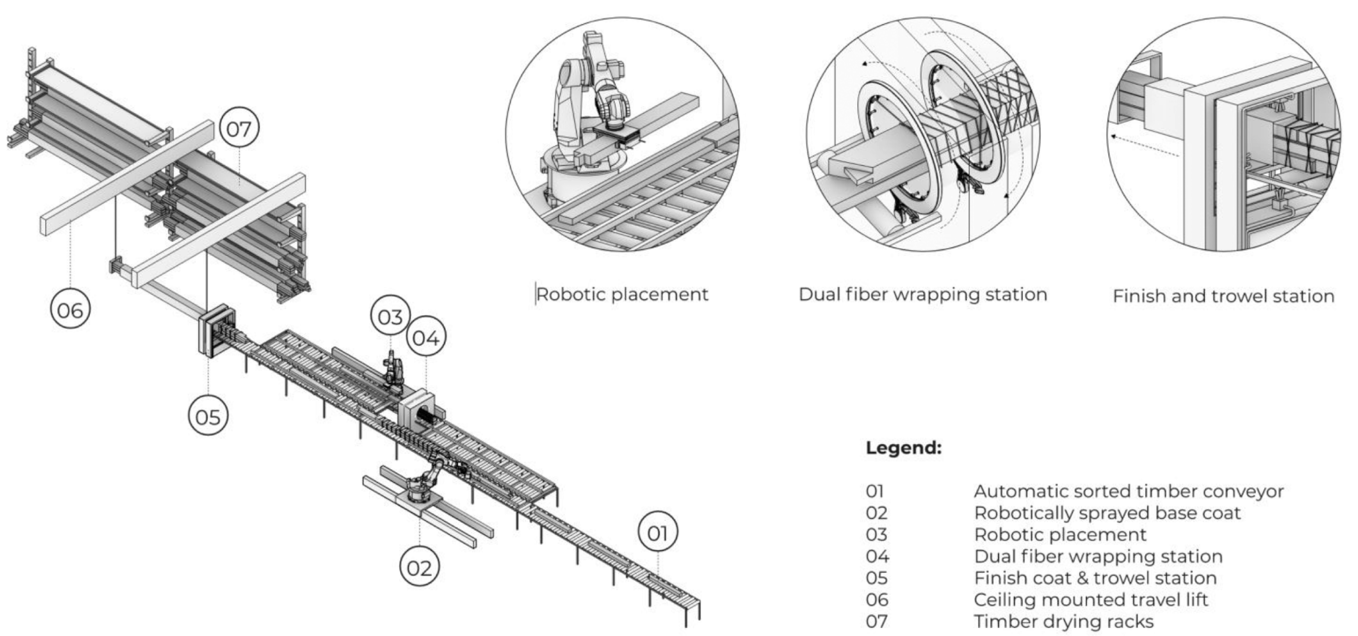


Fig. 25. Automated production line for reclaimed timber composite beams.

damaging or altering the surface treatment of the clay. Once dry, the beams are transported to a building site for rapid construction.

6. Conclusion

6.1. Future research

Natural materials, due to their heterogeneous structures, are more challenging to standardize. Intuitive visual assessment of different elements requires long-term expertise and might not be able to detect exceptional cases. Further incorporating digital tools such as machine vision instead of the manual non-destructive grading methods presented here can help expedite the evaluation process and prevent human errors. Moreover, to better understand the interaction between the timber-clay-fiber composite, more experiments and bending and shear testing should be done to inform the structural analysis and compare different clay and fiber types. Through the creation of a data set, predictive models can be created to more efficiently and accurately evaluate the properties of irregular reclaimed timber pieces. The continuation of this research should investigate the use of a hybrid system of new and reclaimed timber. The integration of new timber would contribute to the overall timber supply available for a building design. Additionally, new timber can be used to make the bottom lamella continuous, greater structural performance can be achieved while using the same methods outlined herein for the remaining lamellae.

Long-term testing of samples should be conducted to check how the moisture regulating properties of the clay affect the fibers and whether the fibers lose tension over time as the fibers used in this study were not impregnated with resin. Large-scale structural testing can also further help to achieve more accurate strength results and standardized beam properties.

6.2. Summary

This paper presents a workflow to non-destructively analyze reclaimed timber elements, to computationally arrange into a beam of any span from irregular pieces, and to robotically fabricate a laminated timber beam using natural fibers.

Embraced Wood introduces methods to overcome material irregularities and contamination that currently prevent structural reuse of timber, and thus expands the amount of waste wood that can be used back into construction that otherwise would have been burned. Moreover, the non-invasive and disassemblable fabrication method applied provides continual reuse value to new or reclaimed timber. While most reclaimed timber use cases extensively cut out material, Embraced Wood simplifies fabrication by using the material without processing. By creating a bio composite structure through integration of clay and fiber, materials are utilized for multiple and complementary purposes such as to provide fire safety and moisture regulation. This biomaterial composition and simplified fabrication have significantly lower carbon emissions than other engineered timber products. By creating a component that can span longer than any individual piece, greater design freedom is achieved that can mitigate the extra resource consumption and emissions of future high-density construction.

CRediT authorship contribution statement

Knippers Jan: Writing – review & editing, Supervision. **Menges Achim:** Writing – review & editing, Supervision. **Tahouni Yasaman:** Writing – review & editing, Supervision, Conceptualization. **Wagner Hans Jakob:** Writing – review & editing, Supervision, Conceptualization. **El Feghali Christelle:** Writing – original draft, Visualization, Software, Methodology, Investigation, Conceptualization. **Steixner Christian:** Writing – original draft, Visualization, Software, Methodology, Investigation, Conceptualization. **Asa Pelin:** Writing – original draft, Visualization, Software, Methodology, Investigation, Conceptualization.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests. Pelin Asa, Christelle El Feghali, Christian Steixner reports equipment, drugs, or supplies was provided by CLAYTEC GmbH & Co. KG. Pelin Asa, Christelle El Feghali, Christian Steixner reports equipment, drugs, or supplies was provided by H. Werner Recycling GmbH & Co. KG.

Data Availability

Data will be made available on request.

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References

[1] F. Privat, Faisabilité du recyclage en boucle fermée des déchets post-consommateurs en bois massif, PhD Thesis, 2019.
[2] European Parliament, Renewable Energy Directive, 2022. [Online]. Available: https://www.europarl.europa.eu/doceo/document/TA-9–2022-0317_EN.pdf.
[3] Bundesministerium für Wohnen, Stadtentwicklung und Bauwesen and Bundesministerium für Ernährung und Landwirtschaft, Holzbauinitiative: Strategie der Bundesregierung zur Stärkung des Holzbaus als ein wichtiger Beitrag für ein klimagerechtes und ressourceneffizientes Bauen, Jun. 2023.
[4] La Dépêche, Tous les bâtiments publics devront être construits à plus de 50% en bois d'ici à 2022. Accessed: Dec. 14, 2021. [Online]. Available: https://www.ladepeche.fr/2020/02/05/tous-les-batiments-publics-devront-etre -construits-a-plus-de-50-en-bois-dici-a-2022,8712149.php.
[5] S. Breneman, M. Timmers, and D. Richardson, Tall Wood Buildings in the 2021 IBC. WoodWorks, 2022. [Online]. Available: https://www.woodworks.org/wp-content/uploads/wood_solution_paper-tall-wood.pdf.
[6] K. Appunn, Next German government's key climate and energy plans in 2021 coalition agreement, Clean Energy Wire. Accessed: Dec. 14, 2021. [Online]. Available: https://www.cleanenergywire.org/factsheets/future-german-governments-key-climate-and-energy-plans-2021-coalition-treaty.
[7] Statistisches Bundesamt, Forest damage: logging of timber damaged by insect infestation grew more than tenfold within five years. Accessed: Oct. 04, 2022. [Online]. Available: https://www. destatis.de/EN/Press/2021/08/PE21_N050_41.html
[8] Statistisches Bundesamt, Abfallbilanz. Accessed: Oct. 04, 2022. [Online]. Available: https://www.destatis.de/DE/Themen/ Gesellschaft-Umwelt/Umwelt/Abfallwirtschaft/_inhalt.html#
[9] M. Heinrich, Material Flows of the German Building Sector. International HISER Conference on Advances in Recycling and Management of Construction and Demolition Waste, Jun. 2017. Accessed: Oct. 04, 2022. [Online]. Available: https://www.bamb2020.eu/wp-content/uploads/2017/07/Material-flows-of-the-German-building-sector.pdf.
[11] United Nations Environment Programme, 2022 Global Status Report for Buildings and Construction: Towards a Zero-emission, Efficient and Resilient Buildings and Construction Sector, Nairobi, 2022.
[12] A. Klinge and E. Roswag-Klinge, Holz- ein zirkulärer Baustoff, presented at the 25. Internationales Holzbau-Forum, 2019.
[13] D. Parigi, Minimal-waste design of timber layouts from non-standard reclaimed elements: a combinatorial approach based on structural reciprocity, Int. J. Space Struct. vol. 36 (4) (. 2021) 270–280, https://doi.org/10.1177/09560599211064091.
[14] L. Giordano, M. Derikvand, G. Fink, Bending properties and vibration characteristics of dowel-laminated timber panels made with short salvaged timber elements, Buildings vol. 13 (1) (. 2023) 199, https://doi.org/10.3390/buildings13010199.
[15] S. Huuhka, Tectonic use of reclaimed timber: Design principles for turning scrap into architecture, Archit. Res. Finl. vol. 2 (. 2018) 130–151.
[16] B. Wibranek, Carbon sequestration in lumber columns: facilitating the reuse of lumber waste for prefabrication through computational design and augmented fabrication, Green. Build. Constr. Econ. (2023) 90–103, https://doi.org/10.37256/gbce.4120232309.
[17] K. MacDonald and K. Schumann, Twinned Assemblage: Curating and Distilling Doppelgangers, presented at the CAADRIA, Hong Kong, 2021, pp. 693–702.
[18] D. Bergsagel, F. Heisel, Structural design using reclaimed wood – a case study and proposed design procedure, J. Clean. Prod. vol. 420 (. 2023) 138316, https://doi.org/10.1016/j.jclepro.2023.138316.
[19] Urban Machine, The Machine, Urban Machine. Accessed: Jul. 18, 2023. [Online]. Available: https://urbanmachine.build/the-machine/.
[20] W. Dong, C.M. Rose, J.A. Stegemann, Cross-Laminated secondary timber: validation of non-destructive assessment of structural properties by full-scale bending tests, Eng. Struct. vol. 298 (. 2024) 117029, https://doi.org/10.1016/j.engstruct.2023.117029.
[21] A. Cavalli, D. Cibecchini, M. Togni, H.S. Sousa, A review on the mechanical properties of aged wood and salvaged timber, Constr. Build. Mater. vol. 114 (. 2016) 681–687, https://doi.org/10.1016/j.conbuildmat.2016.04.001.
[22] W. Sonderegger, K. Kránitz, C.-T. Bues, P. Niemz, Aging effects on physical and mechanical properties of spruce, fir and oak wood, J. Cult. Herit. vol. 16 (6) (. 2015) 883–889, https://doi.org/10.1016/j.culher.2015.02.002.
[23] B. Falk, D. Devisser, S. Cook, D. Stansbury, Effect of damage on the grade yield of recycled timber, . Prod. J. vol. 49 (7/8) (. 1999) 71–79. Accessed: Aug. 04, 2023. [Online]. Available, 〈https://www.fpl.fs.usda.gov/documnts/pdf1999/falk99c.pdf〉.
[24] C.A. Garcia, G. Hora, State-of-the-art of waste wood supply chain in Germany and selected European countries, Waste Manag vol. 70 (2017) 189–197, https://doi.org/10.1016/j.wasman.2017.09.025.

[25] J.J. Janowiak, R.H. Falk, J.D. Kimmel, Feasibility of producing value-added wood products from reclaimed hemlock lumber. U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, 2007, https://doi.org/10.2737/fpl-rp-645.
[26] J. Brütting, G. Senatore, C. Fivet, Form follows availability – designing structures through reuse, J. Int. Assoc. Shell Spat. Struct. vol. 60 (4) (. 2019) 257–265, https://doi.org/10.20898/j.iass.2019.202.033.
[27] M. Condotta, E. Zatta, Reuse of building elements in the architectural practice and the European regulatory context: inconsistencies and possible improvements, J. Clean. Prod. vol. 318 (. 2021) 128413, https://doi.org/10.1016/j.jclepro.2021.128413.
[28] W. Wuyts, A. Miatto, K. Khumvongsa, J. Guo, P. Aalto, L. Huang, How can material stock studies assist the implementation of the circular economy in cities? Environ. Sci. Technol. vol. 56 (24) (. 2022) 17523–17530, https://doi.org/10.1021/acs.est.2c05275.
[29] A. Kühlen, R. Volk, and F. Schultmann, State of the Art of Demolition and Reuse and Recycling of Construction Materials, in *Proceedings of the CIB World Building Congress 2016: Volume V - Advancing Products and Services. Ed.: N. Achour, in* Tampere University of Technology. Department of Civil Engineering. Construction Management and Economics. Report, vol. 18. Tampere University of Technology. Department of Civil Engineering, 2016, pp. 664–678.
[30] B.S. Byers, C. De Wolf, QR code-based material passports for component reuse across life cycle stages in small-scale construction, Circ. Econ. vol. 1 (2) (. 2023) 1–16, https://doi.org/10.55845/IWEB6031.
[31] M. Irle, et al., Advanced recycling of post-consumer solid wood and MDF, Wood Mater. Sci. Eng. vol. 14 (1) (. 2019) 19–23, https://doi.org/10.1080/17480272.2018.1427144.
[32] C. Rose, et al., Cross-laminated secondary timber: experimental testing and modelling the effect of defects and reduced feedstock properties, Sustainability vol. 10 (. 2018), https://doi.org/10.3390/su10114118.
[33] D. Fernandez Llana, V. González-Alegre, M. Portela, J. García-Navarro, and G. Íñiguez-González, ENGINEERED WOOD PRODUCTS MANUFACTURED FROM RECLAIMED HARDWOOD TIMBER, in World Conference on Timber Engineering (WCTE 2023), Oslo, Norway: World Conference on Timber Engineering (WCTE 2023), 2023, pp. 3594–3599. doi: 10.52202/069179–0468.
[34] S. Schuster, S. Geier, circularWood: Paradigmenwechsel für eine Kreislaufwirtschaft im Holzbau, 15/2023, Bonn (2023), 15/2023.
[35] C. Cristescu, D. Honfi, and K. Sandberg, Design for deconstruction and reuse of timber structures – state of the art review, 1, Dec. 2020.
[36] V. John and T. Stark, Wieder- und Weiterverwendung von Baukomponenten (RE-USE), 27/2021, 2021.
[37] M. Risse and K. Richter, CaReWood: Ökologische und ökonomische Bewertung der kaskadischen Holznutzung, Technische Universität München, Munich, Jan. 2018.
[38] Y. Huang, L. Alkhayat, C. De Wolf, and C. Mueller, Algorithmic circular design with reused structural elements: method and tool, Sep. 2021, pp. 457–468. doi: 10.35789/fib.PROC.0055.2021.CDSymp.P056.
[39] J. Brütting, J. Desruelle, G. Senatore, C. Fivet, Design of truss structures through reuse, Structures vol. 18 (. 2019) 128–137, https://doi.org/10.1016/j.istruc.2018.11.006.
[40] J. Trummer, Timber-Clay Composite Slabs. TT Professorship Digital Fabrication Department of Architecture Technical University Munich, 2021. [Online]. Available: https://mediatum.ub.tum.de/doc/1631990/1631990.pdf.
[41] J. Mutis and L. Polanski, Engineered Wood Construction: Using Robotic Fabrication Techniques to Create Carbon Negative and Low Embodied Energy Composite Wood Structural Elements, Phase One, Perkins+Will, 2017.
[42] People's Pavilion / bureau SLA + Overtreders W., ArchDaily. Accessed: Sep. 19, 2022. [Online]. Available: https://www.archdaily.com/915977/peoples-pavilion-bureau-sla-plus-overtreders -w#:~:text =The%20pavilion%20is%20a%20design,250%20m2%20building%20were%20borrowed.
[43] A. Kunic, R. Naboni, A. Kramberger, C. Schlette, Design and assembly automation of the Robotic Reversible Timber Beam, *Autom. Constr.* vol. 123 (. 2021) 103531, https://doi.org/10.1016/j.autcon.2020.103531.
[44] Nature's Technology, Euclid Timber Frames. Accessed: Dec. 21, 2023. [Online]. Available: https://euclidtf.com/pages/natures-technology
[45] R.E. Smith, INTERLOCKING CROSS-LAMINATED TIMBER: alternative use of waste wood in design and construction, presented at the BTES: Convergence and Confluence, 2011.
[46] DIN EN15497:2014 Keilgezinktes Vollholz Für Tragende Zwecke - Leistungsanforderungen Und Mindestanforderungen An Die Herstellung. Deutsches Institut für Normung, Berlin, 2014.
[47] F. Arriaga, C. Osuna-Sequera, I. Bobadilla, M. Esteban, Prediction of the mechanical properties of timber members in existing structures using the dynamic modulus of elasticity and visual grading parameters, Constr. Build. Mater. vol. 322 (2022) 126512, https://doi.org/10.1016/j.conbuildmat.2022.126512.
[48] R. Falk, D. Devisser, S. Cook, D. Sttansbury, Effect of Damage on the Grade Yield of Recycled Lumber, . Prod. J. vol. 49 (7/8) (1999) 71–79.
[49] Normenausschuss Bauwesen, Deutsches Institut für Normung, Berlin, DIN 4074, 2008.
[50] DIN EN338:2016 Bauholz für tragende Zwecke – Festigkeitsklassen. Deutsches Institut für Normung, Berlin, 2016.
[51] Qlone. EyeCue Vision Technologies LTD. [Online]. Available: https://www.qlone.pro/
[52] Robert McNeel & Associates, Rhinoceros. 2020. [Online]. Available: https://www.rhino3d.com/
[53] Rutten, Grasshopper 3D. 2007. [Online]. Available: https://www.grasshopper3d.com/.
[54] D. Piker, Kangaroo Physics. 2017. [Online]. Available: https://www.food4rhino.com/en/app/kangaroo-physics.
[55] C. Preisinger, Karamba3D. [Online]. Available: https://karamba3d.com/.
[56] Sofistik. [Online]. Available: https://www.sofistik.com/
[57] A. Thomson, D. Maskell, P. Walker, M. Lemke, A. Shea, and M. Lawrence, Improving the hygrothermal properties of clay plasters, Aug. 2015.
[58] J. Liblik, A. Just, Performance of constructions with clay plaster and timber at elevated temperatures, Energy Procedia vol. 96 (2016) 717–728, https://doi.org/10.1016/j.egypro.2016.09.133.
[59] Product Information Zwick Z100/Z250 materials testing machine with central ball-lead screw, ZwickRoell. Accessed: Dec. 22, 2023. [Online]. Available: https://www.zwickroell.com/fileadmin/content/Files/SharePoint/user_upload/PI_EN/08_437_Single_screw_testing_machine_PI_EN.pdf
[60] DIN EN 408, 2012-10 Holzbauwerke - Bauholz Für Tragende Zwecke Und Brettschichtholz - Bestimmung Einiger Physikalischer Und Mechanischer Eigenschaften, Deutsches Institut für Normung, Berlin, 2012.
[61] Clay adhesive and reinforcing mortar, Claytec. Accessed: Oct. 07, 2022. [Online]. Available: https://www.claytec.de/en/products/clay-drybuilding/clay-adhesive-and-reinforcing-mortar_pid224
[62] Clay plaster SanReMo, Claytec. Accessed: Oct. 08, 2022. [Online]. Available: https://www.claytec.de/en/products/clay-plaster/clay-plaster-sanremo_pid160
[63] Niton™ XL3t XRF Analyzer, Thermo Fisher. Accessed: Dec. 22, 2023. [Online]. Available: https://www.thermofisher.com/order/catalog/product/de/en/10131166
[64] Flax mesh, Claytec. Accessed: Oct. 08, 2022. [Online]. Available: https://www.claytec.de/en/products/clay-plaster/flax-mesh_pid189
[65] YOSIMA clay designer plaster, Claytec. Accessed: Oct. 08, 2022. [Online]. Available: https://www.claytec.de/en/products/fine-finish_surfaces/yosima-clay-designer-plaster_pid6
[66] S. Vadstrup, Rehabilitation of Half Timbered Houses with Clay Fillings in Denmark. Aarhus School of Architecture, 2017. [Online]. Available: https://9pdf.org/article/rehabilitation-half-timbered-houses-clay-fillings-denmark.q052×5gx.
[67] H. Kaufmann, S. Krötsch, and S. Winter, Manual of Multi-storey Timber Construction. in Construction Manuals. Detail Business Information, 2018. [Online]. Available: ⟨https://books.google.com/books?id=ZURzxAEACAAJ⟩.
[68] T. Bowers, M. Puettmann, I. Ganguly, I. Eastin, Cradle to gate life cycle impact analysis of glued-laminated timber: environmental impacts from glulam produced in the U.S. Pacific Northwest and Southeast, . Prod. J. vol. 67 (. 2017), https://doi.org/10.13073/FPJ-D-17-00008.
[69] C.M. Ouellet-Plamondon, et al., Carbon footprint assessment of a wood multi-residential building considering biogenic carbon, J. Clean. Prod. vol. 404 (. 2023) 136834, https://doi.org/10.1016/j.jclepro.2023.136834.
[70] Finscan. Microtec. [Online]. Available: https://microtec.eu/en/applications/all/finscan/
[71] Glulam allrounder, Ledinek. [Online]. Available: https://www.ledinek.com/glt-allrounder-for-customer-in-poland