# INTERLOCKING SOLID GLUED TIMBER FROM RECLAIMED STOCKS

*MSc in Architecture, Urbanism and Building Sciences (Building Technology)*


Technical University of Delft (TU Delft)

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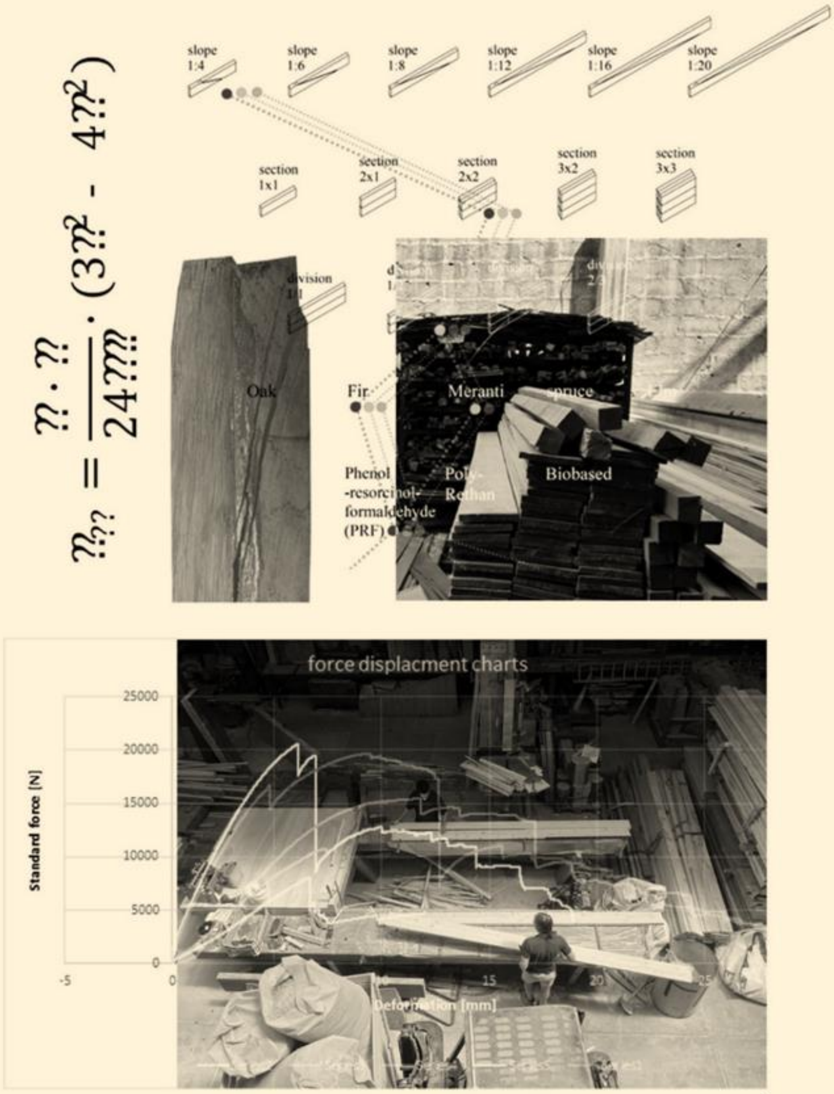
***Industry Partner : Ssse|OvO associates amsterdam and Lorin Brasser Workshop Amsterdam***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# CONTENTS

# Acknowledgment

First and foremost, all thanks go to almighty Allah, who granted me the health, time, and strength to start this journey, which I carry with His name in my heart.

I remember last summer being overwhelmed by the amount of furniture waste from the student housing I lived in. This sparked numerous ideas, from rethinking economic models to exploring different aesthetics. Curious about how our world views its finite resources, I dived into the topic. Four months later, I saw it in the graduation manual and contacted Stijn Brancart, my main supervisor, to discuss it further. Stijn guided my enthusiastic mind, giving me the freedom to explore and wonder, making the challenges feel light. Thank you, Stijn, for all your support.

I would also like to thank my second mentor, Gilbert Koscamp, who helped me understand timber deeply, reminding me of the uniqueness of each piece. His vast knowledge in timber research was invaluable. Thanks to Gilbert, I had the chance to work with Lorin Brasser, a talented and kind carpenter, and his amazing team. My gratitude goes to Martijn Bow, Willem, and Santiago for their hard work during our two-week workshop.

Lastly, I dedicate this work to my people in Palestine/Syria, especially my beloved family. Though miles away, they are always in my thoughts and have supported me throughout. This work is a gift to my father, Khalid Alsalhi, my mother, Nuzha AlHuniedi, and my sisters, Leen and Lana.

I also want to thank all the woodworkers in Congo, Indonesia, and all the countries where people have no choice but to sacrifice their resources and work in the worst conditions to earn a living. I hope the day when you can control and enjoy your resources will come soon.

# 1. Introduction

## 1.1 Abstract

The project investigates methods to enhance the practicality of sustainable buildings by addressing the impact of material availability on the construction industry. Rather than assuming construction materials are infinitely available, this study explores the implications of considering them as finite resources. Timber was selected for this investigation due to the inherent complexities in reusing this material and the absence of established workflows for its reuse.

A comprehensive literature review was conducted to identify the key aspects necessary for developing effective timber reuse practices. Based on this review, a series of workflows were devised to translate critical research aspects—such as structure, grading, matching, and product—into practical applications. These workflows are intended to assist carpenters and wood structural designers in creating structural elements, particularly interlocking solid timber joists. These joists are designed for ease of assembly and to enhance the structural performance of wooden beams without relying on complicated techniques.

The proposed workflows were thoroughly investigated and refined to ensure their feasibility. Additionally, experiments were conducted to assess material behaviour, focusing on the topological potential, challenges, and limitations of the workflows. This research aims to contribute to the development of robust material workflows that support the sustainable reuse of timber in construction.

### 1.2 Scope of research

This master thesis focuses on creating an integrated workflow to produce optimized structural elements from reclaimed timber using interlocking glued joints. The research spans two main chairs in the TU Delft MSc. Architecture program (Building Technology track and Architecture):

Structural Design and Mechanics (SDM): Mentored by **Stijn Brancart**.

Design for Construction within the Department of Architecture Engineering: Mentored by **Gilbert Koskamp.**

Additionally, I collaborated with **Lorrin Brasser**, a specialist in reclaimed timber and a carpenter, who supervised, manufactured, and facilitated the second phase of the mechanical tests conducted at his workshop in Amsterdam.

## 1.3 Why reclaimed timber:

### 1.3.1 Ethical Timber: Addressing Risks of Illegal Sourcing

In 2006, Indonesia and Malaysia collectively supplied around 40% of the Netherlands' timber imports, highlighting the significant reliance on Southeast Asian sources for timber. Alarmingly, approximately 80% of the tropical timber imported by the Netherlands was illegally sourced, exacerbating the environmental and social risks associated with uncertified timber. The environmental risks of such timber include illegal logging and deforestation, which contribute to biodiversity loss and climate change. Additionally, the social risks are profound, encompassing poor labor conditions, human rights violations, and land rights disputes, as local communities often suffer from the unregulated exploitation of their natural resources. This uncertified timber forms a considerable part of waste timber, which has significant value beyond the borders of the European continent. Burning this valuable timber for energy consumption or recycling it into particle boards raises important questions about accountability and responsibility in handling the world's natural resources. It is more ethical to reclaim this timber wisely to avoid depleting our collective resources without unlocking their full potential, a potential that the people of the source lands might not have had the chance to explore. By doing so, we can at least partially compensate for the illegal sourcing with circular knowledge that can be shared and collaboratively utilized by both sides.

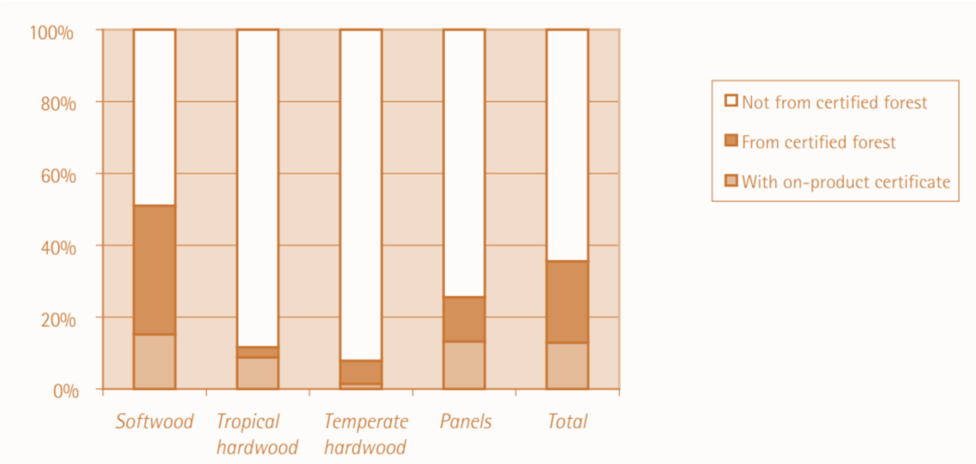



**FIGURE 4: CERTIFIED/UNCERTIFIED TIMBER**

**FIGURE 5FIGURE 6: CERTIFIED/UNCERTIFIED TIMBER**

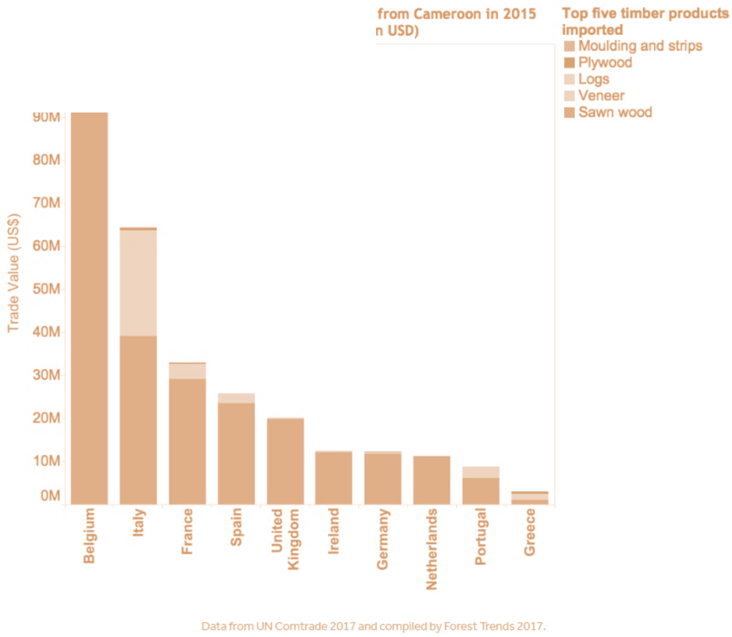



**FIGURE 1:EU WOOD IMPORT**

**FIGURE 2FIGURE 3:EU WOOD IMPORT**

### 1.3.2 "Timber's Role in Carbon Neutrality and Sustainable Construction

The global commitment to achieving carbon neutrality by 2050 is steering the world toward a net-zero plan. Various sustainability legislations, exemplified by France's recent mandate requiring new buildings to incorporate at least 50% timber or other natural materials starting in 2022, have been introduced to propel this agenda. However, the push for sustainable construction materials raises the crucial issue of sourcing additional wood. Forecasts indicate a 37% increase in the consumption of primary processed wood products by 2050 in a business-as-usual scenario and an additional 8% growth in a bioeconomic scenario. The bioeconomic approach considers modern wood products, such as mass timber and man-made cellulose fibers, as substitutes for non-renewable materials like concrete and steel. Consequently, a careful examination and potential restructuring of the forestry value chain are imperative to ensure sustainable wood production.

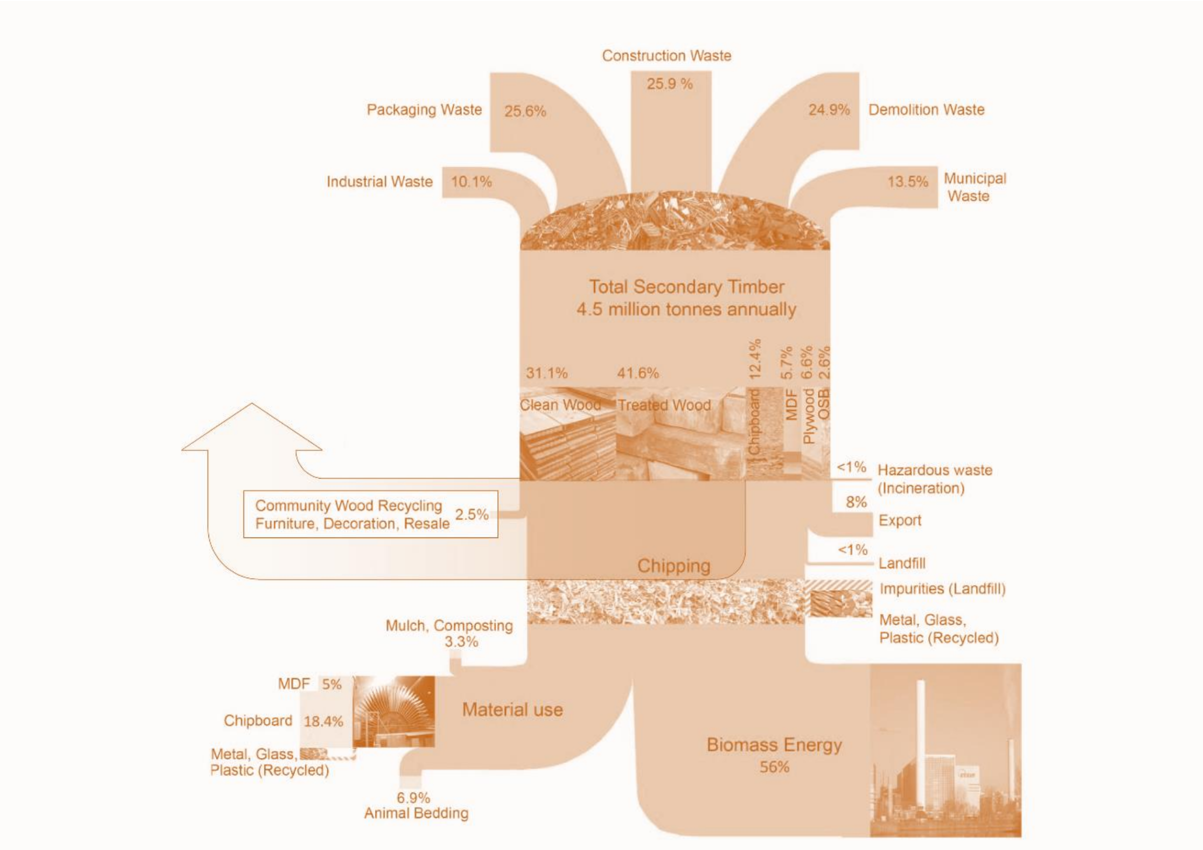



**FIGURE 7: WOOD WASTE MATERIAL FLOW FROM UK**

## 1.4 Digital Age and DIY Culture: Impact on Manufacturing and Circular Economy

Simultaneously, we cannot overlook the transformative impact of the digital age, data abundance, and social media on manufacturing methodologies. DIY videos circulating on the internet showcase diverse activities, from crafting small tools to constructing structures. The underlying principle is to utilize available tools, techniques, and materials to craft desired outcomes, presenting a significant opportunity for a more substantial consideration of the circular economy. Researchers globally, including Tsui and Peck at TU Delft, who initiated the Pop-Machine project, envision a people-centric economy where consumers transition into makers and owners of their products, contributing to a sustainable, clean-energy future.(*Meeting the Makers: The Circular Economy as a Matter of DIY?*, n.d.)

In essence, if freshly sourced timber signifies the core material for a consumer-driven economy, then reclaimed timber emerges as the focal point for a circular economy. Integrating this concept into societal norms broadens the scope of available tools and techniques to encompass diverse materials. This inclusivity becomes more efficient by revisiting traditional or computational techniques to produce a revolutionary timber product. Structural efficiency, capable of competing in the building industry market, becomes paramount, potentially leading to new business models where circular structure designers are liberated from the constraints of the current consumer-based business paradigm.

## 1.5 Enhancing Structural Applications with Reclaimed Timber

### 1.5.1 Evaluating the Structural Capacity of Reclaimed Timber in Modern Construction

The transition from visually graded to machine-graded timber since the 1950s, marked by reduced safety margins, raises concerns about the long-term viability of reusing timbers from demolition for structures due to potential strength degradation. This situation emphasizes a potential preference for recycling timbers as a more sustainable option(Richardson Editor, n.d.). Therefore, the use of reclaimed timber is intricately tied to the concept of its structural capacity. Acknowledging that each element undergoes a certain amount of degradation, the utilization of an aggregation of these elements can result in structural components with enhanced performance.

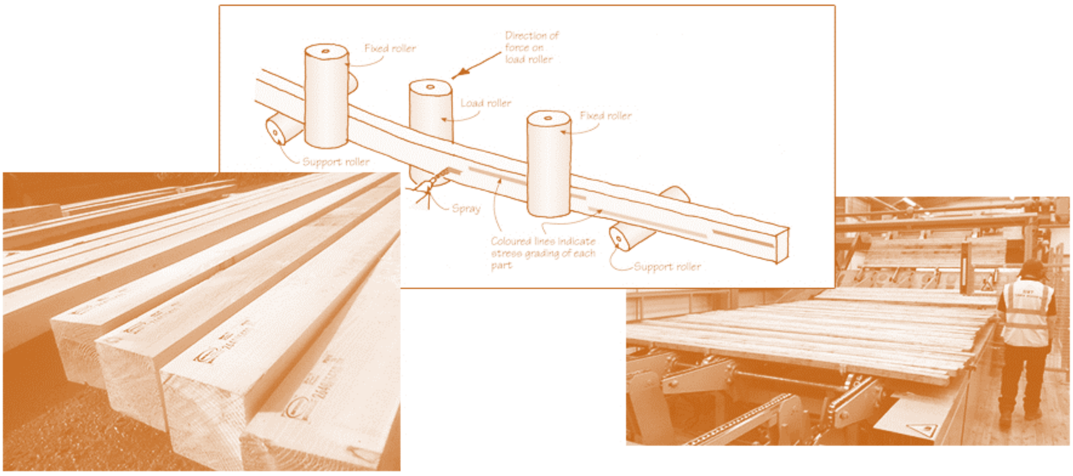



**FIGURE 8: MACHINE GRADING**

### 1.5.2 Cost-Effectiveness of Reclaimed Timber in Structural Applications

Despite research indicating that structurally elements made from newly cut timber generally outperform those made from reclaimed timber, glulam from reclaimed timber has been proven to satisfy the structural needs in the construction market(Llana et al., 2023). Additionally, sustainably procured timber products often come with a higher price tag. Consequently, the construction of a standard mass timber building currently incurs an additional cost of approximately 5–15% compared to a conventional building (Mayencourt & Mueller, 2020). This significant added expense restricts its widespread adoption. However, considering the production of engineered timber from reclaimed sources could offer a more cost-effective solution, thereby supporting the market at a lower expense than using newly sourced timber.

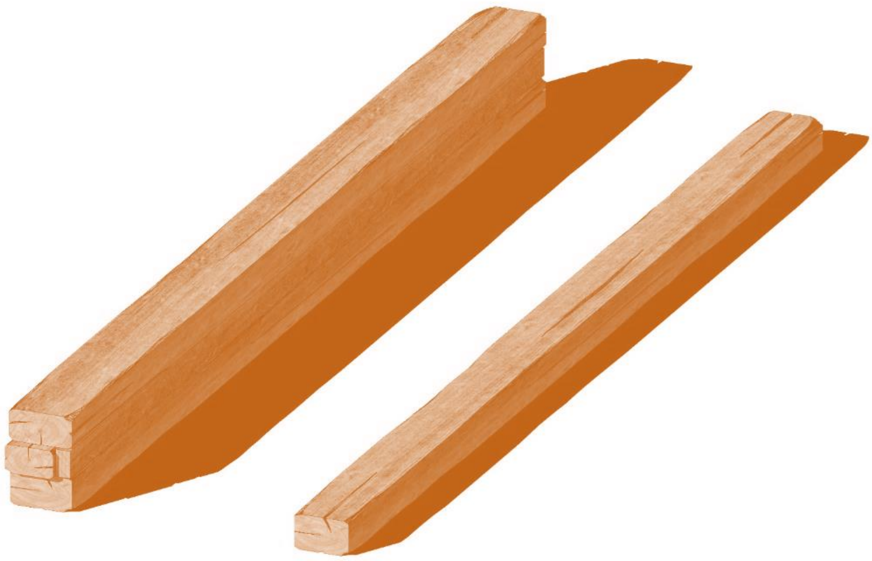


**FIGURE 9: ELEMENT VS BUNDLE OF ELEMENTS**

### 1.5.3 Optimizing Strength in Glulam Structural Elements from Reclaimed Timber

The research interest lies in creating a method for designing glulam structural elements from reclaimed timber to achieve optimum strength for the desired elements. To accomplish this goal, an assessment of the density of available elements is essential, considering their age and evaluating the timber structure(Palma & Fink, 2013). This implies that, in addition to the geometric data of the reclaimed elements, gathering more information about the density, age, and inherent structure of the wood is necessary to commence the analysis.

### 1.5.4 The Impact of Bonding and Joinery on Reclaimed Timber Structural Elements

The assembly of structural elements can be affected by different factors. Since reclaimed timber stocks include a variety of wood species and different methods of surface treatments, more attention should be paid to bonding. Factors like wood chemical extractives, surface pH, and physical (sanded or planed) surfaces might affect the curing behavior and the bonding strength[4]. A weak bond might cause delamination and block shear rupture. Joints in structures are generally fundamental, most research on reclaimed materials primarily focuses on linear structural elements, without paying attention to the joints' geometrical complexity, production cost, and environmental impact.

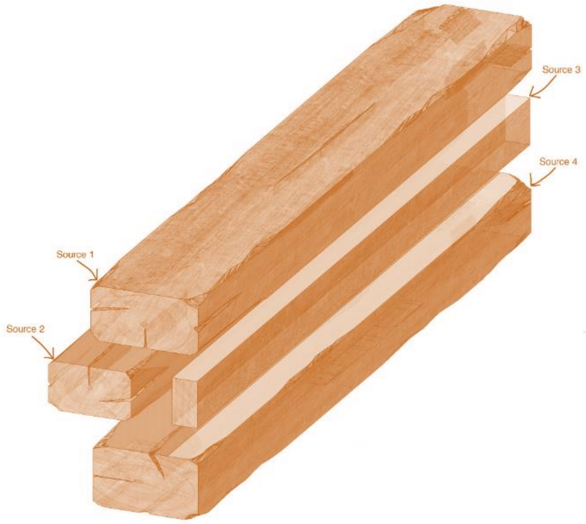



**FIGURE 10: A BUNDEL FROM DIFFERENT WOOD SPECIES**

### 1.5.5 Integrating Joinery Methods into Glulam Production to Enhance Structural Performance of Reclaimed Timber

The interlocking glue laminated timber has demonstrated superior performance compared to solid and parallel glulam joists, presenting an intriguing concept for experimentation (Patlakas et al., 2019a). However, this also introduces various challenges, including the utilization of different types of timber with a range of sections and characteristics, which leaded to us to do more research and test to explore the how the aforementioned aspects affect the performance of the joist, the result of the experiments then used to inform back the production workflows to optimize the production and the performance.

## 1.6 Problem statement

Moving to carbon-neutral construction will likely raise demand for engineered timber, putting pressure on the wooden materials industry and increasing costs for Mass Timber structures, which are already 15% more expensive than concrete buildings. However, creating mass timber structures from reclaimed timber could be an important alternative, despite lacking comprehensive design and production methods.

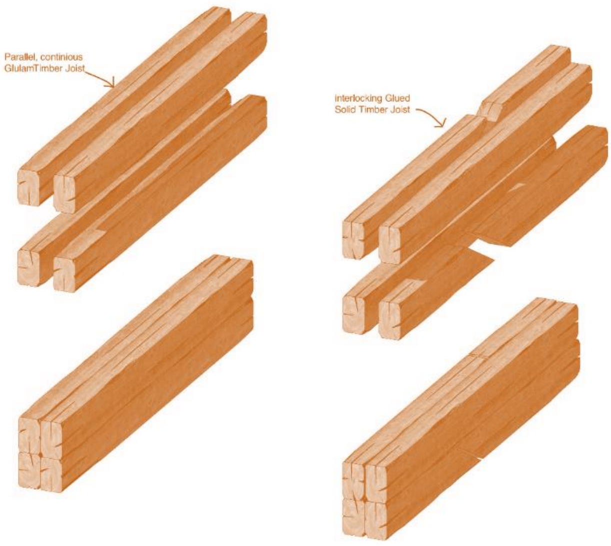



FIGURE 11: PARALLEL / INTERLOCKING SOLID JOIST

## 1.7 research question

**Main research question**

How can we create interlocking glued Solid timber structural components from reclaimed element stocks?

**Preparing the Inventory**

How to evaluate the timber in the stocks, with simple techniques

**Matching algorithm**

How to optimize the quality and quantity of the produced elements by controlling the matching process between design and stock?

**Environmental Impact**

How to calculate the environmental impact of the resulting component and compare it with glulam from newly sawn timber, or combination from both?

**Manufacturing**

What to workflow needed to manufacture the designed structural component?

# LITERATURE REVIEWS

# المراجعات الأدبية

# 2. Literature review

## 2.1 Methedology:

The challenge was to understand the current problem that can be investigated as a building technologist, starting from the work of Jan Brutting's "Form Follows Availability," where the potential of reusing was discussed from different points of view: computationally, materially, structurally, and environmentally. Based on that, I created an attributional scheme for the literature I have to cover (see Figure 1).

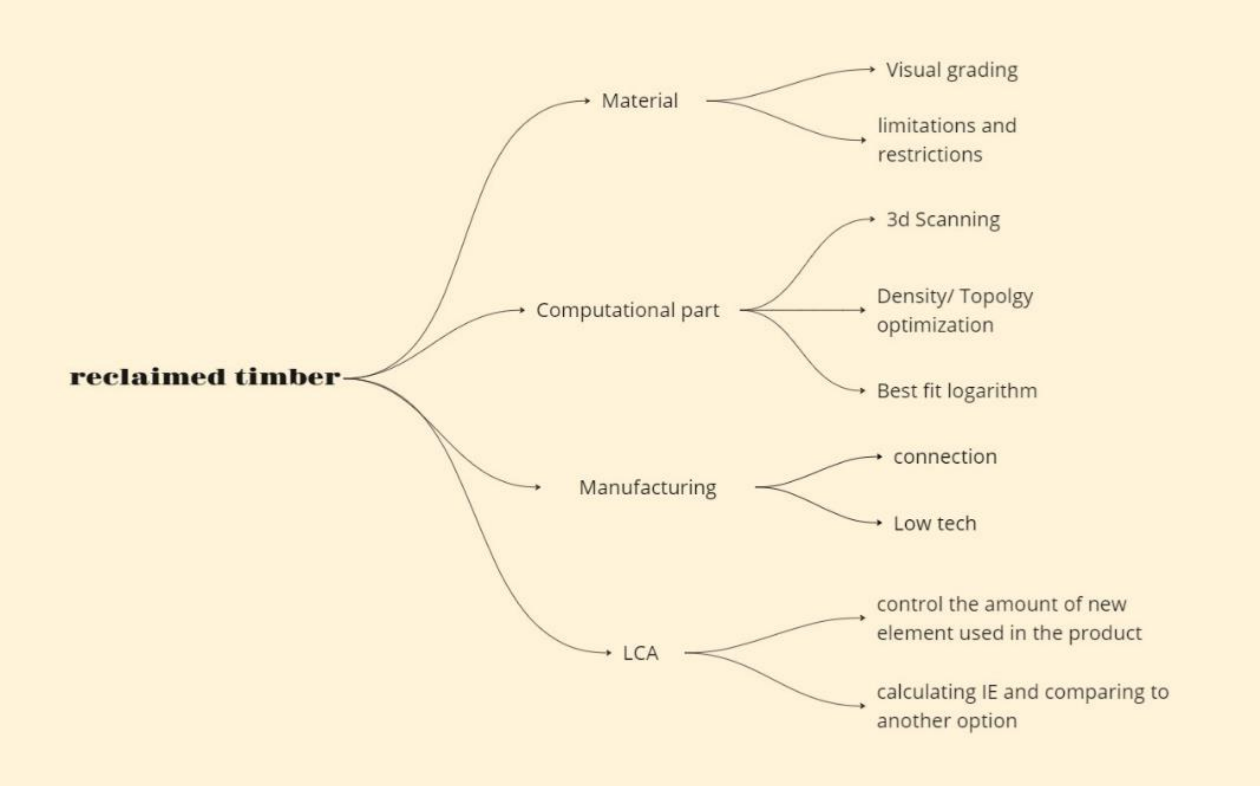



**FIGURE 12: LITERATURE CHART**

Due to the nature of wood as a material, a better understanding is needed for the structural properties of the material. At the same time, the focus is on factors that get affected when timber elements are used in a previous life cycle. This includes how to evaluate their reliability, how to regrade them, how they can be reclaimed, and what are the important characteristics that will be helpful in computational processes, such as length, wood species, and density. Additionally, understanding the current technologies used to measure these factors is crucial.

One of the main differences in studying the reclamation of timber from steel components, as investigated in Jan Brutting's work, is the type of product made using timber. While in steel, the focus is on rectilinear truss elements or space frames, timber is used to produce mass timber structures. This direction directs the research into searching for manufacturing methods that can support the market with efficient structural components made out of reclaimed timber.

The computational part is focused on finding the best matching algorithm. The research of Huang was a good start to check all the available methods already used in previous researches. Thereafter, the literature focused on determining the best algorithm and workflow that can be used for the desired wooden product, according to the design goal. The three main computational methods are Hungarian algorithms, mixed-integer linear programming, and heuristic best-fit algorithms.

For the environmental part, the literature focused on allocating a suitable end-of-life approach among three different ones, as well as finding a valid way to calculate the environmental impact of the resulting products and integrating that into structural optimization. It was found that using new elements might help minimize the environmental impact of the object, making the process more complex. This requires creating a material workflow as a reference for calculating and assessing the environmental impact.

## 2.2 Comprehensive Analysis of Timber

### 2.2.1 Strength and mechanical properties

An essential aspect of designing with timber is recognizing that it is an anisotropic material, meaning its mechanical strength varies in different directions. This variation in strength is due to the biological structure and arrangement of its fibers, as illustrated in Fig 2.3. Essentially, wood can be thought of as a bundle of tubes aligned along the tree's length, providing high compressive and tensile strength parallel to the fibres (Fig 2.4), but significantly lower stiffness perpendicular to the fibers. This characteristic influences the design of timber structures, as aligning the force flow with the timber member's fibers is most effective for load transfer. This principle applies to anisotropic timber products like sawn timber, glulam, laminated-veneer lumber (LVL), or oriented-strand board (OSB). Conversely, cross-laminated timber (CLT), which consists of alternating layers of timber planks oriented at 90 degrees to each other, possesses isotropic properties, making it effective for transferring loads in all principal directions. Thus, the choice of timber products depends on the design's loading conditions. In this thesis, the selection of timber products will also be guided by the design principles derived from a combination between the matching algorithm which take loads and span length in consideration, and the results of the mechanical test conducted, mainly the first phase 3 point bending test where all the failures where observed and documented , to give more idea about the effect of grain direction and load distribution within the different species that has been used in the experiment, resulting in rules of thumb that can be added to the parametric models to increase the accuracy of the matching algorithm

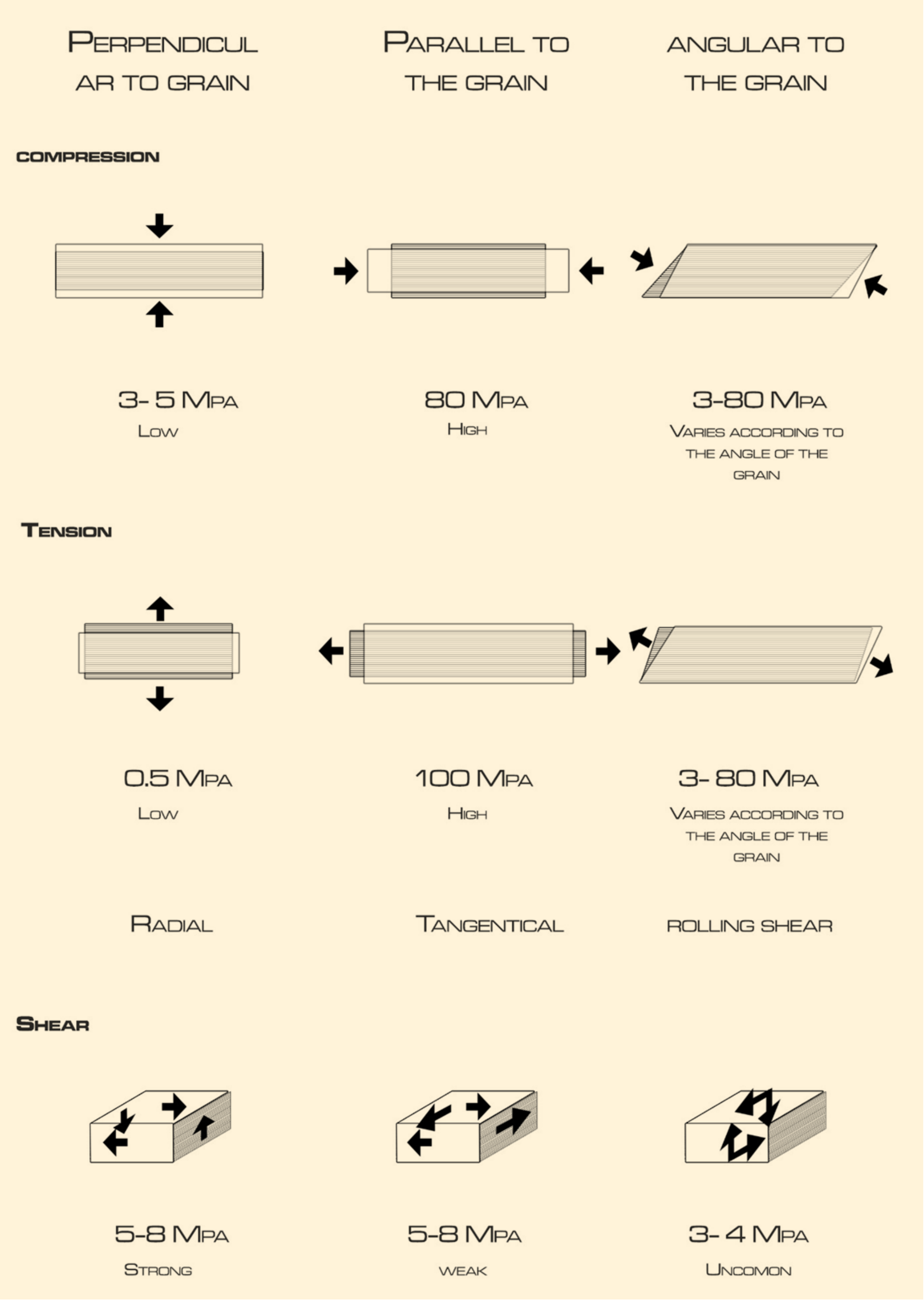



**FIGURE 13: WOOD CHARACTERISTICS INFORMATION SOURCE (*VOLUME 3 EXAMPLES DESIGN OF TIMBER STRUCTURES*, N.D.)**

### 2.2.2Timber structure and density

As reclaimed timber is sourced from diverse origins, salvaged from obsolete buildings, or recovered from various waste types, assessing tensile, compressive, and bending strength proves challenging and expensive. Numerous studies indicate that wood density serves as a valuable indicator for assessing wood strength. The forthcoming paper will explore methodologies utilizing the density of reclaimed timber to accurately position the reclaimed stock within the designed structure(Yu & Fingrut, 2022).

Wood density and wood-based materials significantly influence strength properties, providing an initial, approximate assessment of strength. As density increases, strength linearly improves, facilitating the effective transfer of applied force to a larger, supporting cross-section. This correlation between density and strength holds true within and between various wood types. Factors such as latewood content and growth-ring width impact wood strength, with a notable correlation observed in softwood(Niemz et al., 2023). Despite growth factors, the density of timber cell walls remains relatively constant across species. The primary factors affecting density are cell size, void spaces, and proportions of different cell types. While density reliably indicates strength and other properties, it is essential to consider moisture levels during measurements, as they significantly influence density(Richardson Editor, n.d.).

Over the course of the project density where used in workflow: from stock to grades, where it was a essential input in the Arriaga regrading formulas,  using grasshopper definition

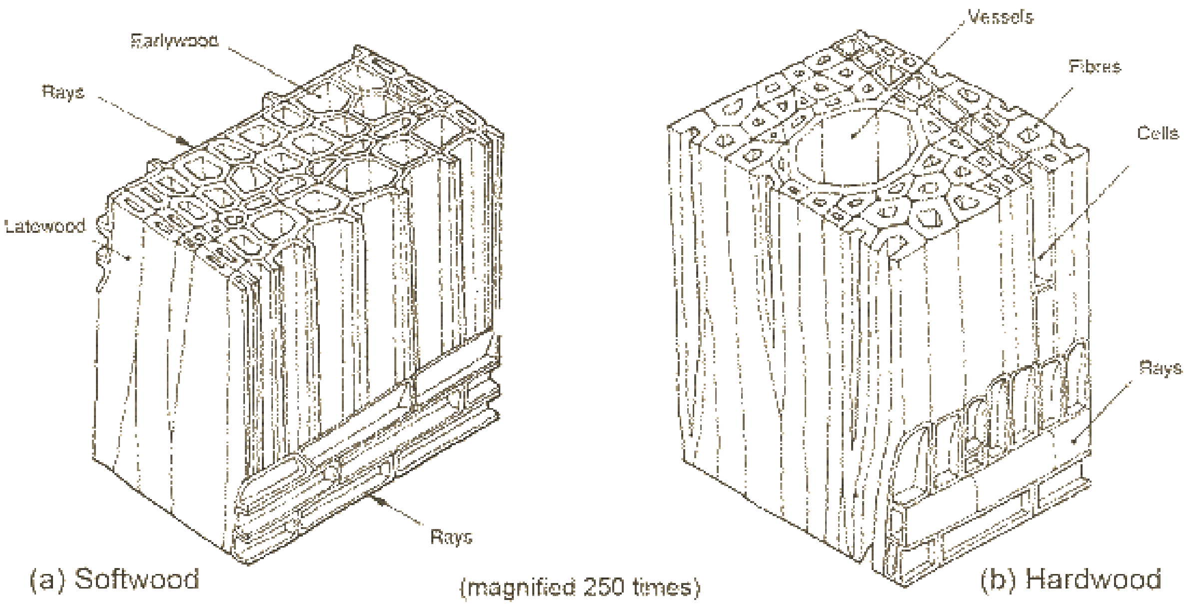



**FIGURE 14: SOFT WOOD / HARDWOOD STRUCTURE**

### 2.2.3 Timber age

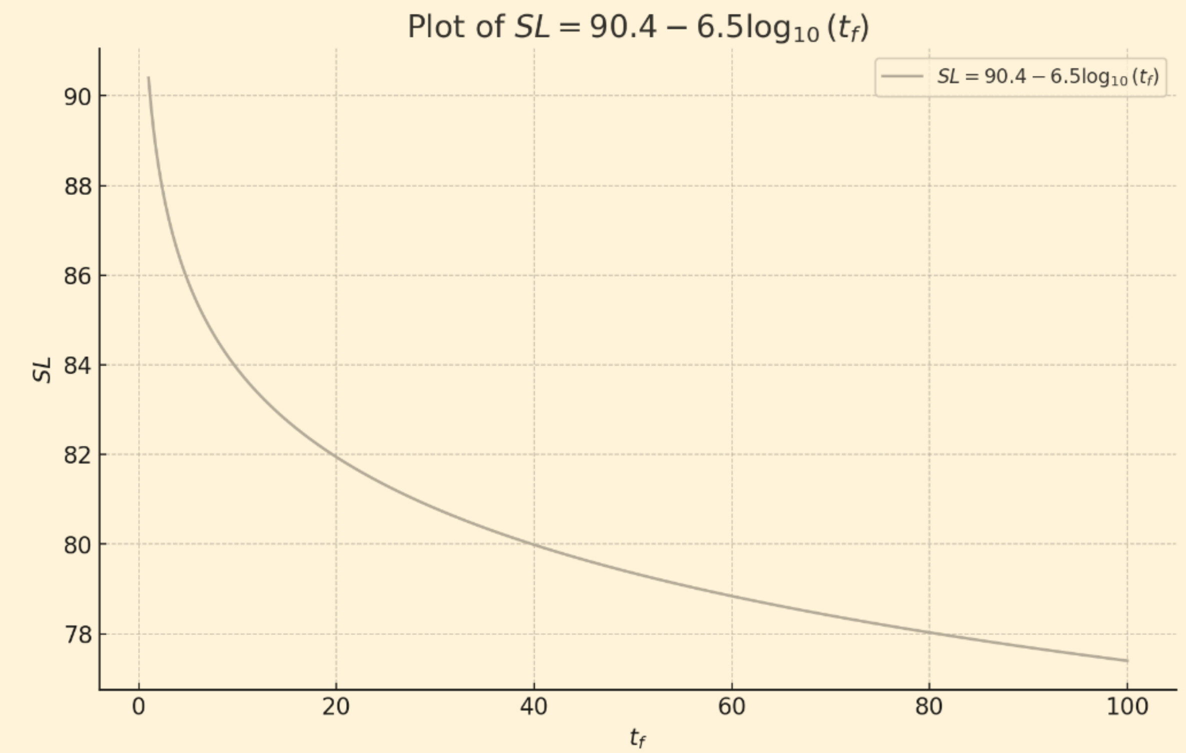
when considering reclaimed timber, several challenges arise. Reclaimed timber experiences a logarithmic loss of strength over time due to the duration of load effect, with difficulties estimating its age, load, and moisture content.

Determining the age of timber joists involves considering the site's location where the specimen was removed. Local inquiries can unveil the site's age or the buildings on it, providing insights into the likely age of the timber used. Another method is to check for date markings on the building, such as dedications or cornerstones, offering a precise date of the initial use of building materials. While dendrochronology and radiocarbon dating are effective yet expensive methods for dating reclaimed timber joists, research by Wood (1951) on the Madison curve indicates a logarithmic loss of strength over time(Richardson Editor, n.d.). Despite variations in species, dimensions, and moisture content, subsequent studies demonstrated good agreement. the most fitting exponential relationship for results below SL = 100% is expressed as:

$$\mathrm{SL} = 90.4 - 6.5\log_{10}\, t_f$$

Where $t\,f$ :Time to failure in hours

*SL* : Actual stress level over predicted short-term strength




Here's the plot of the equation $SL = 90.4 - 6.5\log_{10}(t_f)$. The graph shows how $SL$ varies with $t_f$ over the range from 1 to 100. As $t_f$ increases, $SL$ decreases due to the logarithmic relationship.

**FIGURE 15: AGING OF TIMBERGRAPH**

To safely use reclaimed timber in structural applications, designers must trust its load-bearing capacity. While wood generally exhibits good strength properties, mechanical considerations are critical in applications facing tensile or bending stresses, such as beams and columns. It is believed that aged timber maintains its properties unless damaged biologically or physically. Studies evaluating aged and deconstructed timber suggest that ageing itself does not reduce compressive and tensile strengths, although bending strength may slightly decrease, particularly in impact bending strength due to ageing (Niemz et al., 2023)

### 2.2.4 Timber decay

Timber, though durable, faces susceptibility to two distinct forms of decay: dry rot and wet rot. Dry rot, driven by a destructive fungus, has the capacity to swiftly compromise timber integrity, thriving in moist and poorly ventilated conditions. This fungus can infiltrate brickwork, leading to widespread destruction of structural components, including timbers, skirting boards, door frames, and wood flooring. Conversely, wet rot occurs naturally in highly moist environments, requiring the removal and replacement of affected timbers. In cases of localized damage, the application of epoxy-based repair kits can be considered. A modern approach to managing dry rot involves employing environmental controls like isolation and ventilation to prevent the necessary damp and unventilated conditions. Furthermore, wood-destroying fungi, including brown rot, white rot, and soft rot, induce a significant loss of strength, altering fracture patterns. Brown rot results in both decreased strength and density, with a cubical break, while white rot leads to a clean break with diminished strength and density. Soft rot, causing minimal mass loss, reduces impact strength. In conclusion, rot induces a decline in strength, necessitating drying and treatment for wet rot, and prompt disposal for wood with dry rot to prevent further fungal spread.(Niemz et al., 2023; Richardson Editor, n.d.)

*In the discourse of this thesis, not much attention is paid to methods for evaluating and regrading timber that contains soft, wet, white, or brown rot. However, it is necessary to investigate this further to preserve the stock in a ready-to-use, healthy condition. This includes limiting all vital decay that might result from weather conditions or poor ventilation in storage and warehouses.*

Generally, here are some essential tips to consider while stacking timber products, in addition to the storage ventilation rate:

1. **Ensure Proper Ventilation**: Store timber in a well-ventilated area to prevent moisture buildup and decay.

2. **Use Stickers:** Place small wood pieces (stickers) between layers of timber to allow air circulation.

3. **Consider Wind Direction:** Position storage sheds so the gable faces the wind for better ventilation.

4. **Leave Space**: Maintain space around the storage area for air circulation.

5. **Avoid New Buildings**: Store timber in areas without high moisture levels, which are common in new buildings.

6. **Store on a Flat Surface:** Ensure timber is stored vertically and on a flat, stable surface.

7. **Use Pallets**: Place timber on pallets to avoid direct contact with the floor and prevent warping and moisture buildup.

### 2.2.5 Moisture content and moisture control

The strength of timber is influenced by its moisture content, with bending and compression stresses for 'wet' graded timber being 80% and 60%, respectively, compared to 'dry' graded timber. Changes in moisture content also led to dimensional alterations, such as a 4–6% reduction recorded between moisture levels of 20 and 6%. For structural use, timber must undergo strength grading aligned with the moisture content appropriate for its service exposure. Timber designated for building construction typically receives a grading of Service class 1 or 2, with structural softwood timbers being graded visually or by machine.(Richardson Editor, n.d.)

The impact of moisture content on timber remains consistent, whether it is reclaimed or virgin. It is imperative to keep timber dry to prevent degradation caused by insects and fungi. Effective moisture control starts during the storage phase, continues through construction, and extends after the structure is built. Strategies are crucial to avoid uncontrolled moisture events, and designers should consider constructability, provide appropriate details, especially near water sources, and plan for ventilation of wooden elements. Preservative use is essential, though the discussion involves potential chemical toxicity issues affecting recycling. In the case of reclaimed timber, exposure to conditions affecting moisture content is possible, such as leaving material outdoors before recovery, inadequate covering during deconstruction, or storing recovered timber in high-humidity environments.(*Timber Construction Manual - Thomas Herzog, Julius Natterer, Roland Schweitzer, Michael Volz, Wolfgang Winter - Google Books*, n.d.) Given these considerations, if reclaimed timber is to be deemed a building material, users and contractors must be attentive to these conditions. Treating waste as a potential valuable material becomes a fundamental concept, emphasizing the need for vigilance in handling reclaimed timber to ensure its viability in construction.

There are several methods to measure the moisture content of a piece of timber

The moisture content (MC) of timber, indicated by u (moisture ratio), is determined by comparing the weight of water in the wet material to the weight of the wood after it undergoes drying at 103°C for 24 hours. This calculation can be performed using the following Equation :

$$u = \frac{m_u - m_{\text{dry}}}{m_{\text{dry}}} \cdot 100$$

Equation 1: MC equation, u = Moisture Ratio,
$m_u$ = Mass of Moist Wood, $m_{dry}$ = Mass of Dry Wood

Achieving equilibrium moisture content means that the wood has reached a balance between adsorption and desorption relative to the surrounding conditions. This equilibrium is influenced by changes in Relative Humidity (RH) and temperature due to wood's hygroscopic nature. However, maintaining the moisture content below 20% is crucial for preventing fungal growth and subsequent decay (Design of Timber Structures, 2016.).

*In the workflow for categorizing stock into grade A, a straightforward criterion has been employed to assess whether the timber is suitable for structural applications. This criterion involves utilizing a moisture measurement device; if the moisture content is below 20 percent, the timber piece is incorporated into the stock database for use in subsequent matching workflows.*

## 2.3 Timber regrading

There are numerous established concepts and methods for grading wood waste, each differing in the scale of waste they aim to classify. Some methods focus on primary separation, categorizing materials based on their usability and filtering out those with toxic effects or those more suitable for recycling than reuse. Other grading methods concentrate on evaluating specific characteristics impacting the aesthetics and structural qualities of the waste wood stock. Various techniques have been developed to assess a wood stock and determine the validity of its elements.

In the United Kingdom, the Wood Recyclers Association has defined four main categories for wood waste, according to their cost and type of testament (Ormondroyd et al., 2016). While this categorization aids in assessing the recyclability of wood demolition waste, it does not address the filtering of elements for reuse in other life cycles.

However, grading timber is one of the most important processes for assessing its structural capacity and elasticity, ensuring it can meet the required structural tasks. Without proper grading, the timber choice is not valid. To address this, both visual and machine grading methods are utilized.

### 2.3.1 Visual grading vs Machine grading

**Visual grading**

In visual stress grading, graders evaluate timber's load-bearing capacity based on standard guidelines, limited by observable characteristics. Unlike other methods, visual grading requires no fixed equipment, but relies on available timber properties and usage patterns. Standards such as BSI 1996 and 2011 accommodate timber diversity by considering species, geographic origin, dimensions, intended uses, and material quality. Graders assess defects like knots, grain slope, fissures, wane, distortion, resin and bark pockets, fungal attacks, and insect damage to assign grades or reject pieces.(Bather, 2021).

**MACHINE GRADING**

machine stress grading is used when important timber features can't be seen by eye. this method uses a bending test to measure the wood's strength over short lengths, providing more accurate results than visual grading. however, defects like wane might not show up in the machine test, so a visual check is still needed. these machines measure the wood's elasticity by applying a load with rollers, with settings adjusted for different wood types to assign a strength class immediately.

According to BS EN 519 (BSI 1995), grading machines must meet specific standards, including how they work, suitable operating conditions, maintenance instructions, calibration methods, and the types of timber they can grade. There are two types of systems: output controlled, which is best for large volumes of similar timber and requires frequent testing, and machine controlled, which is better for smaller volumes of varied timber and involves checking machine settings. Combining stress grading with other factors like density can improve accuracy (Richardson Editor, n.d.).

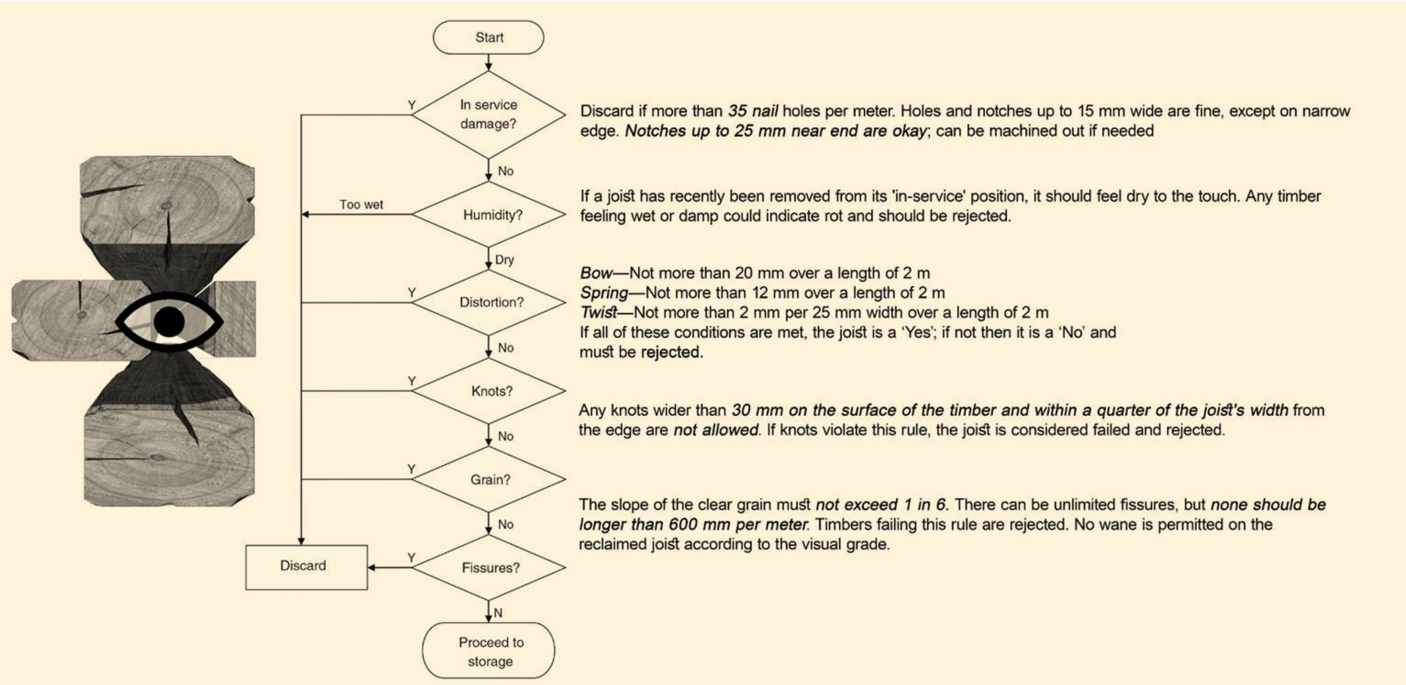



**FIGURE 16: VISUAL GRADING SOURCE :**(RICHARDSON EDITOR, N.D.)

*As mentioned in the problem statement, grading timber is crucial for increasing the use of reclaimed wood in the market. Reclaimed timber often suffers a loss in its elastic properties, making it important to determine its grade after use. Visual grading cannot adequately assess the physical and moisture conditions of the wood, nor can it determine essential values like the Modulus of Elasticity (MOE) and Modulus of Rupture (MOR), which are necessary for structural design according to Eurocode standards. Therefore, it is essential to find a grading method that accurately determines the equivalent grade of reclaimed wood. More details about this process are provided in the following chapters.*

## 2.4 TECHNOLOGIES ABOUT EVALUATING THE TIMBER

### 2.4.1 Defect Detection

Numerous literature case studies lack a comprehensive focus on integrated visual grading workflows; however, specific approaches have been developed for targeted research objectives. For instance, Jansen and Foged utilized a camera-based routine to select and position poplar shingles for a façade system, showcasing adaptation to material variations. The paper emphasizes the importance of tailored workflows in timber research, evaluating material samples using labelled zones for features like knots and grains.(Jensen & Foged, n.d.)

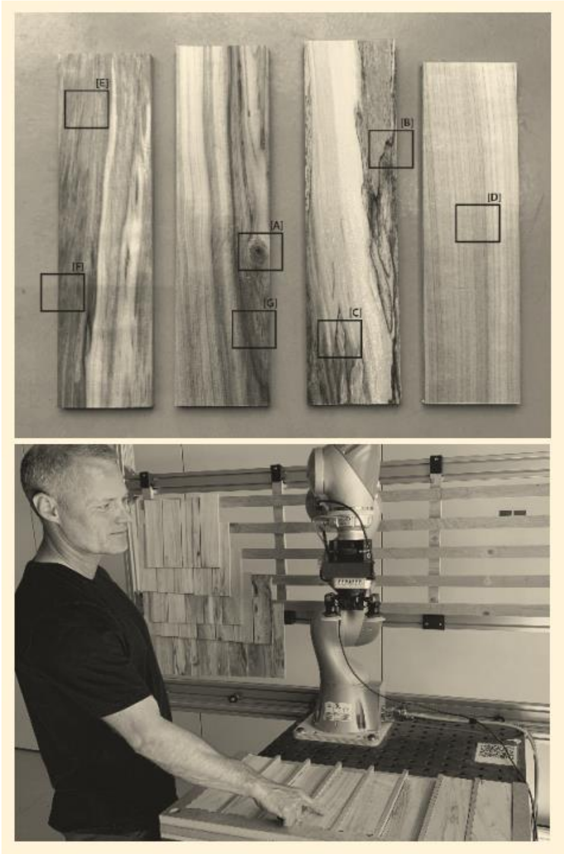



**FIGURE 17 SOURCE: (JENSEN & FOGED, N.D.)**

Another research paper focused on utilizing a deep learning algorithm to detect defects on the surface of wood. The authors modified the YOLOX algorithm, incorporating attention mechanisms, adaptive feature fusion, and different loss functions. The method claimed high accuracy and speed in detecting wood defects, with potential applications in similar surface defect detection tasks.(Li et al., 2022)

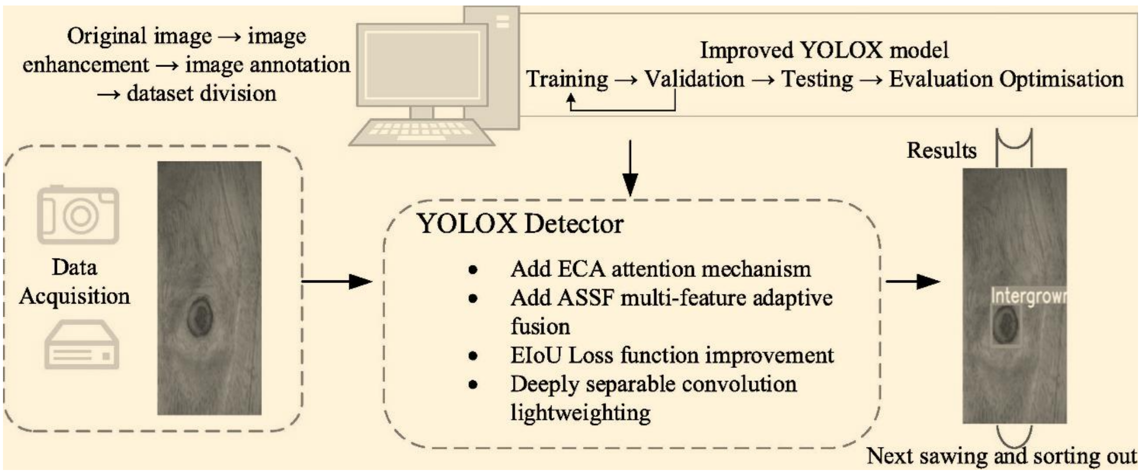



**FIGURE 18 SOURCE :** (LI ET AL., 2022)

## 2.4.2 Photogrammetry and 3d Scanning

In another context, a scanning workflow was employed to digitize reclaimed timber, resulting in a 3D material library for sustainable building design. This involved categorizing wood waste from London factory sites into waste, underused, and off-cut categories. The utilization of 3D scanning, photogrammetry, laser scanning, and analysis tools facilitated the creation of a material library, providing insights into force, structure, and porosity.(Yu & Fingrut, 2022)

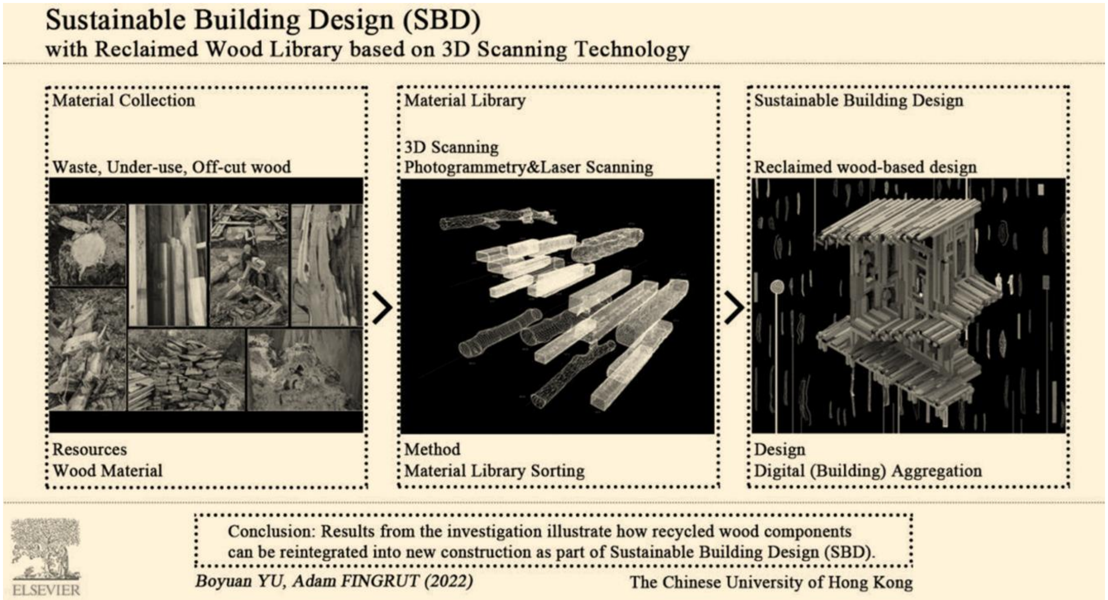



**FIGURE 19**

## 2.4.3 Wood species Detection

Research focusing on timber as a structural element also proves valuable for reclaimed timber projects. A study on classifying wood species using deep learning introduced a large dataset and compared deep learning methods with traditional ones, achieving a remarkable 98.75% accuracy. While microscopic images and lab equipment are currently necessary, the researchers aim to develop a method using macroscopic images for mobile devices, potentially aiding in preventing illegal timber trade.(de Geus et al., 2020)

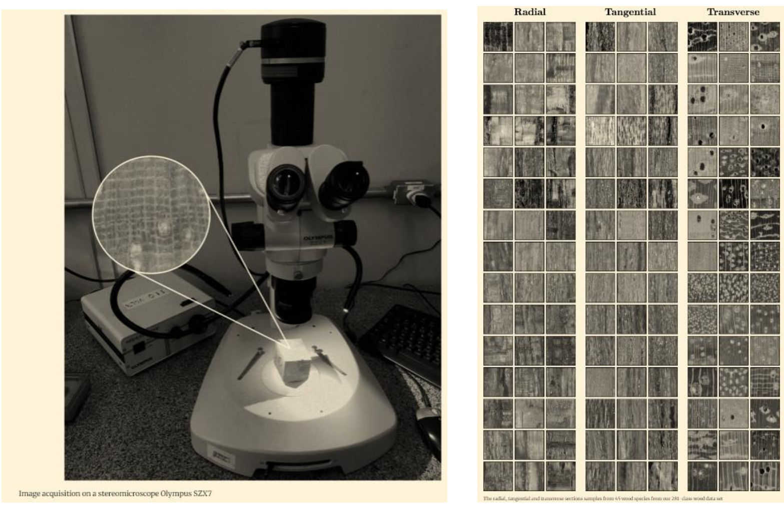



**FIGURE 20 : ML TOOL FOR WOOD SPECIE DETECTION**

### 2.4.4 Moisture Detection:

Similarly, a novel method for detecting timber moisture using sound signals and machine learning was explored, comparing different approaches. The study found that MFCC + 2D-CNN was more effective, suggesting the potential for significant improvements in timber inspection.(Yuan et al., 2021)

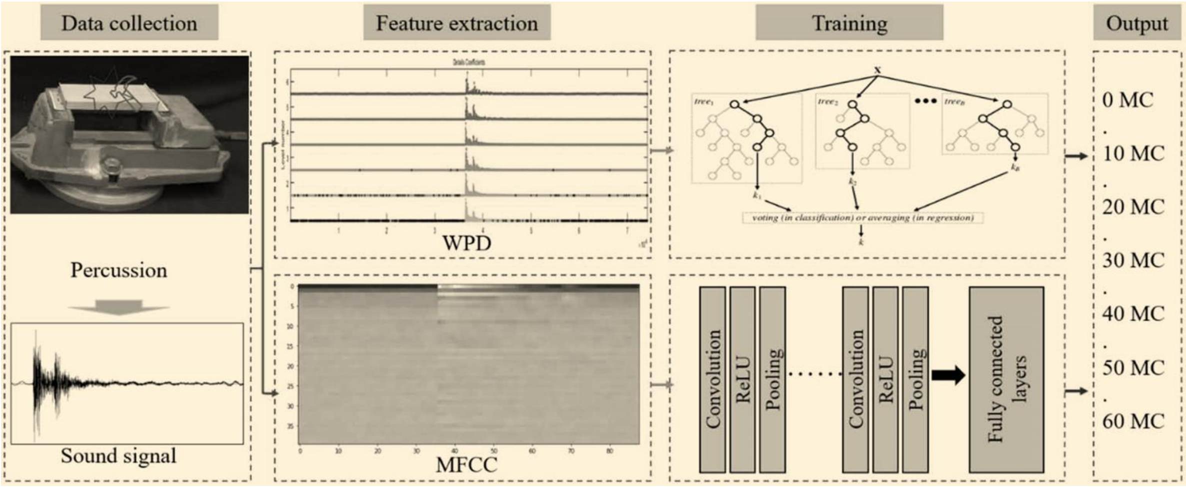



**FIGURE 21: MACHINE LEARING MODEL FOR MOISTURE CONTENT DETECTION**

### 2.4.5 Conclusion

In conclusion, this literature review underscores the significance of technologies related to visual grading, scanning, and sorting in the realm of timber research. The focus on simple techniques utilizing off-the-shelf RGB cameras or phone cameras to assess timber quality is evident. While the development of computer vision and machine learning techniques makes evaluation via smartphones increasingly feasible, there remains a gap in user-friendly tools and interfaces to translate this knowledge to a broader user base. Future developments in this area could democratize the use of these technologies in assessing and utilizing reclaimed timber resources.

## 2.5 CASE STUDIES ABOUT RECLAIMED TIMBER

Wooden structure from laminaed timber elements

Case 6: KEVN
©Superuse studio, Frank Hanswijk

The pavilion was predominantly constructed using recycled materials, with some, like the stelcon plates and steel profiles in the foundation, originating from the nearby Strijp-S. Notably, the trusses were repurposed from an old chicken shed, undergoing processing and cutting to enable the creation of purlins from the same wood.

Reusing reclaimed structural truss components

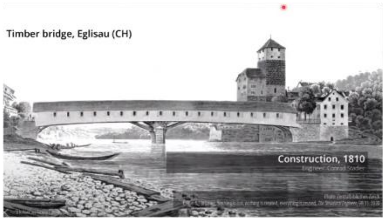
Case 7: Materials Testing Facility
©Will Perkins, Fast+Epp

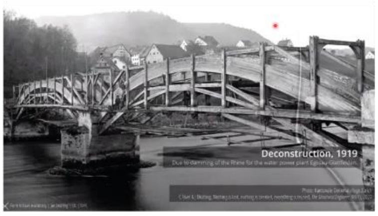
Given an unconventional directive to use recycled materials from a recently demolished warehouse, Paul Fast and the architect embarked on the project armed only with a pocket calculator, measuring tape, and a conceptual program. The resulting building's dimensions and construction method were dictated by the lengths and sizes of the available materials, including a substantial stock of glulam purlins, robust timber trusses, and tongue-and-groove decking that might otherwise have been discarded in the past.

Using a ollection of reclaimed component

Case 10: The Natural Pavilion
©abt,Noordereng Groep, DP6 architectuurstudio, Oosterhoff

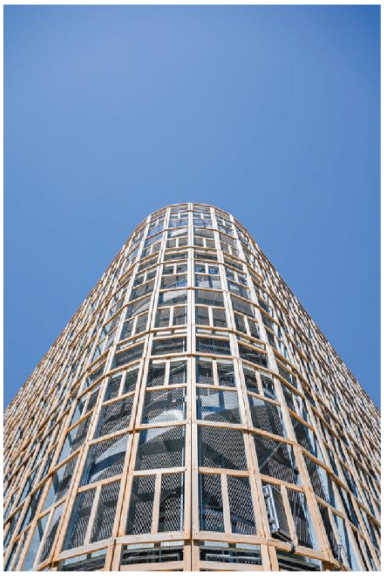
- The design begins with the intention to repurpose the entire modules in future stages of their life. The pavilion is designed for effortless disassembly and transport.
- Recycled glass sourced from a building on Koningskade in The Hague is incorporated. Additionally, the design is influenced by the available materials, with frames tailored to the dimensions of the existing glass.
- Circular window frames and walls utilize frames crafted from reclaimed Velux skylights.






Reuse timber Elements
From a Bridge 1810 to a barn 1920

In 1919, the massive oak and spruce members of a 109-year-old timber bridge in Eglisau, Switzerland, were dismantled and reassembled for the construction of a new barn nearby in Rheinau, Switzerland. The original members were well protected from moisture, and it can be assumed that their strength could safely be approximated via visual grading. Today, the barn is 100 years old, while its components are more than 200 years old.




Facade from Reclaimed timber component

Case 2: crèche Justice
©Jean Bocaeile

The building's robust oak front is constructed entirely from repurposed and converted landing doors. This wooden exterior layer imparts a feeling of unity, allowing for a play of air, light, and openness, providing both protection and a sense of porosity. The architectural character of the building, including its façade and overall structure, reflects this design approach.

Case 3: EUROPA building
©Quentin Olbrechts

The exterior is crafted from a mosaic of rejuvenated wooden window frames sourced from renovation or demolition sites across the EU nations. .

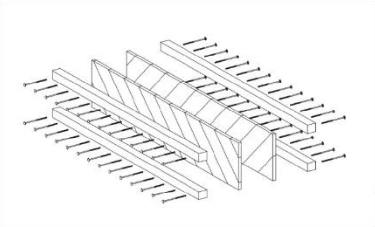

Facade system from reclaimed timber elements

Case 4: Kringloopwinkel Houten
©Arcadis

The project involved the integration of recycled building materials and items obtained through waste separation, such as stelcon plates, concrete clinkers, and salvaged wood, for the facade.

Case 5: Kaap Skil
©Mecanoo, Thijs Wolzak & Christian Richter

The front structure is made up of sawn hardwood sheet piling sourced from the Noord-Hollands Canal, featuring a distinctive roof with four peaks that mirrors the pattern of the neighboring rooftops in Oudeschild village.



Structural Component, waste wood beam

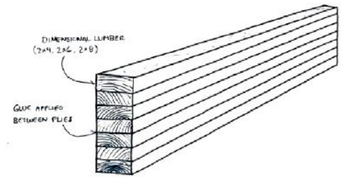
Case 9: Structural waste wood beam prototype
©Xan Browne, Olga Popovic Larsen

The structural integrity of the waste wood beam depends on the collaboration of individual short wood pieces to distribute and transmit the load to the beam support. Despite each wood piece maintaining its individuality, they work collectively to establish a seamless load path. In the event of one piece failing, the beam remains stable as long as the continuous transfer of the load is maintained.design approach.

Art installtion from reclaimed timber elements

Case 8: Re-Emerge
©Hassell, Architecture Association

Constructed utilizing wooden pallets obtained from timber recycling facilities in the London area, the building represents an investigation into material repurposing, showcasing a sophisticated construction achieved through uncomplicated gestures and minimal principles. The framework consists of structural ribs created by scoring and steam-bending the wood, connected with lap joints.




Using a ollection of reclaimed component

Case 11: Engineered Wood Products Manufactured From Reclaimed Hardwood Timber
©Daniel F. Llana, Violeta González-Alegre, María Portela, Justo García-Navarro, Guillermo Íñiguez-González

Various 3-layer CLT panel and 5-lamella glulam configurations were produced using both reclaimed and new European oak timber. Findings indicate substantial potential for manufacturing Engineered Wood Products (EWP) with recovered timber. The modulus of elasticity is comparable for CLT panels and glulam pieces from both recovered and new timber, with slightly lower bending strength in EWP from recovered timber. Despite this, the strength remains sufficient for structural applications. However, the timber yield for EWP from recovered timber is notably low due to the substantial wood waste generated during the manufacturing process.

Using salvaged CLT Panel

Case 12: Salvage swings
©Somewhere studio

Salvage Swings harnesses discarded cross-laminated timber panels to craft a delightful and welcoming summer pavilion. The structure comprises 12 repeating modules that encase individual swings, providing perspectives of the park and the surrounding city.

Waste Wood Panels

Case 13: Panles made from mixed wooden boards,
panels made from profiled baords
©NTNU social center

During a session at the NTNU social center workshop, student groups were promptly inspired by the potential of waste wood materials. They appreciated the diverse range of possibilities, evident in the resulting panels that showcase both the distinct creativity of each group and the unique characteristics of the materials.

Waste Wood Panels, human-Robot Co-creation

Case 14: A Method for Integrating Complex Material Variation in Human-Robot Co-Creation Design Processes
panels made from profiled baords
© Mads B. Jensen, Isak W. Foged

The research investigates a crucial approach to address technological, cognitive, and architectural challenges by embracing non-deterministic co-creation workflows, coupled with a greater utilization of biogenic and recycled materials.

## 2.6 PRODUCTS FROM RECLAIMED TIMBER:

Timber has been used in construction since ancient times due to its workability, availability, and strength-to-weight ratio. While traditional use of timber isn't new, innovative applications, such as cross-laminated timber (CLT), significantly enhance its properties like dimensional stability and fire safety. This highlights how advanced methods can make timber more effective. The following sections will define engineered wood products and explore the most common types and their comparative advantages.

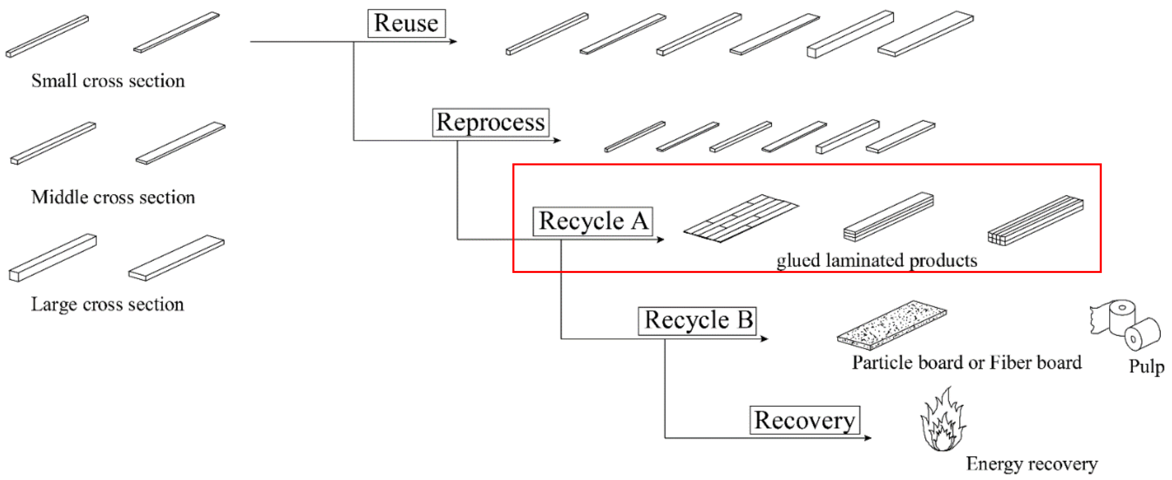



**FIGURE 22: TIMBER PRODUCT CASCADING**

### 2.6.1 Engineered timber:

An engineered wood product (EWP) is a man-made timber construction element optimized for mechanical properties and material efficiency by bonding individual timber elements into a composite unit. Common EWPs share key properties:

- starting elements (small to large timber pieces),
- connection methods (glue or mechanical fasteners like dowels and nails),
- element orientations (parallel, orthogonal, or random).

The next section will describe the most common EWP types based on these characteristics.

### 2.6.2 ENGINEERED TIMBER PRODUCTS:

Based on the characteristics mentioned earlier, the most common types of engineered wood products (EWPs) are introduced and categorized into three groups:

- General Types
- Non-Glued Types
- Structural Composite Lumber

#### *2.6.2.1 GENERAL TYPES:*

**Glue-laminated timber (glulam):** is made by gluing wooden planks together in the same direction, with thicknesses from 6 to 45 mm. Finger-jointing can extend its length up to 80 meters, though practical limits often reduce this. Patented in 1906, glulam is used today for columns, beams, headers, and trusses.

**Cross-laminated timber (CLT)** is made by gluing wooden planks orthogonally in layers of three, five, or seven. This gives CLT good dimensional stability and strength, allowing for two-way spanning. Panels can be up to 500 mm thick, 4.5 m wide, and 25 m long, and can be precisely customized. Used since the 1990s, CLT is common in structural walls, floors, and roofs.

#### *2.6.2.2NON-GLUED TYPES*

**Dowel-laminated timber (DLT)** uses dowels to connect wooden planks. Dry hardwood dowels are inserted into moist softwood planks, causing the dowels to swell and bind the planks together without glue or nails. Invented in Germany in the 1970s, DLT has lower structural performance compared to CLT.

#### *2.6.2. 3 STRUCTURAL COMPOSITE LUMBER*

**Nail-laminated timber (NLT)** is another non-glued engineered wood product where wooden planks are connected using nails. This method has been used in North America for about 150 years and doesn't need advanced machinery, often crafted by skilled carpenters, which contributes to its enduring popularity.

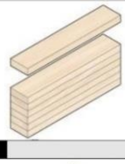
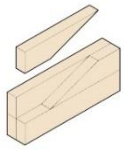
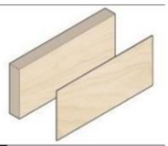
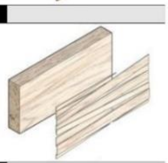
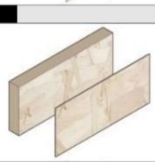
**cross-laminated timber (ICLT***)*, where interlocking planks serve as the connection method. Like DLT, ICLT is entirely timber-based, requiring no glue or nails for production. It is a newer innovation, with research and development beginning in the 2000s, limiting its current construction application compared to more established EWPs.

**Laminated Veneer Lumber (LVL)** is an engineered wood product made by bonding multiple layers of veneer, each 3 mm thick. This creates a highly homogeneous material with increased strength and stiffness. Any defects in the original veneer are minimized by the large number of layers surrounding them. LVL is typically glued parallel to the grain for strength, but crosswise veneers enhance dimensional stability. Invented in the 1970s in North America, LVL is now widely used in various construction applications, including beams, columns, floors, and walls.

**Parallel-strand lumber (PSL)** is another type of structural composite lumber where veneer strips are glued together in parallel. These strips, typically up to 15 mm wide and 2.5 m long, are smaller than those used in Laminated Veneer Lumber (LVL). PSL veneer strips are often leftover materials from LVL production, making efficient use of resources. PSL products offer high strength and consistent performance, similar to LVL, making them suitable for large span structures.

**Laminated Strand Lumber (LSL),** also known as Oriented Strand Lumber (OSL), is similar to PSL, as it involves bonding smaller timber elements to form a larger product. However, LSL uses smaller wooden strands, often leftover from timber manufacturing, and their orientation can be parallel, orthogonal, or random. While LSL typically has less strength than PSL, it is more cost-effective to produce. A common example of LSL is oriented strand board.

### TABLE 1: ENGINEERED WOOD PRODUCT

| Product: | Starting element: | Element connection method: | Element orientation: | Image: † |
|---|---|---|---|---|
| | | General types: | | |
| Glulam | Wooden planks | Glue | Parallel |  |
| CLT | Wooden planks | Glue | Orthogonal |  |
| IGST | Wooden planks | GLUE | Parallel Orthogonal |  |
| | | Non-glued types: | | |
| DLT | Wooden planks | Dowels | Parallel Orthogonal |  |
| NLT | Wooden planks | Nails | Parallel Orthogonal |  |
| | | Structural Composite Lumber types: | | |
| LVL | Veneers | Glue | Parallel Orthogonal |  |
| PSL | Wooden strands | Glue | Parallel |  |
| LSL | Wooden strands | Glue | Parallel Orthogonal Random |  |

2.6.3 A table that shows the Engineered wood products with the span linear beam span indicator

## 2.6.4 Interlocking solid glued timber

Interlocking Glued-Strip Timber (IGST) utilizes standard-sized solid timber joists as building blocks, glued together in overlapping patterns to create large-scale engineered wood members. These elements are glued in two dimensions: first on the xy planes to form layers, and then along the xz plane to assemble the layers into a complete element. Unlike glulam and CLT, IGST does not rely on finger joints; instead, it employs simple diagonal cuts to bond adjoining elements. The specific type of cut described in the paper involves a 4:1 slope across the x-z axes, but variations in cut types and orientations are possible(Patlakas et al., 2019b).

According to the researcher who developed these novel technique, they reasoned the importance of this technique due to the following reasons:
1- IGST utilizes standard softwood joists with larger cross-section sizes, requiring fewer glued interfaces, leading to cost savings and reduced manufacturing time.

2- Unlike finger joints found in other engineered wood products like glulam and CLT, which can weaken highly stressed areas, the overlapping of IGST members provides strength across the entire length without introducing weak points.
3- The use of standard softwood joists offers inventory flexibility to manufacturers, as these elements can be readily sourced from standard stock and sold independently if needed.

The choice of this technique for research, involving the use of reclaimed timber as a material, is based on several factors:

1. The simplicity of the technique makes it cost-efficient and doesn't require complex carpentry skills, making it suitable for utilizing reclaimed timber economically.
2. The aggregation of joists from pieces of different lengths offers the opportunity to incorporate varying lengths into the design, as well as the possibility of using different cross-sections without additional sawing.
3. Previous research by Patlakas et al. (2019a) demonstrated improved structural performance compared to parallel joists. Therefore, it is worth exploring whether this enhanced performance can compensate for the strength loss often observed in reclaimed timber.

### 2.6.4.1 Topological exploration:

to easily understand the anatomy of the igst, we can say it consists of parallelly glued joists in both the xy and zx planes (which could be considered partially as glulam), interrupted by diagonal cuts in the yz plane. These diagonal cuts could be considered as inner splayed plain scarf joints. By assuming this, we can conduct more thorough research regarding these two characteristics to unlock the potential of this product.
Based on the previous assumptions, to design and verify the igst beam, the rules of thumb for the sls (serviceability limit state) and uls (ultimate limit state) mentioned in "the glulam handbook - volume 2" could be used for verification.

### 2.6.4.2 ULS verifications:

**We calculate the load with the safety factor**

a) Compression perpendicular to the grain

$$N_{\mathrm{Ed}} = q_{\mathrm{dII}} \times \frac{l_{\mathrm{tot}}}{2}$$

$N_{\mathrm{Ed}}$: *design force*

$q_{\mathrm{dII}}$: *design load per unit*

$l_{\mathrm{tot}}$: *total length*

$$\sigma_{\mathrm{c,90,d}} = \frac{N_{\mathrm{Ed}}}{b \times l_{\mathrm{support}}}$$

$\sigma_{\mathrm{c,90,d}}$: The design value of compressive stress perpendicular to the grain

$$\frac{\sigma_{\mathrm{c,90,d}}}{f_{\mathrm{c,90,d}} \times k_{\mathrm{c,90}}} < 1 \text{ OK}$$

$f_{\mathrm{c,90,d}}$: The design compressive strength perpendicular to the grain

$k_{\mathrm{c,90}}$: A modification factor that accounts for specific conditions such as duration of load

b) Shear

$$V_{\mathrm{Ed}} = q_{\mathrm{dII}} \times \frac{l_{\mathrm{tot}}}{2}$$

$$V_{\mathrm{red}} = \frac{2 \times V_{\mathrm{Ed}}}{l_{\mathrm{tot}}} \times \left(\frac{l_{\mathrm{tot}}}{2} - \frac{b_{\mathrm{support}}}{2} - h\right)$$

$$\tau = \frac{3 \times V_{\mathrm{red}}}{2 \times b \times h}$$

$V_{\mathrm{Ed}}$: The design value of the shear force

$V_{\mathrm{red}}$ : The reduced shear force, which is the design shear force

$\tau$: The shear stress

c) Bending moment

>>>

$$M_{\mathrm{Ed}} = q_{\mathrm{dII}} \times \frac{l_{\mathrm{tot}}^2}{8}$$

$$\sigma_{\mathrm{m,d}} = \frac{6 \times M_{\mathrm{Ed}}}{b \times h^2}$$

≫

$$\frac{\sigma_{\mathrm{m,d}}}{f_{\mathrm{m,d}} \times k_{\mathrm{h}}} < 1\text{: OK}$$

$M_{\mathrm{Ed}}$: Design value of the bending moment.

$\sigma_{\mathrm{m,d}}$: is the calculated design bending stress.

$f_{\mathrm{m,d}}$: is the material's design bending strength.

$k_{\mathrm{h}}$: is a modification factor adjusting the bending strength based on various conditions

### 2.6.4.3 SLS verifications

**Calculate row different SLS loads (permeant and variable) factored with the safety values**

| | |
|---|---|
| $w_{inst}$ | Instantaneous deflection. |
| $w_{creep}$ | Deflection due to creep:<br>$w_{creep,p} = k_{def} \times w_{inst}$ due to permanent load.<br>$w_{creep,v} = \psi_2 \times k_{def} \times w_{inst}$ due to variable load. |
| $w_c$ | Possible precamber. |
| $w_{fin}$ | Final deflection:<br>$w_{fin} = w_{inst} + \Sigma\, w_{creep,i}$ |
| $w_{net,fin}$ | Total net deflection:<br>$w_{net,fin} = w_{fin} - w_c$ |

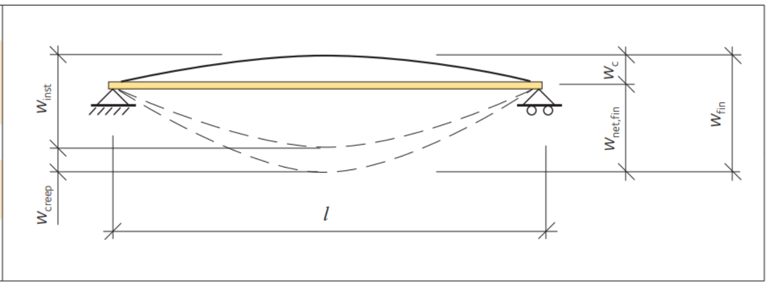



**FIGURE 23: SLS RULE OF THUMBS**

a) Deflection

Verify the figure for instantaneous deflection

$$w_{\text{inst,permanent}} + w_{\text{inst, variable}} < \frac{l_{\text{tot}}}{500}: \text{OK}$$

Final deflection due to permanent load

$$w_{\text{inst,permanent}} + w_{\text{inst, variable}} < \frac{l_{\text{tot}}}{300}: \text{OK}$$

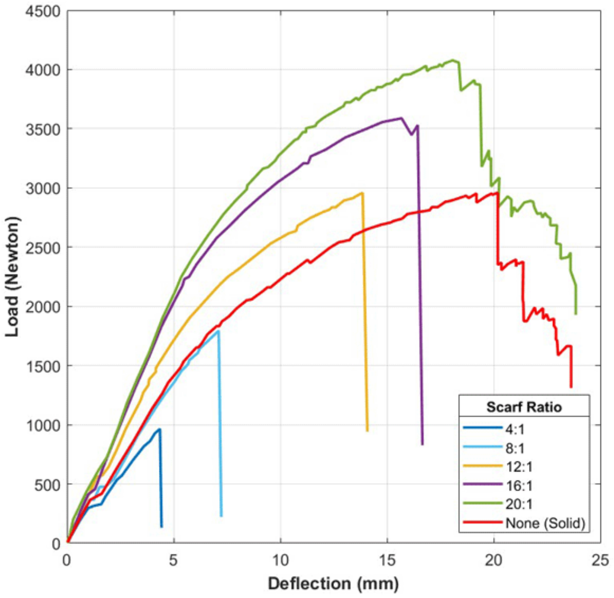
### 2.6.4.3 Regarding The Angle of The Splayed Scarf Joint:

Scarf joints are fundamental in woodworking, offering variations like feathered, tabbed, and hooked types for seamless timber joining. Understanding how altering the angle of these joints impacts the flexibility of interlocking glued solid joists is essential. Historical data indicates that higher scarf ratios typically strengthen joints, though they may introduce weak points under localized stresses.

Research on scarf joint slope in boat carpentry(*The Strength of Scarf Joints | Wooden Boat*, n.d.) shows that higher scarf ratios (12:1, 16:1, 20:1) provide greater resistance and higher modulus of elasticity than solid timber, allowing them to carry more load with less deflection. In contrast, smaller scarf ratios (4:1, 8:1) exhibit lower resistance compared to solid timber.

Additionally, solid timber demonstrates superior deflection capabilities before ultimate failure, despite carrying less load than high-ratio scarf joints.

Those findings, along with the results of the first phase tests conducted earlier (further explained in subsequent chapters), indicate that delamination of the inner scarf joint poses a significant challenge, especially when combining two species of timber. This raises the question of whether higher slope ratios result in increased waste. Developing methods to utilize this excess waste for other products could provide a comprehensive solution. Further research, supported by Life Cycle Assessment (LCA), is necessary to determine the optimal use of this waste and its impact on the overall product's carbon footprint.




| Mechanical Properties | | Ultimate Flexural Strength (MPa) | Young's Modulus (MPa) |
|---|---|---|---|
| ABS Yachts (2017) | | 66.00 | 10,000 |
| ISO 12215-5 (2019) | | 77.00 | 12,060 |
| Experimental | Solid Timber | 73.51 | 11,980 |
| | 4:1 Scarf | 18.28 | 8,045 |
| | 8:1 Scarf | 38.86 | 10,270 |
| | 12:1 Scarf | 48.72 | 12,379 |
| | 16:1 Scarf | 93.43 | 14,486 |
| | 20:1 Scarf | 96.11 | 15,250 |

**TABLE 2:SCARF JOINT ULTIMATE FLEXURAL STRENGTH**

## 2.7 Optimization and Matching Algorithm

### 2.7.1 Available Matching Methods

despite the contemporary examples showcasing material reuse in design and construction, such practices are not yet the norm in the industry. The challenges associated with working with existing, often irregular material resources contribute to this reluctance. Architects and engineers, when opting for material reuse, face the task of designing within the constraints of a limited and varied inventory, requiring time, creativity, and flexibility.

To address these challenges, computational methods have emerged as a response, offering automation to assist in designing with fixed material inventories. These methods, already common in architectural design for non-reuse cases, include parametric design space exploration and rule- or grammar-based design approaches.

**TABLE 3**

| Algorithm | Best- Fit | MILP | Hungarian Algorithm |
|---|---|---|---|
| Definition | A heuristic technique that involves finding the best assignment of either reused or new elements to each member position in the structure, subject to element length and capacity constraints | A mathematical optimization technique that involves finding the optimal values of some variables, subject to linear constraints, where some of the variables are restricted to be integer | A combinatorial optimization algorithm that can find the best way to assign a set of tasks to a set of workers, minimizing the total cost or maximizing the total benefit. |
| Pros | This method can produce **fast and interactive solutions** with slightly higher impact than MILP. It is suitable for early conceptual design stages and large-scale problems | This method can produce **globally optimal solutions** in terms of environmental impact and consider serviceability limit states. | **It is** efficient **and can solve the linear assignment problem to global optimality in polynomial time1.** **It is** flexible **and can be used in a modular and iterative design workflow.** |
| cons | it cannot account for serviceability limit states and may not find the global optimum. | it requires **significant computation time** and may not be efficient for large-scale problems. | It does not guarantee global optimality in terms of structural capacity, since it uses penalties instead of hard constraints. member. It requires a pre-defined cost matrix that encodes the geometric and structural compatibility of the inventory and target elements. |

| | | | |
|---|---|---|---|
| Usage | This method is best used when you need a fast and interactive solution, especially in the early conceptual design stages or for large-scale problems. It's a heuristic that can produce near-optimal solutions quickly, but it does not account for serviceability limit states and may not find the global optimum. | This method is best used when you need a globally optimal solution and when serviceability limit states need to be considered. It's particularly useful when the problem size is not too large, as MILP can be computationally expensive and time-consuming for large-scale problems. | Can provide a tool for designers so they can discover layouts that meet important performance goal, it is more relaxed than MILP as well as more accurate than best-fit algorithm |
| support | Needs Genetic Solver to reach the optimal global solution | | Needs to set up the cost matrix to have a proper optimal solution |
| tools | Phoenix | Phoenix | A collection of codes |
| reference | (Behnejad et al., 2021) | (Behnejad et al., 2021) | (Huang et al., n.d.) |

### 2.7.2 MILP Example:

The article proposes two computational methods for this task: one for designing structures from a stock of available elements, and another for designing a stock of elements that can be used as a kit of parts to build diverse structures. The article also demonstrates the potential environmental benefits of designing structures through reuse.

- The research proposes two computational methods for designing structures through reuse of elements: assignment and topology optimization (P) and stock optimization (S).
- Both methods are formulated as mixed-integer linear programs (MILP) that can be solved to global optimality using branch-and-bound techniques.
- The methods also include structural and geometric optimization techniques to improve the design performance and reduce the cut-off waste of the reused elements.

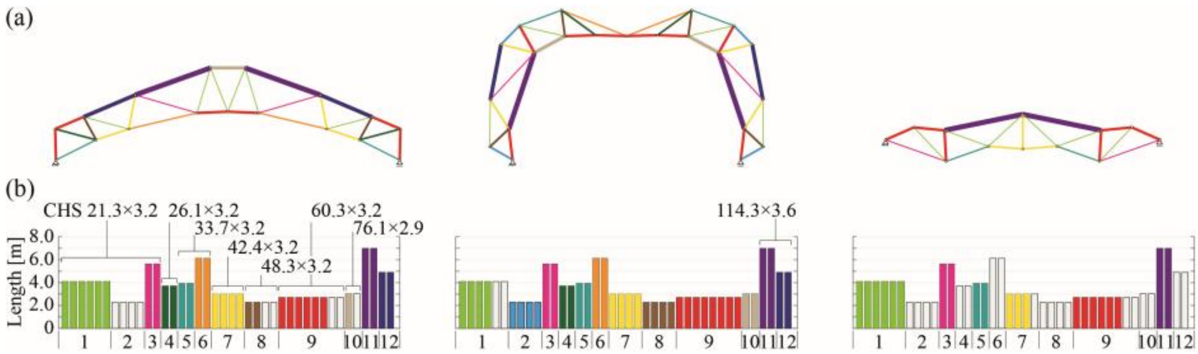



**FIGURE 24: SOURCE (BRÜTTING ET AL., 2019)**

### 2.7.3 Best-Fit Algorithm:

The article presents a new computational workflow for the design of spatial reticular structures made of reused and new components, based on the combination of Combinatorial Equilibrium Modeling (CEM) and Best-Fit heuristics.

Notes from the research:

- The heuristic method combines Combinatorial Equilibrium Modeling, Finite Element Analysis, and Best-Fit heuristics to design structures from reused and new elements.

- The heuristic method allows fast and interactive exploration of different structural configurations and provides feedback on the structure environmental impact.

- The heuristic method shows that structures made of reused and new elements have significantly lower environmental impact than structures made of new elements only.

- The heuristic method can be adapted to different objectives, such as structure mass or cut-off waste minimization, and different element stocks and cross-sections.

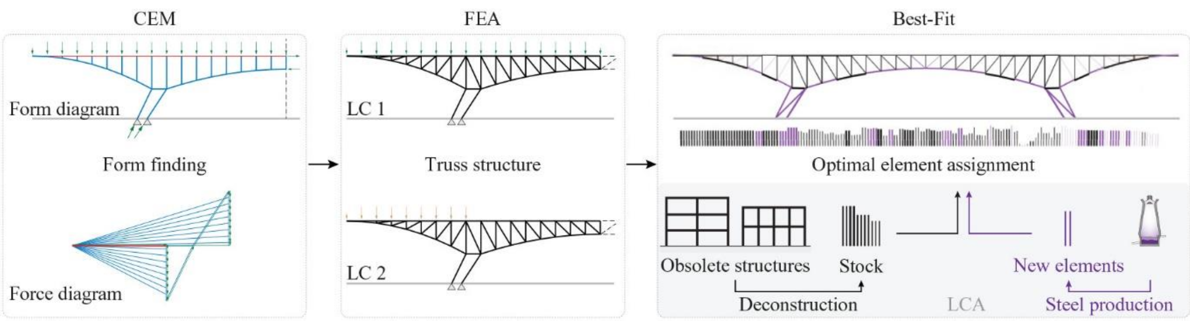



**FIGURE 25: SOURCE(BRÜTTING ET AL., 2021)**

### 2.7.4 Hungarian algorithm:

The paper proposes a method and a tool that can match existing material elements from a stock inventory to a target design, considering both geometric fit and structural capacity. The paper demonstrates the method and the tool on a case study of designing geodesic domes with linear timber elements from a conventional house. The paper also compares different algorithmic formulations for the material reuse problem and discusses the advantages and disadvantages of each.

- Inventory processing: Creating a digital model of the existing material to be reused.
- Cost matrix computation: Comparing each element in the target design with each element in the inventory, and calculating a cost measure1.
- Optimal matching algorithm: Finding the optimal assignment of inventory elements to target elements using the Hungarian Algorithm.

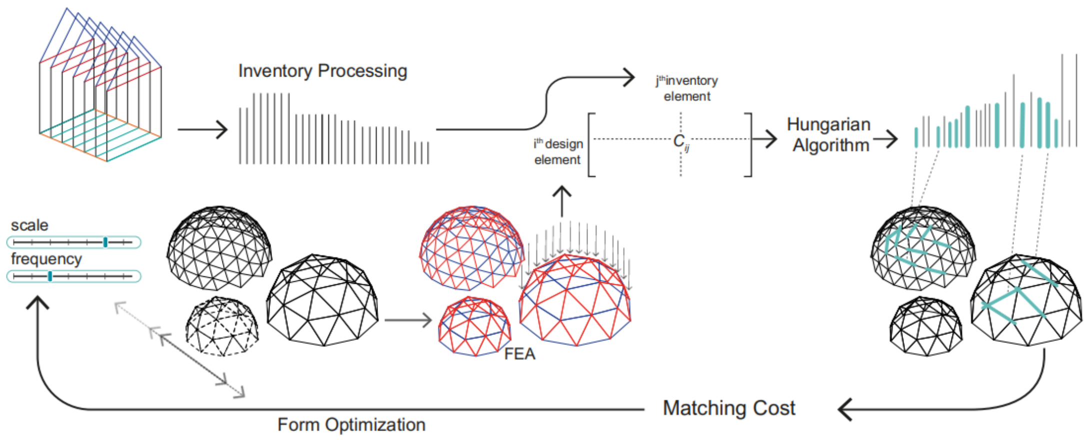



**FIGURE 26**

- Parametric design model and optimization: Creating a flexible design model linked to structural analysis and life-cycle assessment, and finding the best configuration of domes that meets different performance criteria.

Photo content: Material reuse workflow conceptual overview

## 2.8 Life cycle assessment methods:

### 2.8.1 How to perform LCA calculation?

according to(Brütting et al., 2020) to calculate the EI of the structure, the process starts from defining the cost of sourcing an element that has been assigned to a position in the structure, and to install it, like this the main objectives for our LCA optimization is to minimize the EI for all the element along the whole process, the Ei of the structure needs an attributional model LCA, this kind of models is set to fit all process needed to make the structure represented by the flows of matter and energy.

### 2.8.2 Scope and Goal:

the environmental impacts of any chosen element is the sum of all the processes needed to use the element, Each process is defined by a specific functional unit, such as surface area for sandblasting, and its environmental impact is expressed as a single score using the ReCiPe Endpoint method. This method combines 18 mid-point indicators, like particulate matter and global warming, into three end-point indicators: damage to human health, ecosystems, and resource availability(Goedkoop et al., 2009). The assessment spans from sourcing materials from an old structure to assembling the optimized component on a new site, excluding impacts after assembly. Unlike traditional assessments, this one includes the deconstruction or demolition of the old building to reclaim elements or scrap materials, allowing for a thorough comparison between 'New' and 'Reuse' cases.

### 2.8.3 Material flow chart:

The flowchart in the figure bellow outlines the material flow analysis (MFA) and the system boundary for this study's inventory of processes. The MFA encompasses all processes and material flows considered in the Life Cycle Assessment (LCA), sourced from various technical reports and publications. It distinguishes between 'New' and 'Reuse' cases. In the 'New' scenario, new members are produced from newly sawn timber it includes Cutting the wood, preparing it, and loading. while in the 'Reuse' scenario, deconstruction tasks include collecting, cleaning , sorting and re-grading Both cases involve transportation to a fabrication workshop for assembly into Interlocking laminated Timber, with unused elements not contributing to the component’s environmental impact. Each process in the MFA has an inventory of resources and emissions, created using LCA software and data from the Ecoinvent database.

## 2.8.4 LCA processes and System boundary

### 2.8.4.1 IMPACT ASSESSMENT:

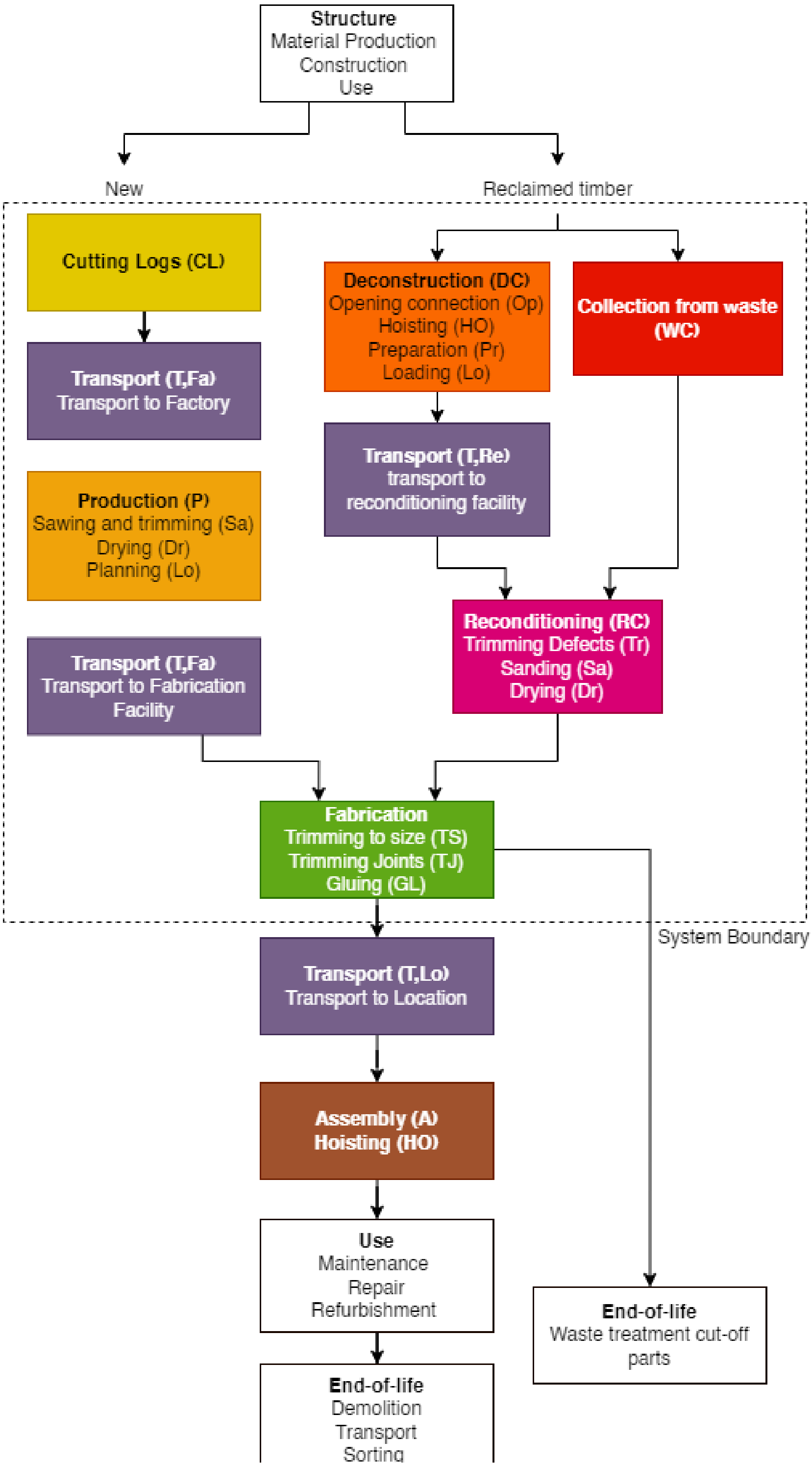



**FIGURE 27: MATERIAL FLOW (OWN WORK )**

**TABLE 4**

| | Process code | Process name | Metric | EIpro in 10^-3 *ReCiPe points/ metrics | Data source |
|---|---|---|---|---|---|
| **Cutting Logs** | CL | cutting | To be filled | | |
| **Production** | Pr | Total | | | |
| | Sa | Sawing and trimming | | | |
| | Dr | Drying | | | |
| | Pl | Planning | | | |
| **Deconstruction** | DC | Total | | | |
| | OP | opening | | | |
| | HO | Hoisting | | | |
| | PR | Preparing | | | |
| | LO | Loading | | | |
| **Reconditioning** | RC | Total | | | |
| | TR | Trimming | | | |
| | SA | Sanding | | | |
| | DR | Drying | | | |
| **Fabrication** | F | Total | | | |
| | TJ | Trimming joint | | | |
| | TS | Trimming to size | | | |
| | GL | Gluing | | | |
| **Collection from waste** | WA | Total | | | |
| **Assembly** | A | Total | | | |
| | HO | Hoisting | | | |
| **Transport** | T | Transport | | | |

evaluating the environmental impact (EI) of various processes involved in a project. Table 1 shows the EI Pro factors in ReCiPe points for processes outlined in Figure 3. The cost (c_j) in Equation (3) represents the environmental impact (EI_j) for reusing stock element (j) and includes impacts from sourcing, deconstruction, reconditioning, and transportation.

For instance, the environmental impact of deconstructing element (j) is determined by multiplying its mass (material density pj, cross-section area aj, and length lj) by the deconstruction impact factor (EI_DC).

The total environmental impact (EI_i,j) of using element (j) at position (i) in the beam considers impacts related to demolition, new element production, fabrication, assembly, and intermediate transport for new elements. For reclaimed elements, impacts related to sourcing are already included, so only fabrication, transport to site, assembly, and transport of waste are considered.

Fabrication impacts are consistent regardless of the element source and are calculated based on factors like sanding per surface area and assembly impacts relate to the final mass of the structure.

### 2.8.5.Conclusion of literature review:

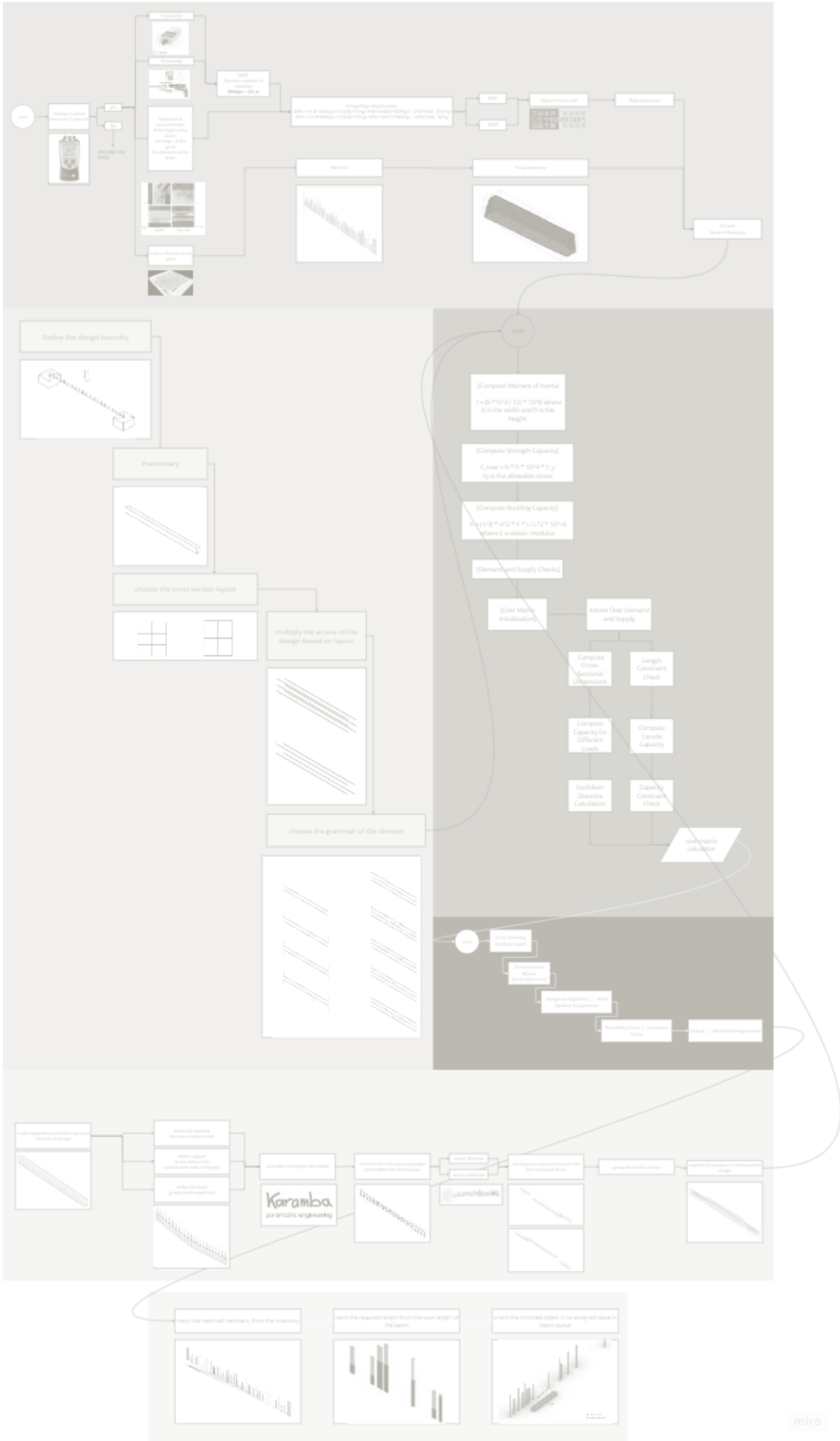
The topics discussed in this paper demonstrate that over the last two decades, numerous studies have been conducted on timber as a material and techniques that can enhance the applicability of reclaimed timber for structural engineers and designers.

The aim of this research is to create interlocking laminated solid timber from reclaimed stock as a solution to several questions. These questions include how grading new timber will affect the future of reclaimed timber, what the best use of reclaimed timber might be to compensate for potential downgrading, and what manufacturing techniques ensure better structural behaviour. The literature review's objective was to gather essential information for designing such structural components. This included methods for regrading and classifying recovered timber elements, ranging from basic human inspection to computer vision and machine learning techniques. The paper highlights the need for a tool that can integrate all necessary evaluation methods, from initial assessment to design. It explains various workflows to incorporate reclaimed timber into designs computationally, optimizing structures to maximize strength and minimize environmental impact. Additionally, the paper proposes a scientific method for calculating the environmental impact of using materials from different sources, based on theoretical and technical approaches.

# WORKFLOW PROGRESSION: FROM DESIGN TO RESULTS

# تقدم سير العمل: من التصميم إلى النتائج

# 3. WORKFLOW PROGRESSION: FROM STOCK TO DESIGN



## 3.1 Design Constraints to Design Layout

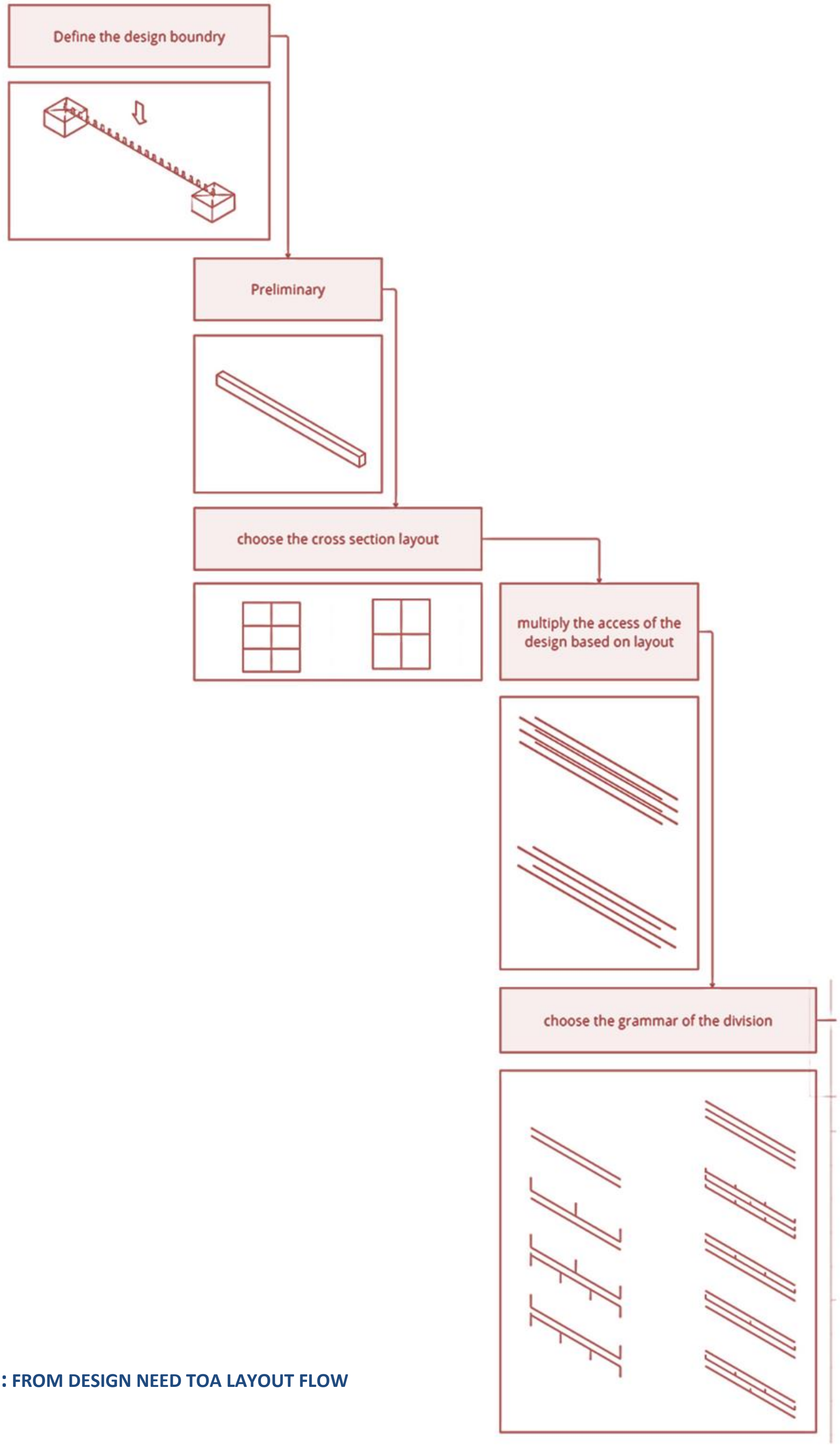



**FIGURE 28: FROM DESIGN NEED TOA LAYOUT FLOW CHART**

The initial step in starting the workflow is to establish the primary constraint, which involves defining the span of the required joist and estimating the load it needs to support.

A- With this information in hand, we can employ preliminary sizing techniques to provide a rough estimation of the required section dimensions using rule-of-thumb calculations.

B- Next, based on the rough section estimate, we introduce the first design parameter: the array of elements. This parameter depends mainly on the available section dimensions within the timber stocks. Currently, two layouts have been defined: a 2x2 grid or a 2x3 grid, with the potential for expansion as needed.

C- Once the basic section layout is defined, we generate a bundle of lines to represent the centres of the demanded pieces spatially, aiding further steps in the process.

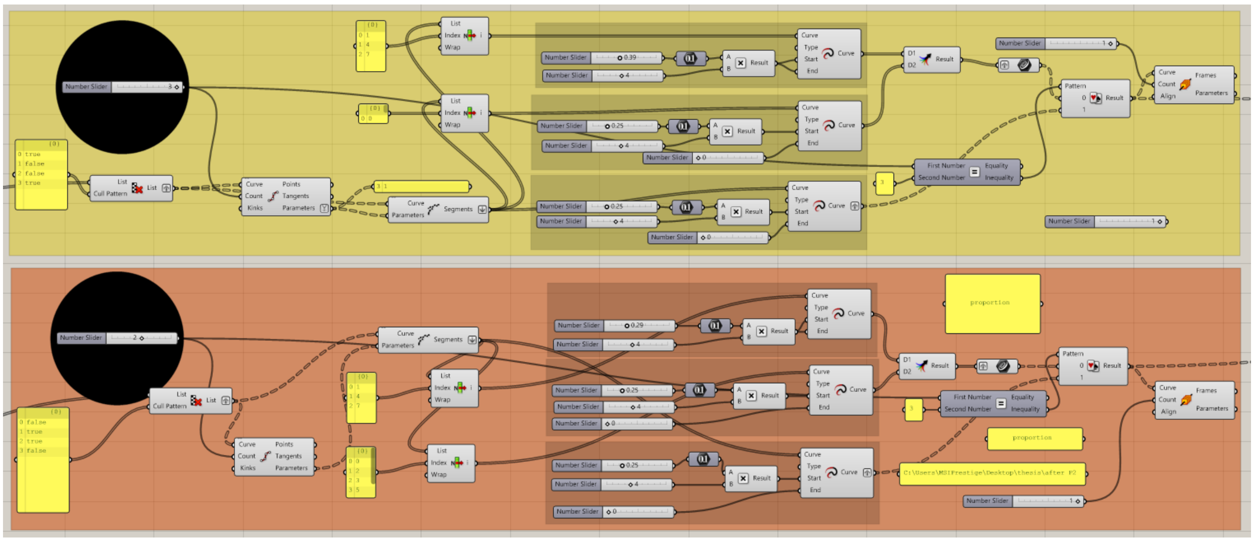


**FIGURE 29: GRASSHOPPER SNIPPET FROM DIVIDING THE LAMELLA (OWN WORK )**

D- Given that the focus of the research is on maximizing the utilization of timber stocks in the design, we presume a variety of lengths are available in the stocks. Additionally, to create the interlocking solid glued joist, a slash cut is already included along the joist section to prevent weak spots along the beam. Thus, to reinforce the alternation between the slashed and un-slashed joists and achieve the interlocking effect, we devise a division grammar. The concept is simple: by implementing at least two distinct length divisions, we ensure the staggering of the pieces within the beam.

To simplify this process, we define three division proportions: 1, 1:2, and 1:3. Then, we cluster the lines within the bundles into two groups. Diagonally adjacent neighbours are combined into one group and assigned a division proportion, while the remaining elements are grouped separately and assigned another division proportion. This ensures that each element within the grid has a different division ratio compared to its

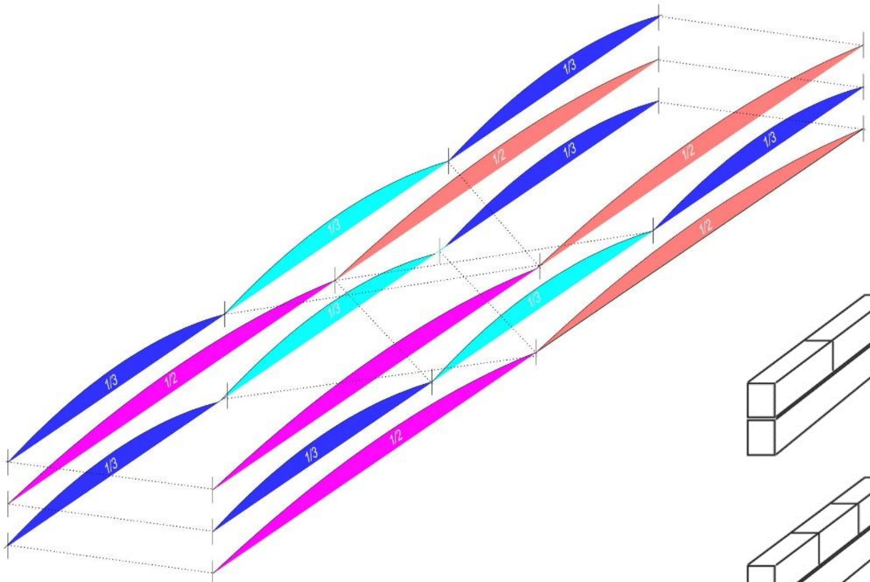


**FIGURE 31:ALTERNATING BETWEEN DIVISIONS RATIOS (OWN WORK )**

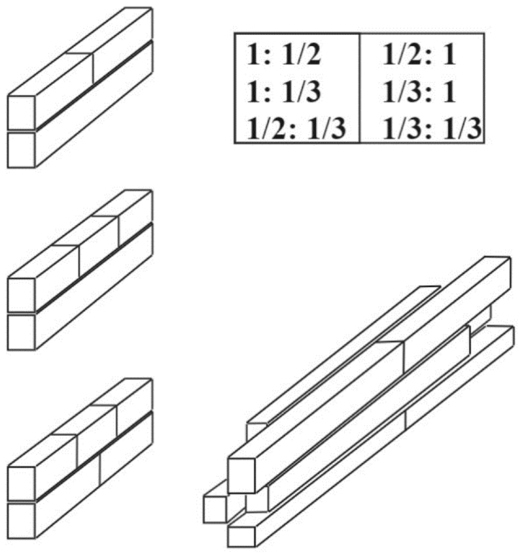



**FIGURE 30 DIVISIONS COMBINATIONS (OWN WORK)**

## 3.2 Design Layout to Structural Layout

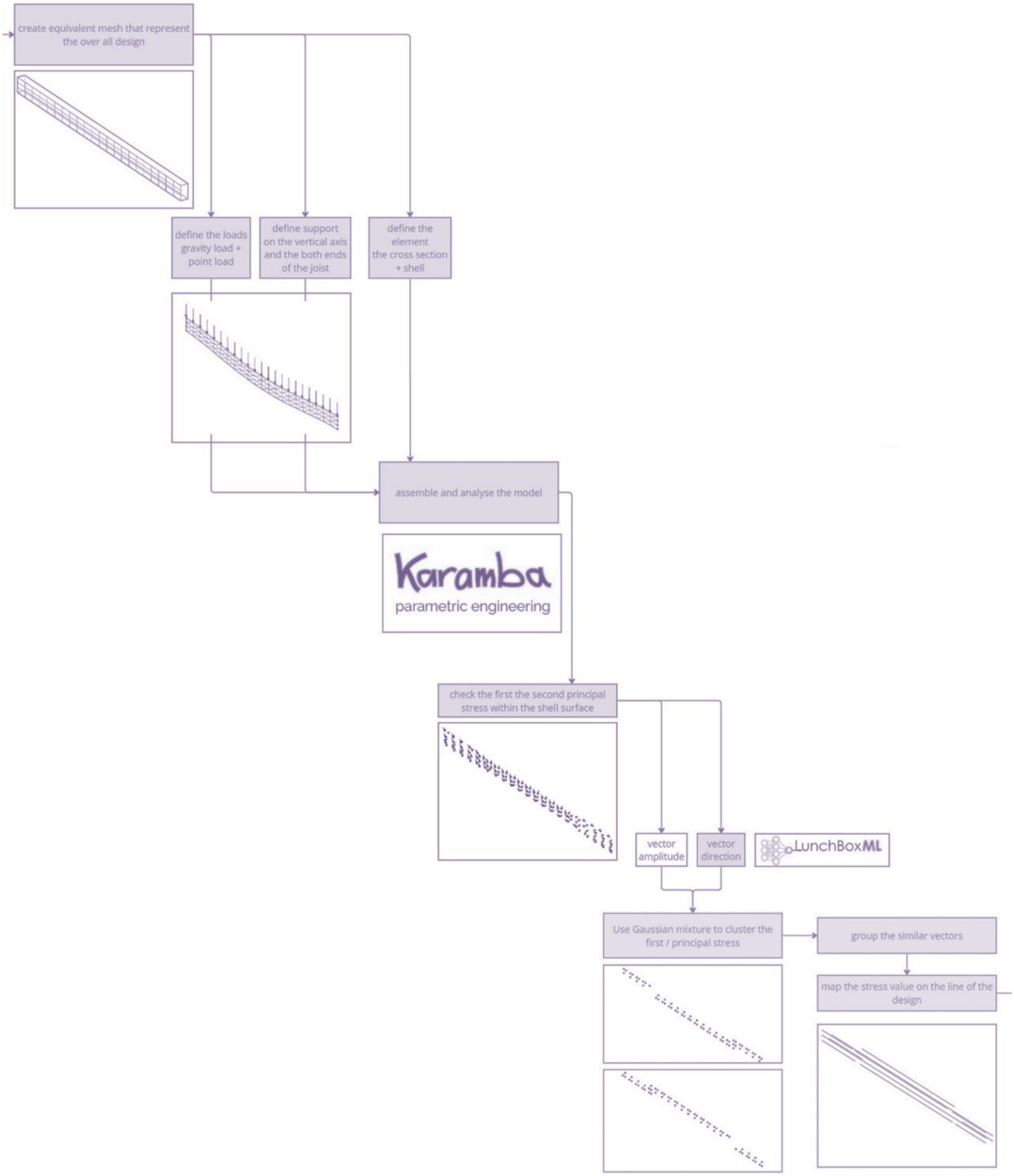



**FIGURE 32 STRUCTURAL ANALYSIS FLOWCHART (OWN WORK )**

Commencing from the linear layout derived from the previous flowchart, this subsequent flowchart endeavours to ascertain the structural demand of each piece constituting the requisite beam.

A- To achieve this objective, it is imperative to assess how forces will be distributed throughout the overall assembly. As a preliminary step, a bounding box encompassing all generated lines is established.

B- In order to evaluate force distribution, scrutiny is directed towards a segment of the beam. Given the spatial layout, Finite Element Analysis (FEA) for a shell is deemed more appropriate. Consequently, the vertical surface of the bounding box is extracted and converted into a mesh with the same number of horizontal rows as the count of joist lamellas, which in the provided image is 3.

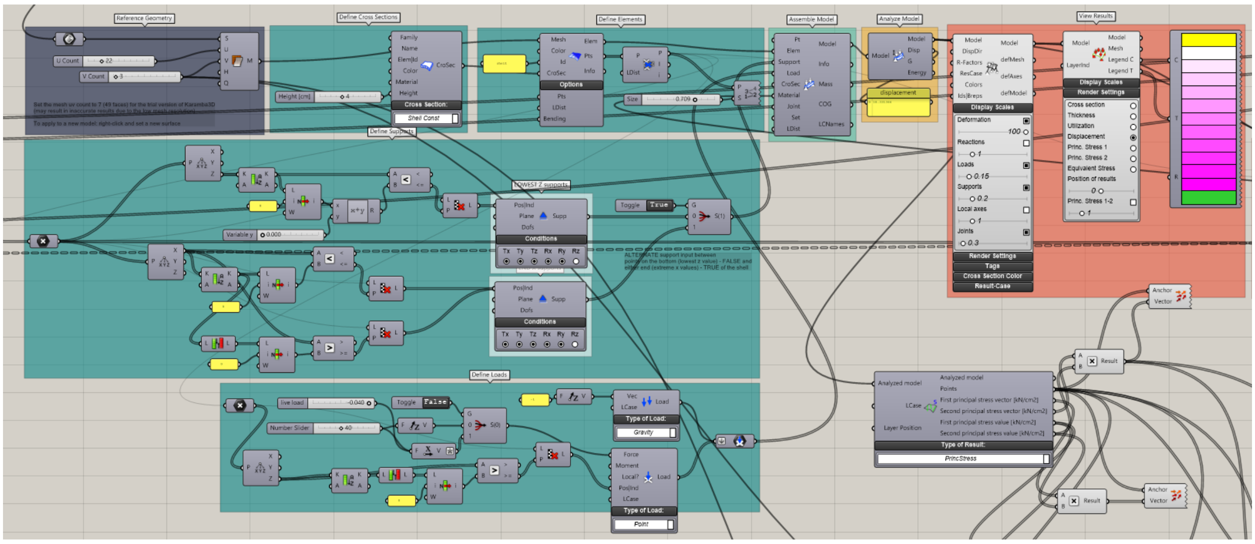



**FIGURE 33: SNIPPET FOR KA()RAMB GRASSHOPPER DEFINITION (OWN WORK)**

Subsequently, loads, supports, and material properties are defined utilizing the Karamba Plugin:

The load comprises gravity load and design load (expressed as point load).

Support at both ends entails a fixed connection.

The material is specified as wood.

By executing these steps, the Karamba model is assembled.

C- A stress analysis within the shell component is then conducted to assess stress values at each cell of the mesh. The outcome of this analysis comprises the first and second principal stresses, both as scalar values and vectors.

D- Once these values are obtained, they are discretized to align with the elements of the design. To facilitate this process, a simple machine learning technique known as Gaussian Mixture is employed. A matrix encompassing vector direction and amplitude is inputted into the component, which is subsequently tasked with categorizing the results into two groups. The rationale behind this categorization is to discern how to integrate the beams utilizing hard timber and soft timber.

E- The outcome of the preceding step yields two groups of points, each characterized by similar stress values and identical vector angle positions. Subsequently, these values are approximately matched with the line's layout.

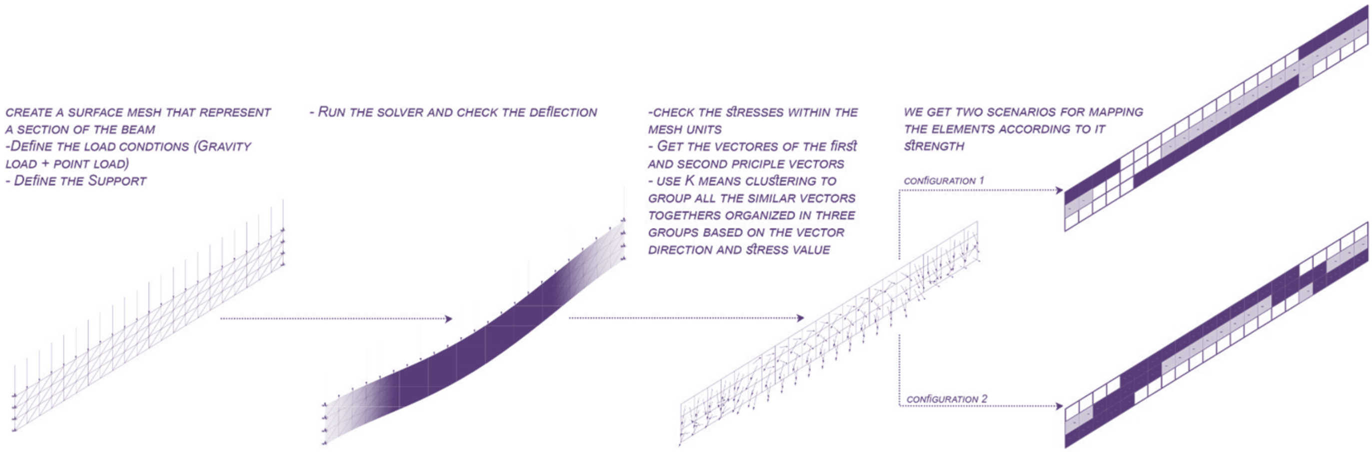



**FIGURE 34: KARAMBA MESH ANALYSIS (OWN WORK)**

## 3.3 Stock to Grade Workflow

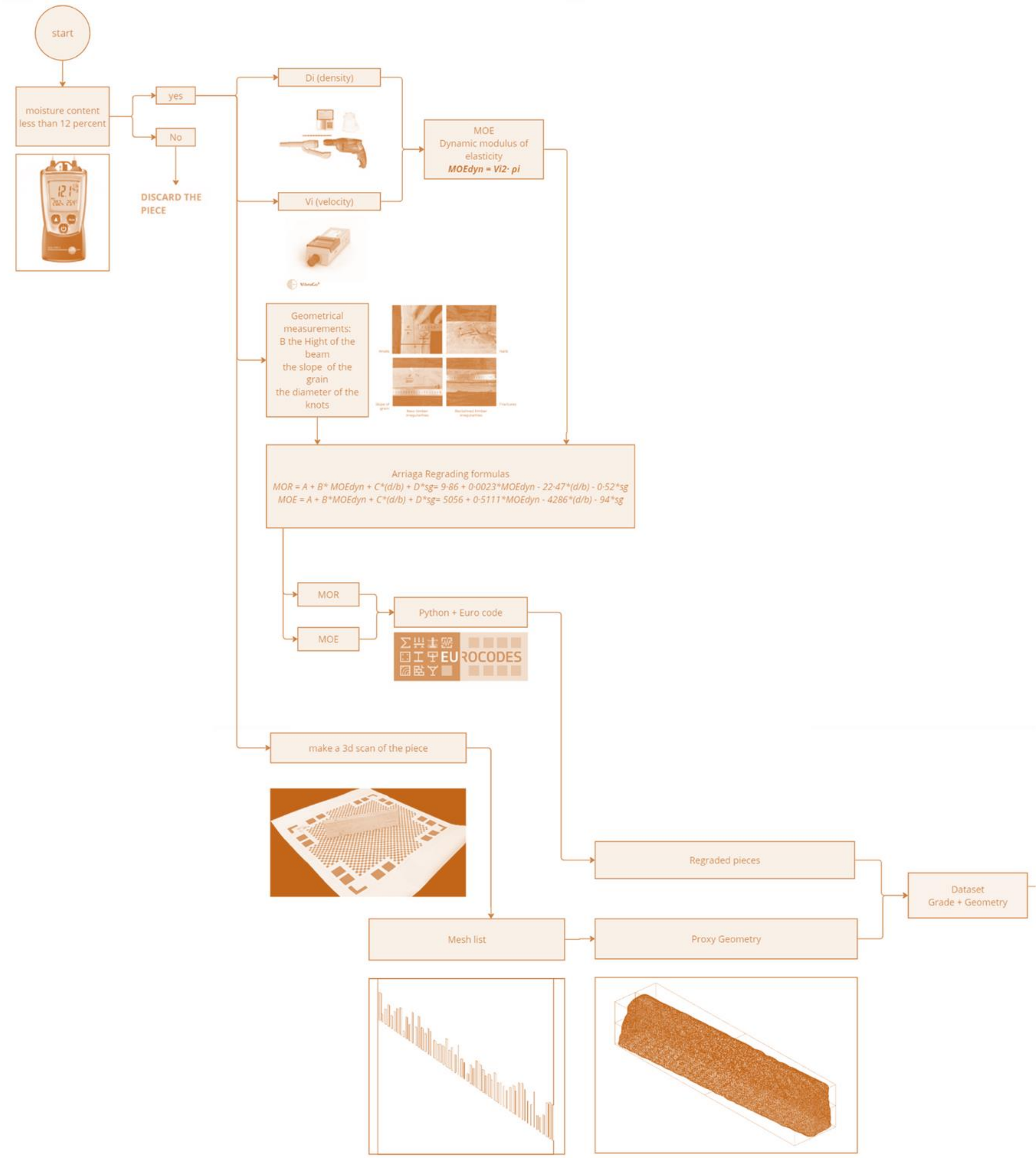



**FIGURE 35: REGRADING FLOWCHART(OWN WORK)**

Assessing the quality of timber stands as a pivotal workflow, particularly concerning reclaimed stocks, as discussed in the literature review. While machine grading techniques are typically employed for newly sawn timber, visual inspection remains fundamental for reclaimed timber. However, if a method exists to approximate the grade of reclaimed timber to Eurocode timber grade classifications, it could enhance the acceptance of this process within the construction sector. Previous research endeavors have adapted Arriaga's formulas to ascertain the grade of the timber:

A- Commencing with the evaluation of the timber piece's moisture content, any piece exceeding 20% moisture is discarded. If not, two crucial values, in addition to geometrical measurements, are required.

B- The first value, density, can be determined using traditional methods based on mass and volume formulas. However, employing more precise techniques such as "resistance drilling" is advisable. This technique estimates timber density by gauging the resistance encountered during drilling. Denser wood offers greater resistance to the drill bit than less dense wood, allowing an estimation of the timber's density.

The second crucial value is the vector velocity within the timber piece, measured using a laser Doppler vibrometer. This device accurately gauges surface vibrations, with meticulous calibration ensuring precise measurements. Data on the timber's vibrations is systematically collected and analyzed to determine the velocity component (Vi).

By combining Vi and Di, a significant value known as the dynamic modulus of elasticity (MOEdyn) is obtained via the formula: MOEdyn = Vi2· ρi.

The third measurement entails determining the slope of grain (Sg) and the ratio of knots diameter to beam diameter (d/b).

C- These values, along with the aforementioned ones, are then plugged into Arriaga's formulas:

MOE = A + BMOEdyn + C(d/b) + Dsg = 5056 + 0·5111MOEdyn - 4286*(d/b) - 94*sg

MOR = A + B* MOEdyn + C*(d/b) + Dsg = 9·86 + 0·0023MOEdyn - 22·47*(d/b) - 0·52*sg

D- These formulas are implemented within Grasshopper. By importing measured values into an Excel sheet, a list of MOE and MOR values is easily derived.

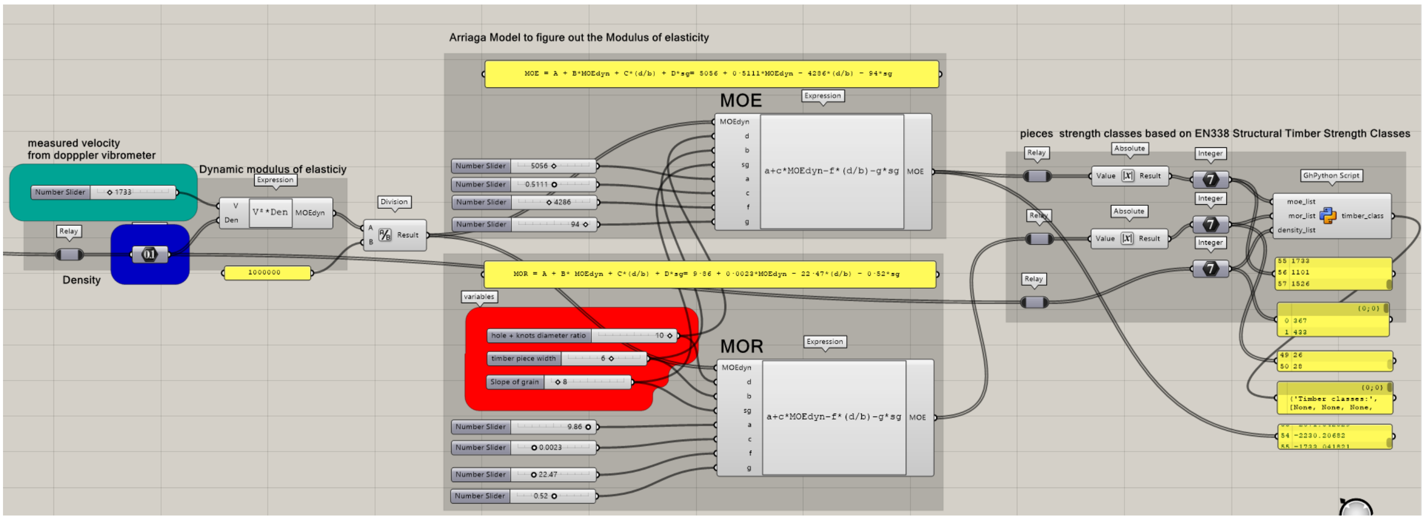



FIGURE 36: SNIPPET FROM CALCULATING THE DYNAMIC MOE IN GRASSHOPPER (OWN WORK )

E- Utilizing GhPython and the Eurocode, each grade's values are coded as ranges. The script reads the density, MOE, and MOR, outputting the timber grade.

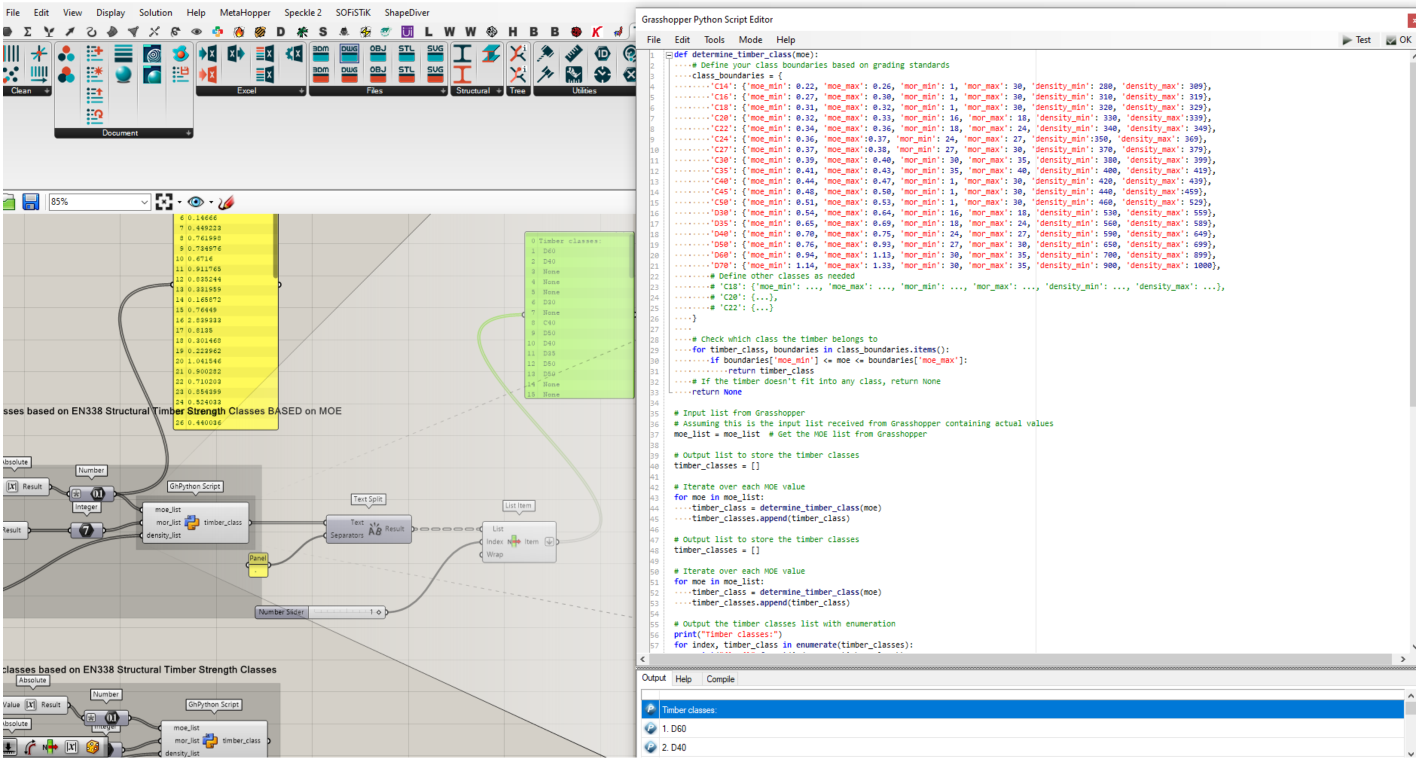



FIGURE 37: SNIPPET FROM ENCODING THE EURCODE INTO PYTHON (OWN WORK)

**Table 1 — Strength classes - Characteristic values**

| | | Poplar and softwood species | | | | | | | | | | | | Hardwood species | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | C14 | C16 | C18 | C20 | C22 | C24 | C27 | C30 | C35 | C40 | C45 | C50 | D30 | D35 | D40 | D50 | D60 | D70 |
| Stiffness properties (in kN/mm$^2$) | | | | | | | | | | | | | | | | | | | |
| Mean modulus of elasticity parallel | $E_{0,mean}$ | 7 | 8 | 9 | 9,5 | 10 | 11 | 11,5 | 12 | 13 | 14 | 15 | 16 | 10 | 10 | 11 | 14 | 17 | 20 |
| 5% modulus of elasticity parallel | $E_{0,05}$ | 4,7 | 5,4 | 6,0 | 6,4 | 6,7 | 7,4 | 7,7 | 8,0 | 8,7 | 9,4 | 10,0 | 10,7 | 8,0 | 8,7 | 9,4 | 11,8 | 14,3 | 16,8 |
| Mean modulus of elasticity perpendicular | $E_{90,mean}$ | 0,23 | 0,27 | 0,30 | 0,32 | 0,33 | 0,37 | 0,38 | 0,40 | 0,43 | 0,47 | 0,50 | 0,53 | 0,64 | 0,69 | 0,75 | 0,93 | 1,13 | 1,33 |
| Mean shear modulus | $G_{mean}$ | 0,44 | 0,5 | 0,56 | 0,59 | 0,63 | 0,69 | 0,72 | 0,75 | 0,81 | 0,88 | 0,94 | 1,00 | 0,60 | 0,65 | 0,70 | 0,88 | 1,06 | 1,25 |
| Density (in kg/m$^3$) | | | | | | | | | | | | | | | | | | | |
| Density | $\rho_k$ | 290 | 310 | 320 | 330 | 340 | 350 | 370 | 380 | 400 | 420 | 440 | 460 | 530 | 560 | 590 | 650 | 700 | 900 |
| Mean density | $\rho_{mean}$ | 350 | 370 | 380 | 390 | 410 | 420 | 450 | 460 | 480 | 500 | 520 | 550 | 640 | 670 | 700 | 780 | 840 | 1080 |

NOTE a Values given above for tension strength, compression strength, shear strength, 5% modulus of elasticity, mean modulus of elasticity perpendicular to grain and mean shear modulus, have been calculated using the equations given in annex A

b The tabulated properties are compatible with timber at a moisture content consistent with a temperature of 20$^{\circ}$C and a relative humidity of 65%

c Timber conforming to classes C45 and C50 may not be readily available.

**TABLE 5: SNIPPET FORM THE EUROCODE**

F- Furthermore, visual scanning of the timber piece is conducted using a mobile phone application called Qlone. The scanned meshes are imported into Rhino Grasshopper, where bounding boxes with tolerances are employed to generate proxy elements. These boxes are subsequently utilized within the design work-flow.

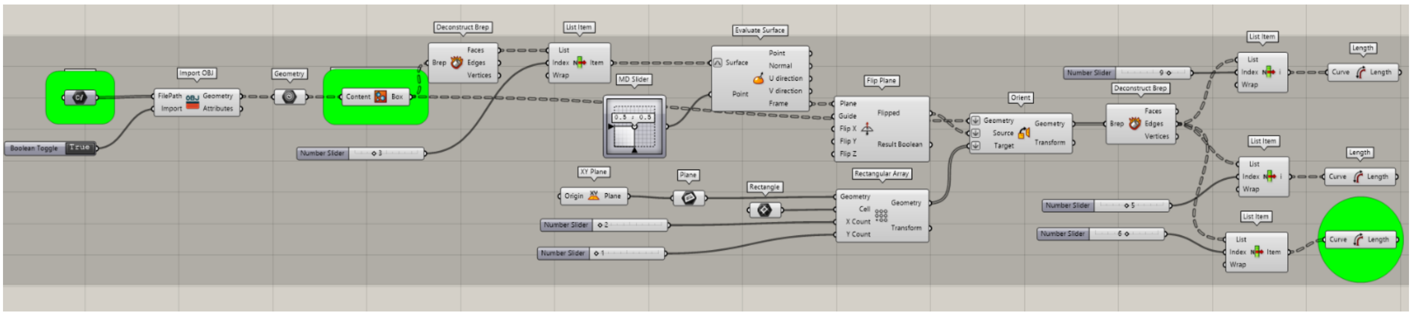


**FIGURE 38: GRASSHOPPER SNIPPET FOR IMPORTING THE SCANNED MESH (OWN WORK)**

In summary, this process involves inputting measured values such as Di, Vi, Sg, d/b, and the scanned mesh to output a proxy geometry for the timber piece, along with its roughly esti-mated grade according to the Eurocode.

## 3.4 Availability, Demand, and Matching Results

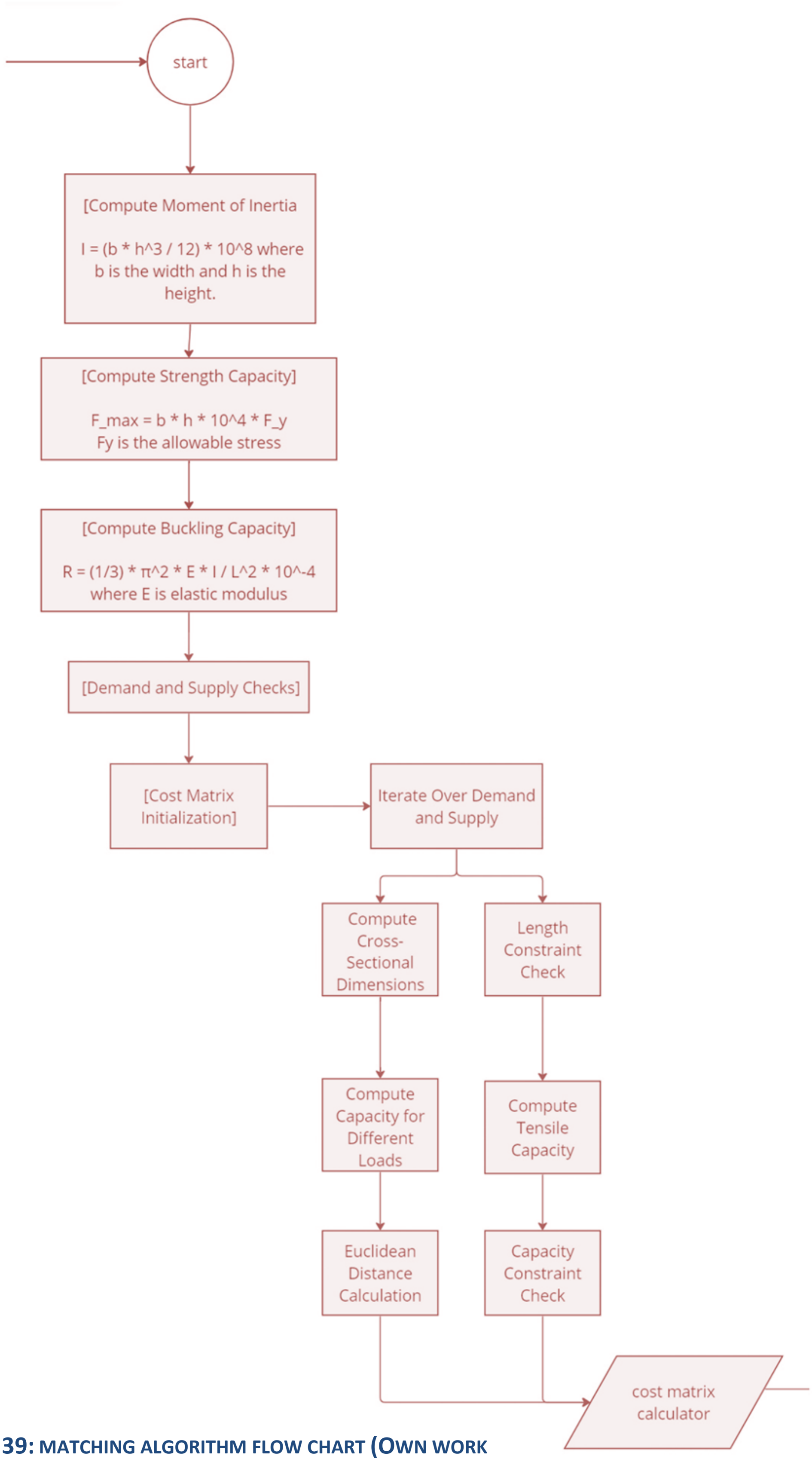



**FIGURE 39: MATCHING ALGORITHM FLOW CHART (OWN WORK )**

The script begins by importing essential libraries and modules, including `Grasshopper.DataTree`, `Grasshopper.Kernel.Data.GH_Path`, `System`, `List`, and `math`. Additionally, it imports functions from `ghpythonlib.treehelpers` for managing Grasshopper data trees.

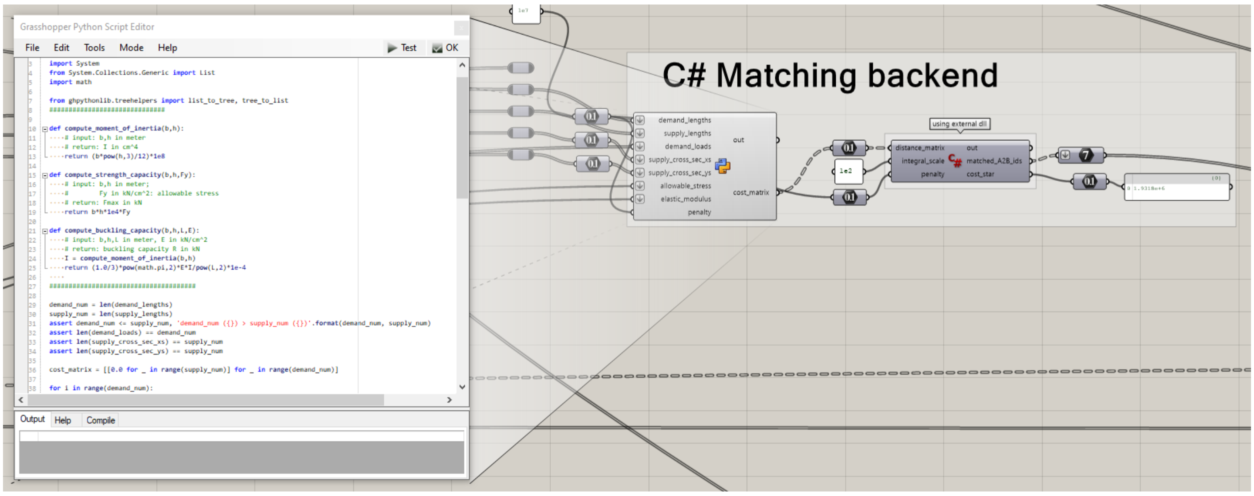



**FIGURE 40**

Following the imports, three functions are defined:

- compute_moment_of_inertia(b,h)`: This function calculates the moment of inertia (I) for a given beam cross-section, based on its width (b) and height (h).

- compute_strength_capacity(b,h,Fy)`: This function computes the strength capacity (Fmax) of a beam cross-section, considering its dimensions (b, h) and allowable stress (Fy).

- compute_buckling_capacity(b,h,L,E)`: This function determines the buckling capacity (R) of a beam column, accounting for its dimensions (b, h), length (L), and modulus of elasticity (E).

After function definitions, the script initializes variables `demand_num` and `supply_num` to represent the number of demand and supply lengths, respectively. It also ensures the consistency of input list lengths.

The core of the script lies in the calculation of the cost matrix for transportation problem resolution:

- It iterates over each combination of demand and supply lengths.

- For each combination, it computes the cost considering various constraints such as length, tensile/compressive demand, and capacity.

- If any constraint is violated, a penalty value is assigned to the corresponding entry in the cost matrix.

- Otherwise, it calculates the Euclidean distance between demand and supply lengths, factoring in differences in length and demand capacity.

- Finally, the resulting cost matrix is converted from a nested list to a Grasshopper data tree format using `list_to_tree`.

The script is designed to find the most optimal assignment between available timber stocks

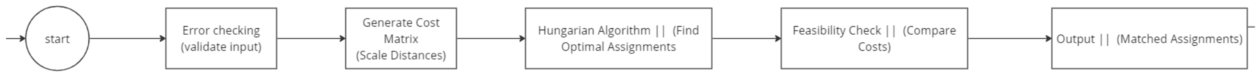



**FIGURE 41:GENERATING COST MATRIC FLOW CHART (OWN WORK)**

and structural elements, considering factors such as distance, cost, or other criteria represented in the input data.

Algorithm Execution: It utilizes the Hungarian algorithm, a combinatorial optimization algorithm, to determine the best matching between the timber stocks and structural elements. The algorithm minimizes the total cost or distance associated with the assignments, ensuring efficient resource allocation.

Input Parameters:

distance_matrix: Represents the distances or costs associated with matching each timber stock with each structural element.

integral_scale: A scaling factor used to adjust the input data for compatibility with the algorithm.

penalty: Represents a penalty term used for error checking and handling in case of infeasible solutions.

Output Parameters:

matched_A2B_ids: Represents the optimal assignments between timber stocks and structural elements.

cost_star: Represents the final cost associated with the optimal assignments.

Error Handling: The script includes error handling mechanisms to detect and handle cases where the computed assignment cost exceeds the specified penalty terms. This ensures that the matching process adheres to predefined constraints and requirements.

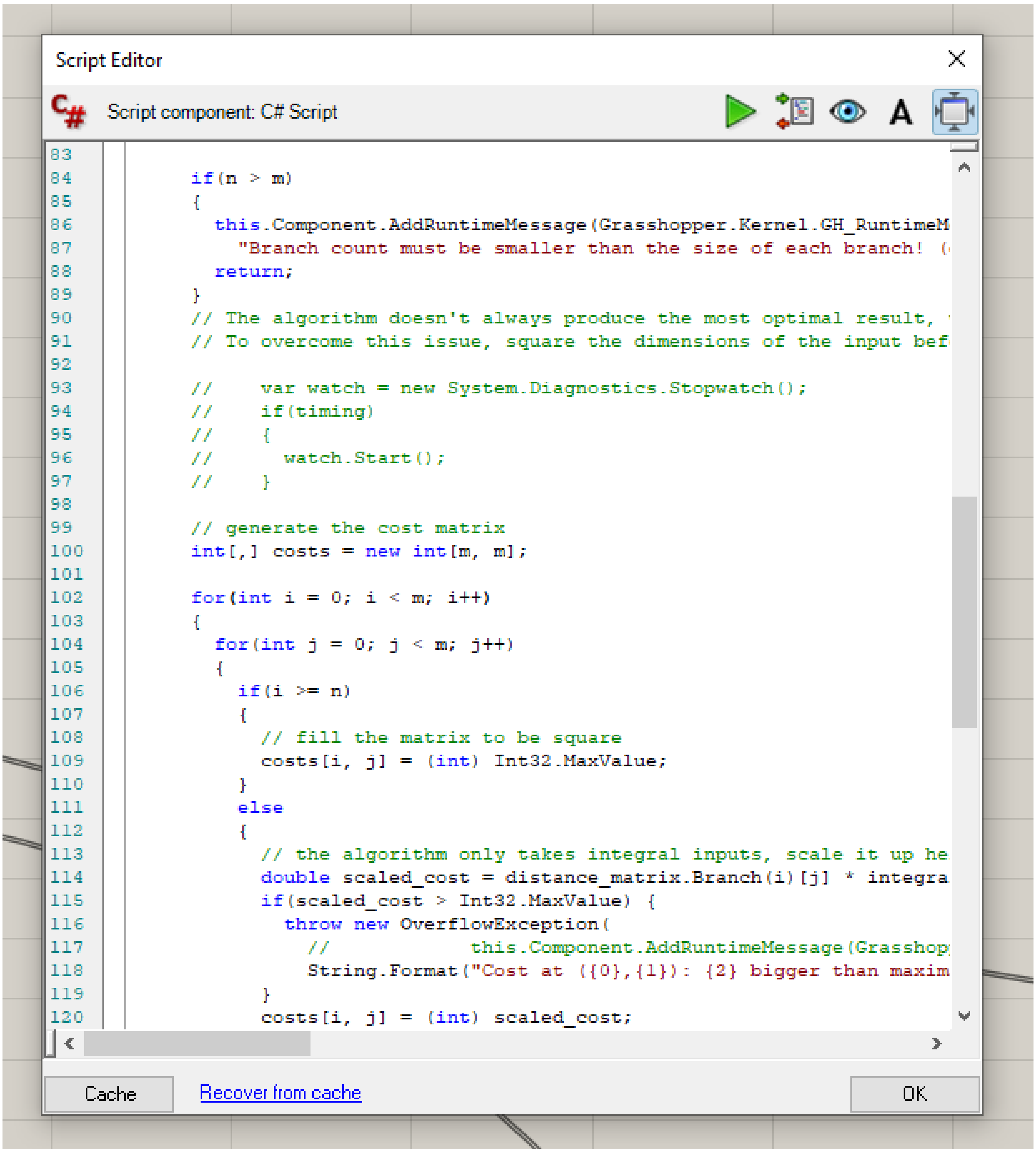



**FIGURE 42: HUNGARIAN ALGORITHM SNIPPET,CODE SOURCE**(HUANG ET AL., N.D.)

## 3.4 Visualizing Results

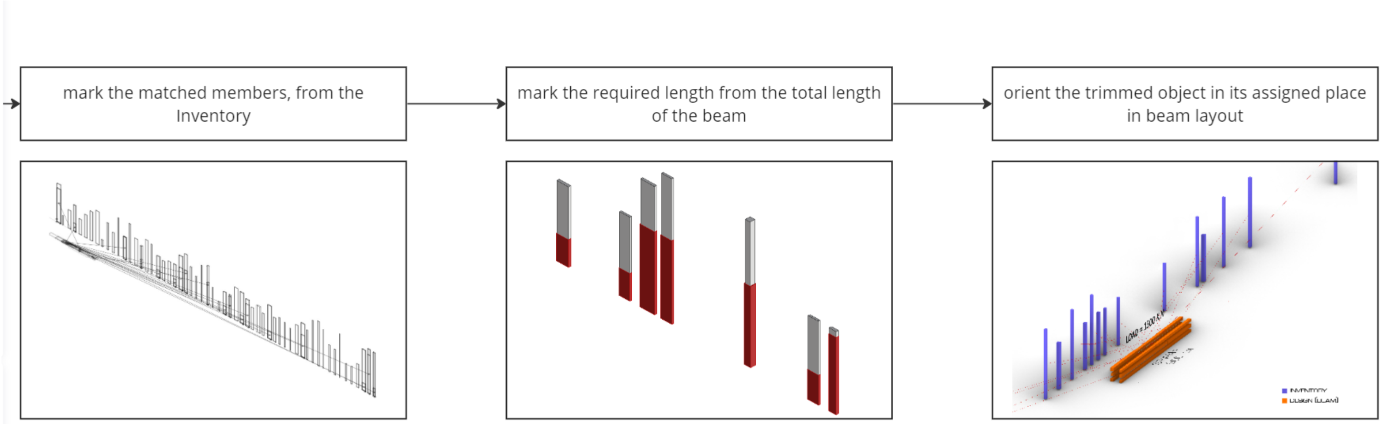



**FIGURE 44: FLOW CHART FOR THE VISUALIZING THE MATCHED ELEMT (OWN WORK )**

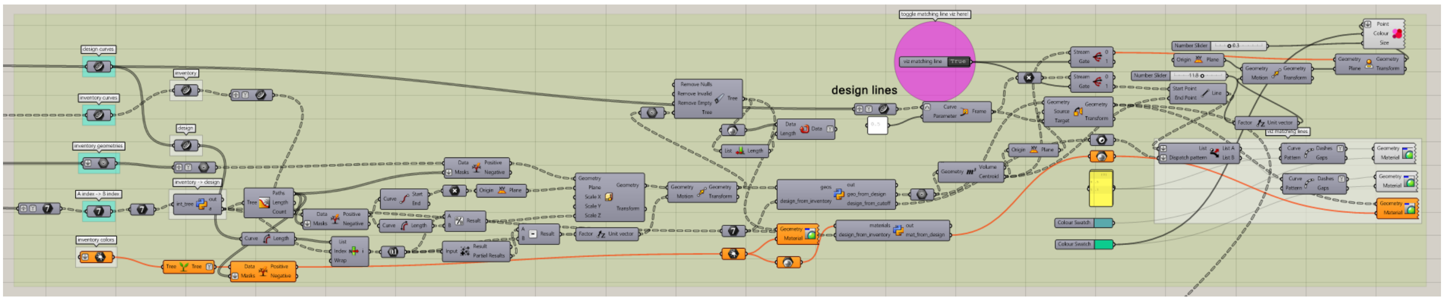



**FIGURE 43: SNIPPET FORM THE GRASSHOPPER CODE FOR VISUALIZATION (OWN WORK)**

## 3.4.1 Fix the load, and increase the Length

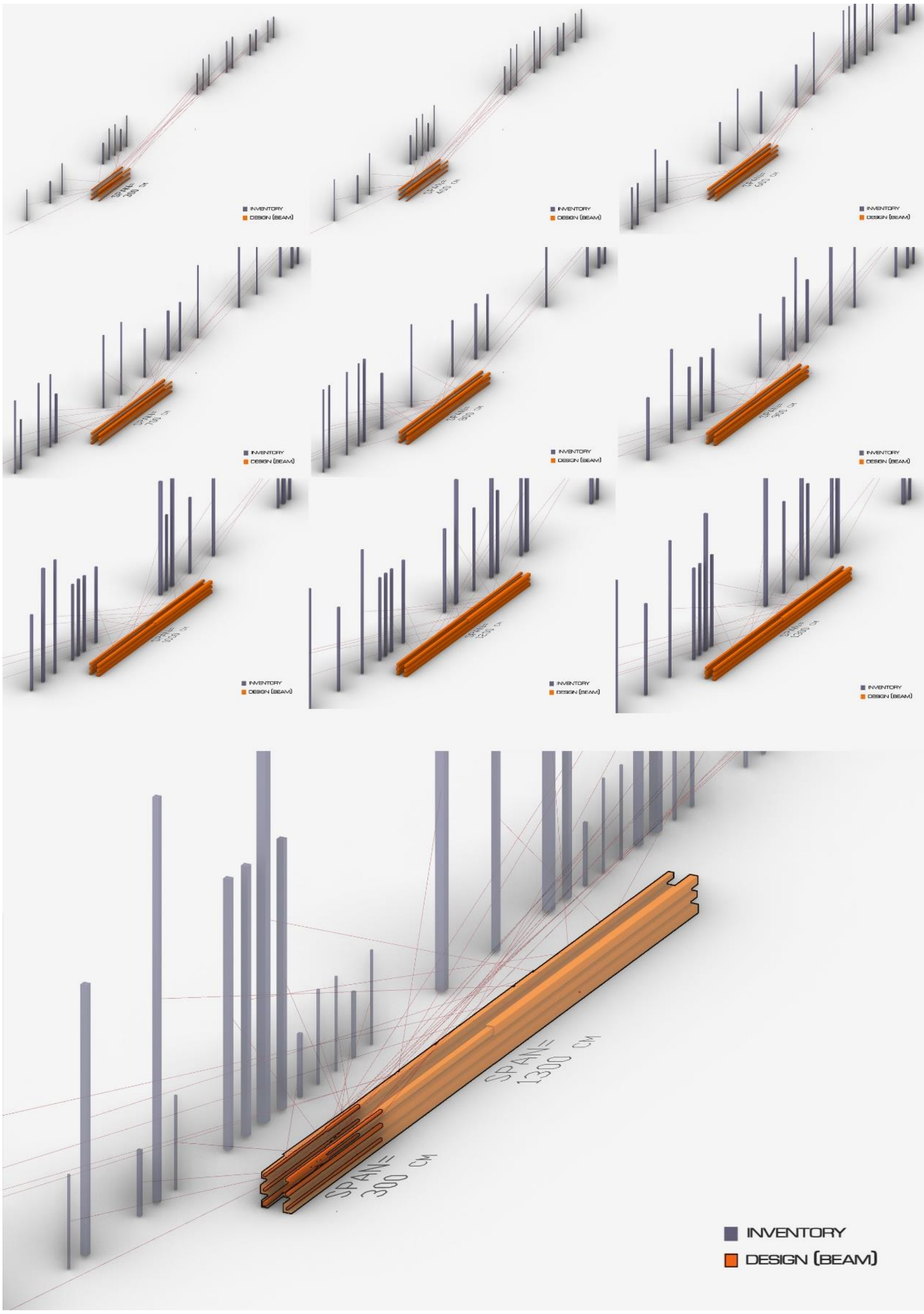



**FIGURE 45: VISUALIZING MATCHING RESULTS (OWN WORK )**

### 3.4.2 Fixed Length, and increase the load

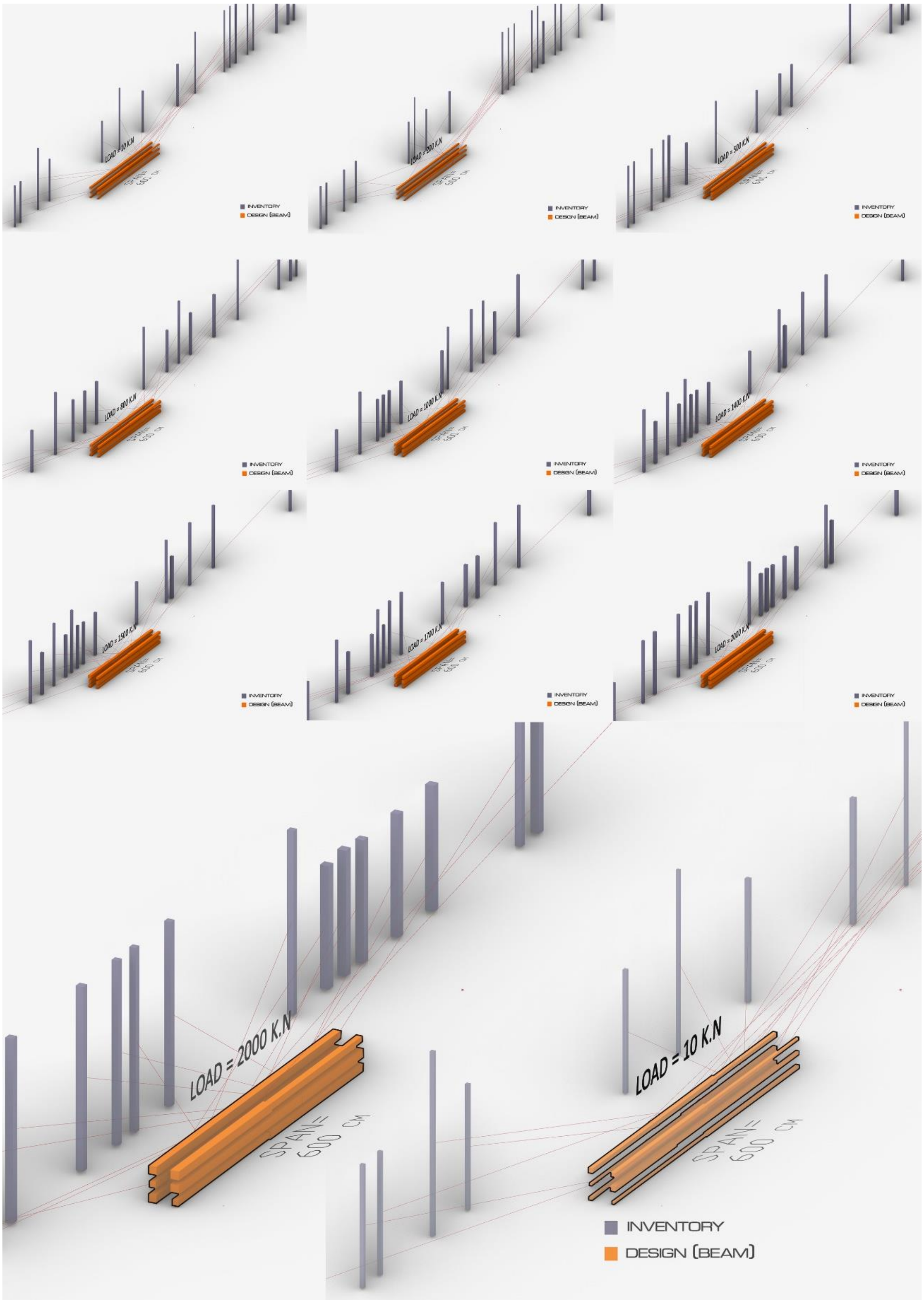



**FIGURE 46: VISUALIZING MATCHING RESULTS(OWN WORK )**

## 3.5 CONCLUSION:

Even though the total workflow used an arbitrary dataset, it was challenging to figure out valid methods from grading toe design to matching, and still it needs to be checked and further developed to include all the aspect that affect the process:

- design boundaries, to a beam layout workflow: the workflow was able to transform the span into a very simple bundle of lines, which is the base for the matching, this process can be developed more by:

a- adding a parameter for the slope of the scarf joint, (4:1, 6:1 ,…,20:1),

b- In case further research has been conducted about the direction of the grain, it would be beneficials to assign a recommended grain direction to each line of the pieces

From design layout to structure layout:

This workflow is the most critical workflow, where we find away to deal with the beam design as mesh instead of simplified linear element, and we were able to find out the principal stresses in different location across the beam, however:

- transforming these principal stresses to grades in order to be assigned to the lines to form the list for required grades grade, it still need more development in grouping and averaging the principal stresses to represent the demanded capacity for each piece of the design,
- furthermore, when the deflection is calculated using Karama it is done by considering the design a solid joist and then doing an FEA analysis for this solid joist, however in reality it's a bundle of glued element with inner scarf joint, in order to that it is more recommended to use another FEA analysis methods and engine where these parameters are considered in the analysis,

From stock to a grade:

In theory this workflow was tested in previous work, and based on the information from that research we assume that this process is working, in future research it would be a nice idea to conducted the grading method using the workflow discussed in the project, to check its viability and all the aspects that might affect the accuracy of the grading, either from calibrating measurement devices, to tune the coded ranges of MOE inside the python code to get more accurate grading results

the matching algorithm:

the Hungarian algorithm aimed at finding the suboptimal solution in terms of grade and length, by minimizing the cost of the match between the available and the demand, it is working quite well, but it needs to integrate the minimizing the environmental impact of the beam design and find the solution that has fulfil the requirements at the same time has less environmental impact

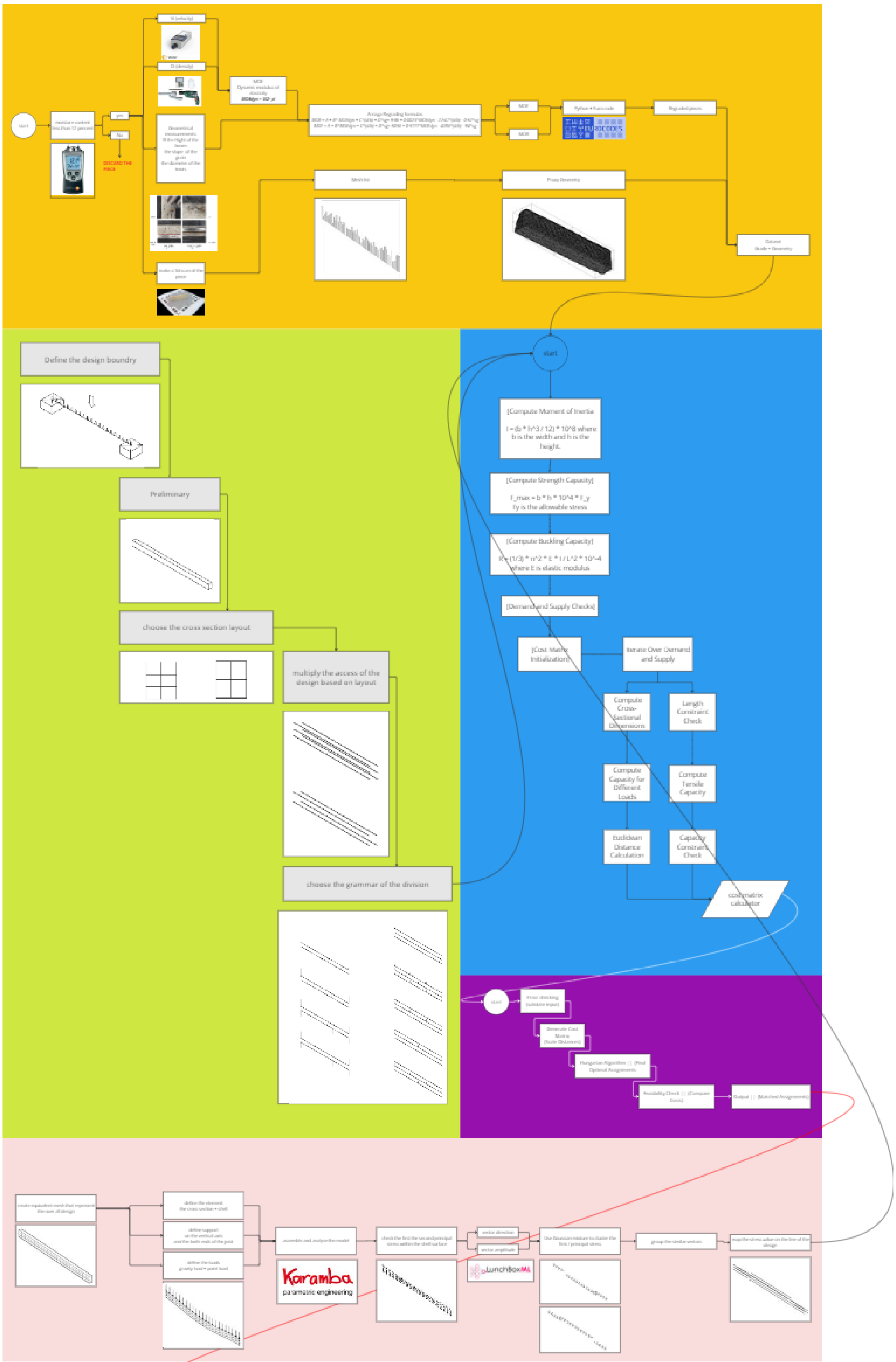



**FIGURE 47**

Integrated flowchart (Own work)

# First Phase Experiments Reclaimed Oak , Meranti, Fir

# التجارب الأولى الأخشاب المستصلحة ميرانتي , فير ,بلوط

# 4 First phase of experiments:

## 4.1 Aim of the experiments:

- To explore the potential of using different timber species that has different strength in the making of the samples

- check what aspects need to be taken in consideration to increase the performance of the product, based on the observation from a destructive test:

1- The angle of the grain

2- The glue serviceability

## 4.2 Objective of the experiments:

To conduct 3 point bending test to figure the load that each sample can handle, with record of the deflection caused by that load.

To document and analyse the failures that happened at each specimen

## 4.3 Hypothesis:

Using a mix between hard timber and soft timber will increase the strength of the joist

## 4.4 Experimental questions:

- What is the best layout for the combination of the Two different species to increase the performance of the joist ?

## 4.5 Timber sourcing


**FIGURE 48; FIRST ROUND OF COLLECTING TIMBER (OWN WORK )**

In the initial phase of the project aimed at creating prototypes for mechanical testing of small specimens, a straightforward approach was employed to procure raw materials. This involved scouring nearby locations in Delft for reclaimed timber. Specifically:

- Samples of Fir and Meranti were salvaged from the waste area of a student housing facility.
- A visit to the waste area in front of BK yielded two pieces of aged oak and three spruce pieces. It's worth noting that the timber collected from this location had absorbed a significant amount of rainwater due to recent heavy rainfall, evident when placed on a piece of paper.
- Additionally, during a renovation along Prins Bernhardlaan, permission was granted to gather dismantled, dry-aged spruce.
- The collection process was personally conducted by the researcher without the use of any transportation other than public transit to transport the pieces from the Van Hasseltlaan location to storage.

As for storage arrangements, access was granted to a limited storage space on the campus of TU Delft. The timber pieces are housed on a shelf within the Building Technology studio.

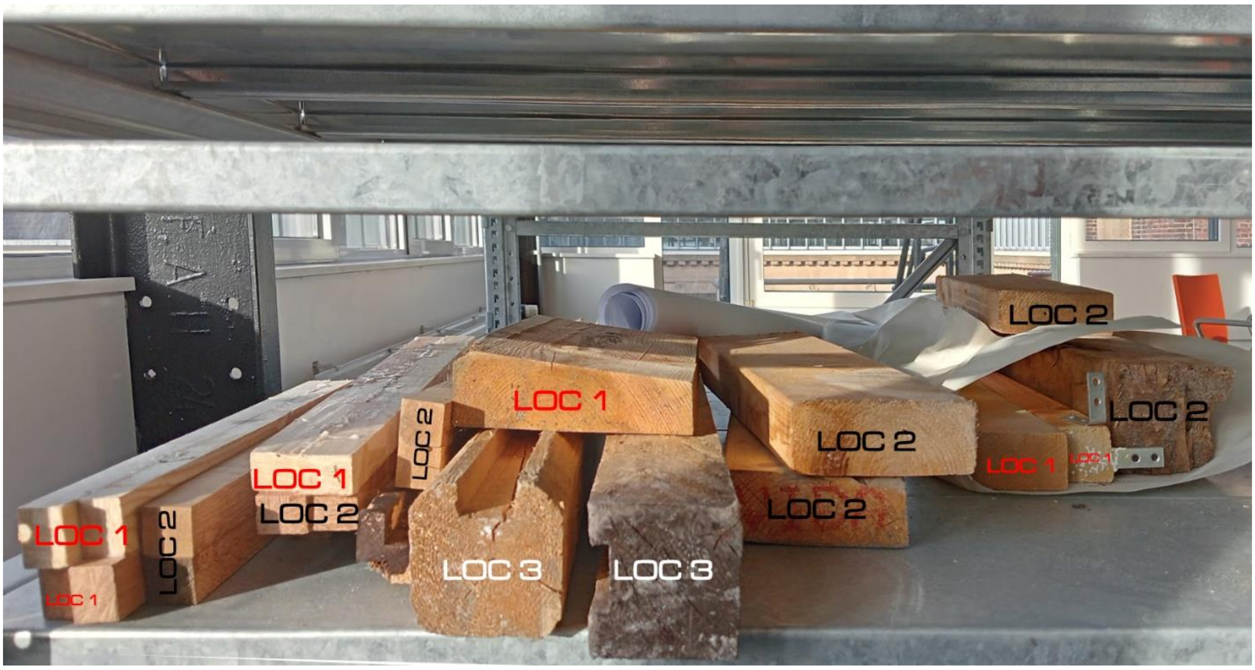



**FIGURE 49: TIMBER STORAGE AT BT STUDIO (OWN PHOTO )**

## 4.6 Manufacturing of the specimens

After collecting the initial series of timber, the subsequent process involved a straightforward visual grading to identify pieces suitable for use, with a primary focus on excluding elements with excessive moisture content. The selected timber specimens encompassed a variety of species, densities, and ages. Given prior research advocating techniques for newly sawn spruce, it was deemed valuable to assess the efficacy of interlocking joints across different timber sources, particularly in mixing hard and soft woods.

This objective led to the development of five initial configurations, which will be elaborated upon in subsequent chapters.

Owing to predetermined parameters and experimental constraints, the timber selection process was relatively uncomplicated, obviating the need for computationally intensive workflows.

The chosen timber comprised sections of Douglas fir, complemented by meranti, all in satisfactory condition. Additionally, an aged oak piece measuring 7 x 7 cm was included.

While planning the cuts for the fir and meranti pieces at the BK Wood Workshop proved manageable, extra care was required for the meranti due to its hardness. Cutting and sanding meranti necessitated additional time and assistance.

The oak piece posed a unique challenge due to its irregular surfaces. With guidance from the wood workshop mentor, the large section was divided into four smaller sections to create Specimens 3 and 4. The cuts were executed using a table saw, followed by meticulous cleaning and planning. Approximately 20% of the section was discarded during this process to ensure uniformly straight sections for subsequent gluing. After the planned cuts and sanding, the pieces were prepared for gluing. The gluing process followed a systematic approach: be-

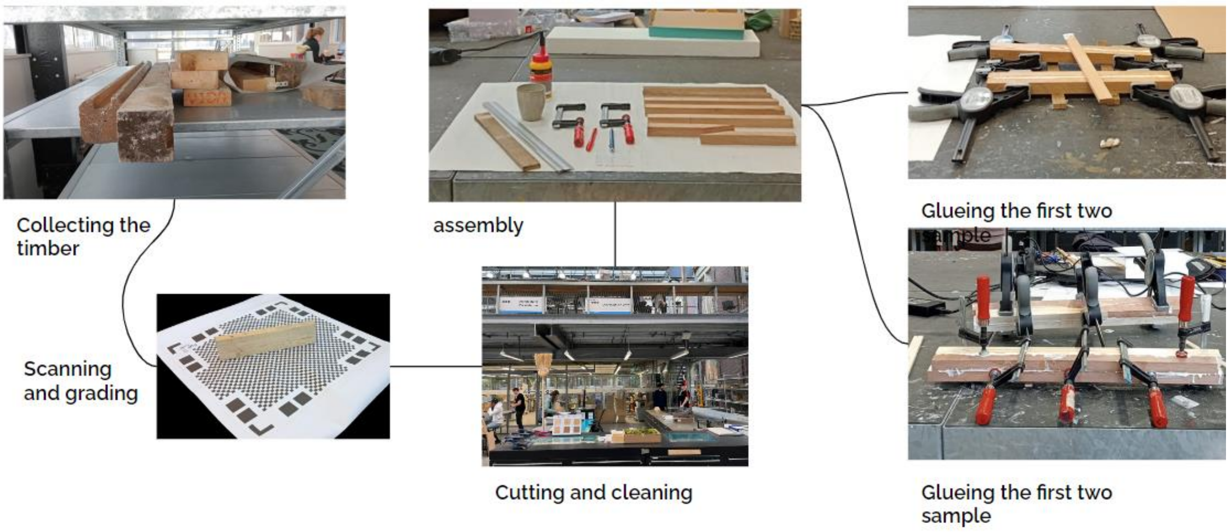



**FIGURE 50: PROCESSING THE COLLECTED TIMBER(OWN WORK)**

ginning with the bottom straight lamellas, then the two adjacent pieces of the slashed lamellas, and repeating the same process for the upper layer of lamellas.

1- The straight part of the bottom lamellas was placed, and the connected side was glued.

2- The first part of the slashed piece, which has the cut face, was attached, and the slashed surface was glued.

3- The third piece of the bottom part lamellas was attached alongside its twin piece and next to the straight lamella.

4- The top surface of the bottom part lamella was glued, and the straight long piece was placed in its place.

5- The side of the upper straight piece was glued, and the first half of the slashed piece was added, following the same order as the first layer of lamellas.

6- Finally, the second piece of the upper slashed lamella was added after gluing the surface of the slash cut.Throughout the gluing process, no binding was applied. However, immediately after aggregating the whole joist, five clamps were utilized along the joist, with each half clamped in both directions. Additionally, a clamp was used to secure the middle of the joist where the pieces were slashed.

The last clamps were positioned perpendicular to the area containing the two slashed surfaces.

The pieces were left to dry with clamps for 10 days. A week after releasing the clamps, the bending test was conducted.

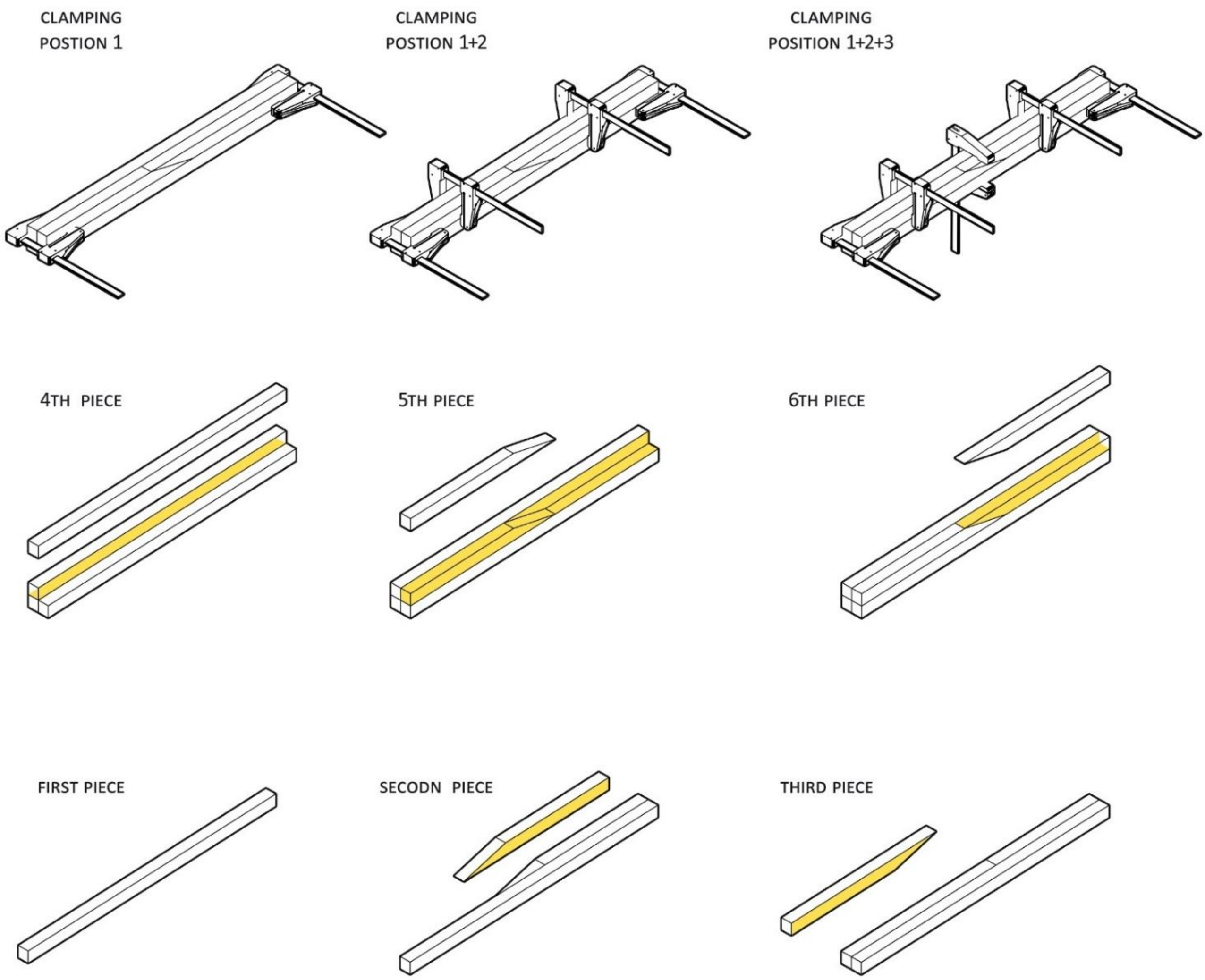
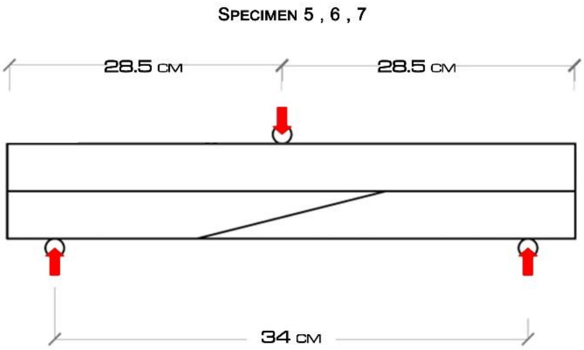



**FIGURE 51: FIRST SPECIMENS GLUEING SEQUENCE (OWN WORK)**

## 4.7 Test condition

The 3-point bending mechanical test occurred in the 3ME faculty, in the lab of material mechanical behaviour, with the assistance of Dr. ir. F.A. Veer. The test utilized a low- and high-temperature tensile and fatigue testing machine with a span of 34 cm between the supports, a cylindrical pressure head with a diameter of 6 cm, and a pressure speed of 5 mm per s 53econd.



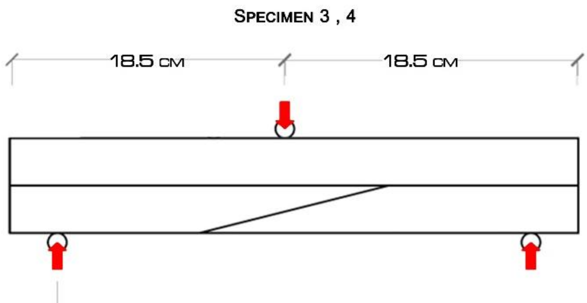
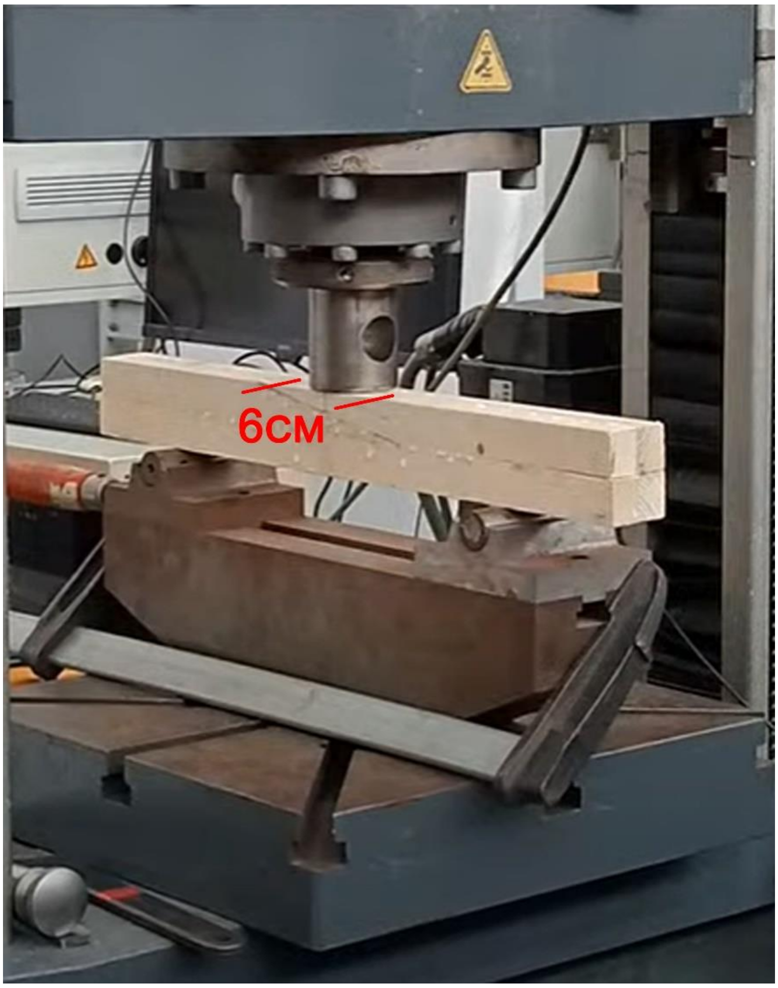




**TABLE 7**



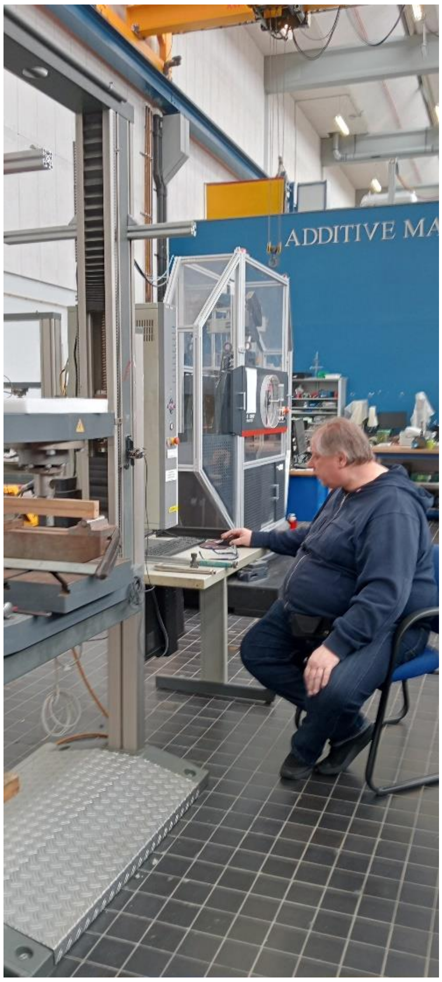




**FIGURE 52: 3 POINT MECHANICAL TEST AT MATERIAL BEHAVIOUR LAB IN 3ME (OWN PHOTO)**

## 4.8 Conducting the three-point bending test:

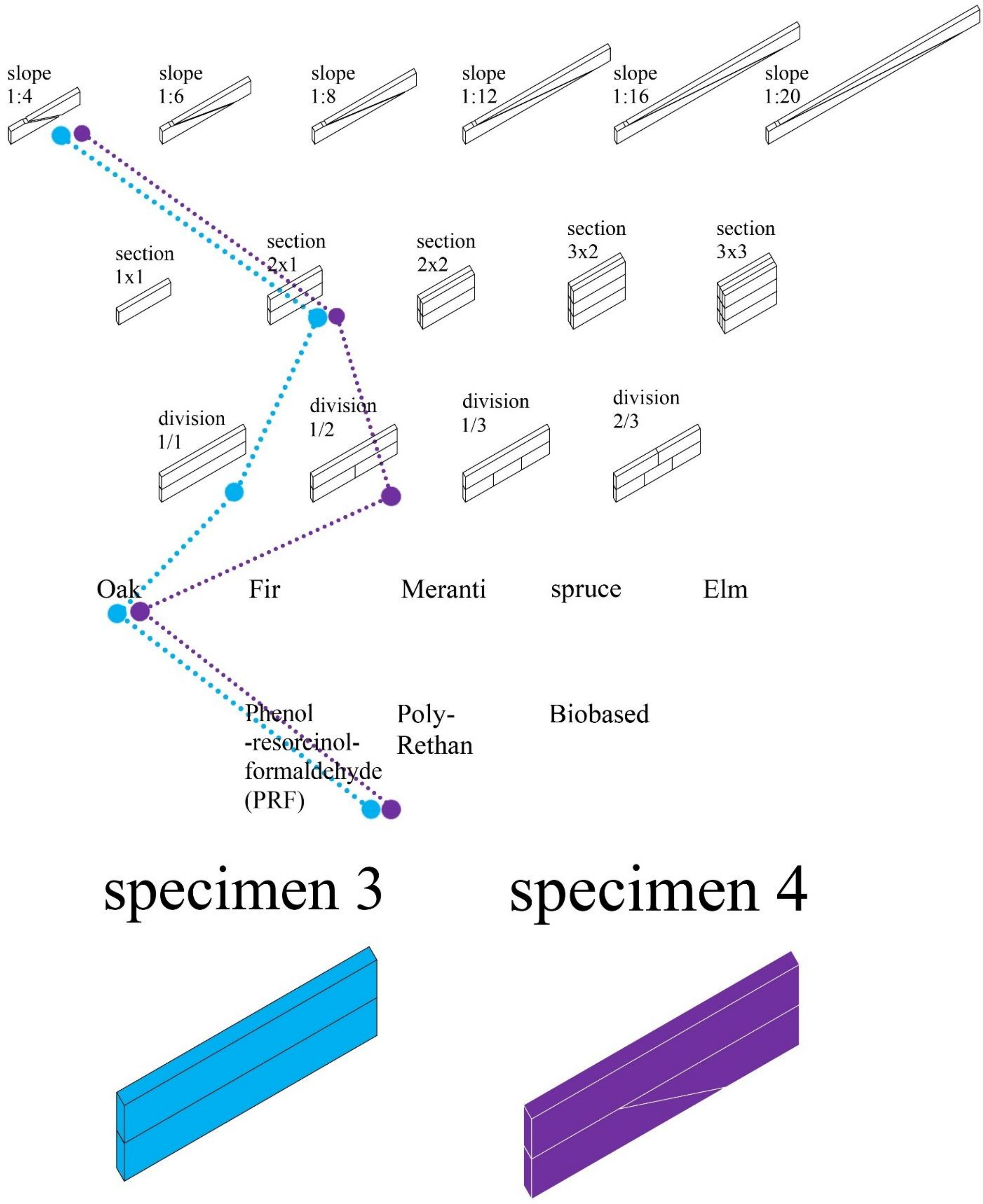
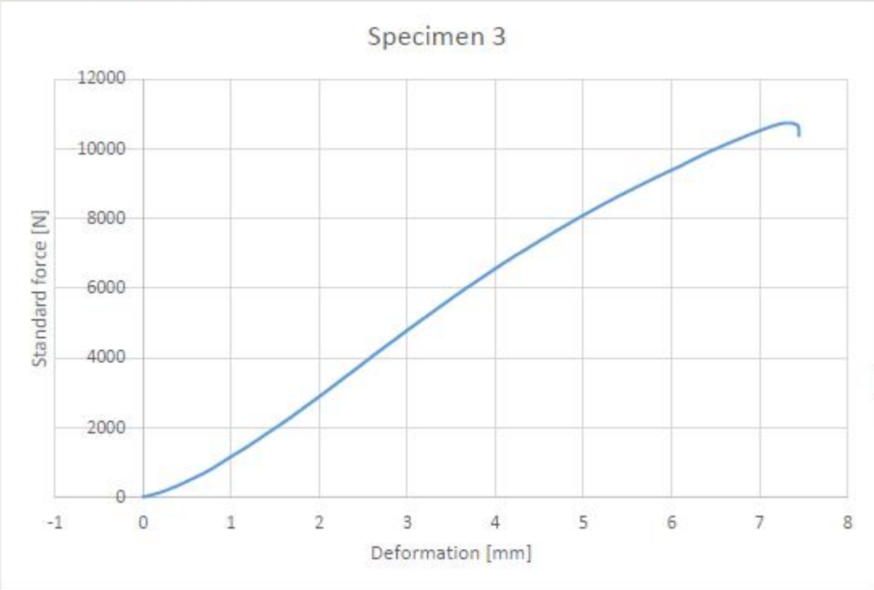



**FIGURE 54: SELECTION CRITERIA FOR SPECIMENS 3,4 (OWN WORK)**

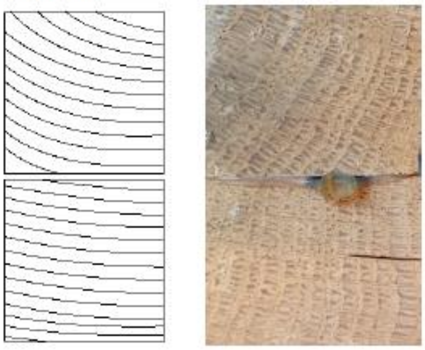
## 4.8.1 Specimen 3: Oak parallel joist from two Lamellas

- The specimen is made from a reclaimed oak piece collected from BK campus waste.
- The length of the piece is 37 cm.
- The height of the piece is 6 cm.
- The depth of the piece is 3.2 cm.

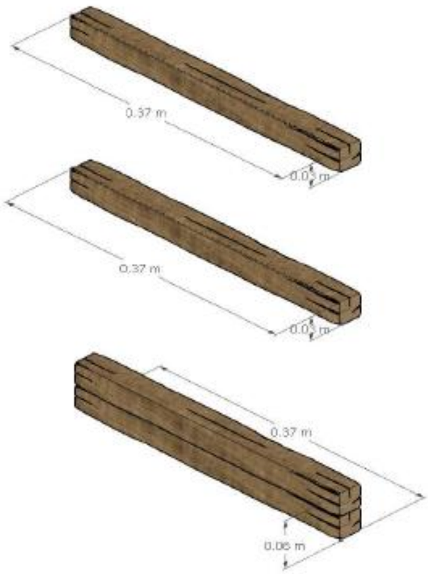
**3 Point test Results**




**Grain direction**



**Piece anatomy**




**Before the breaking test**

**After the breaking test**

**FIGURE 55: SPECIMEN 3 REPORT (OWN WORK )**

### Type of failure description:

- The specimen reached approximately 1 ton of strength before breaking and exhibited a maximum deflection of 7mm.

  - the piece did not experience any delamination before breaking.

The crack originated near the support, following the grain angle of the lower lamella, and then crossed to the upper one with almost the same path.

  - This could be attributed to the fact that both pieces were sawn from the same section and share the same grain angle and condition.
  - The specimen reached approximately 1 ton of strength before breaking and exhibited a maximum deflection of 7mm.
  - The piece did not experience any delamination before breaking.
  - The crack originated near the support, following the grain angle of the lower lamella, and then crossed to the upper one with almost the same path. This could be attributed to the fact that both pieces were sawn from the same section and share the same grain angle and condition.

### 4.8.2 Specimen 4: two lamellas with a diagonal slop cut at the top layer

- Similar to the previous specimen, this one is made of oak, but with the grain orientation of the upper lamella flipped, and with a 1:4 slope cut position at the middle of the span.

- The specimen is made from a reclaimed oak piece collected from the BK campus waste.

- The length 37 cm. The height is 6 cm, The depth is 3.2 cm.

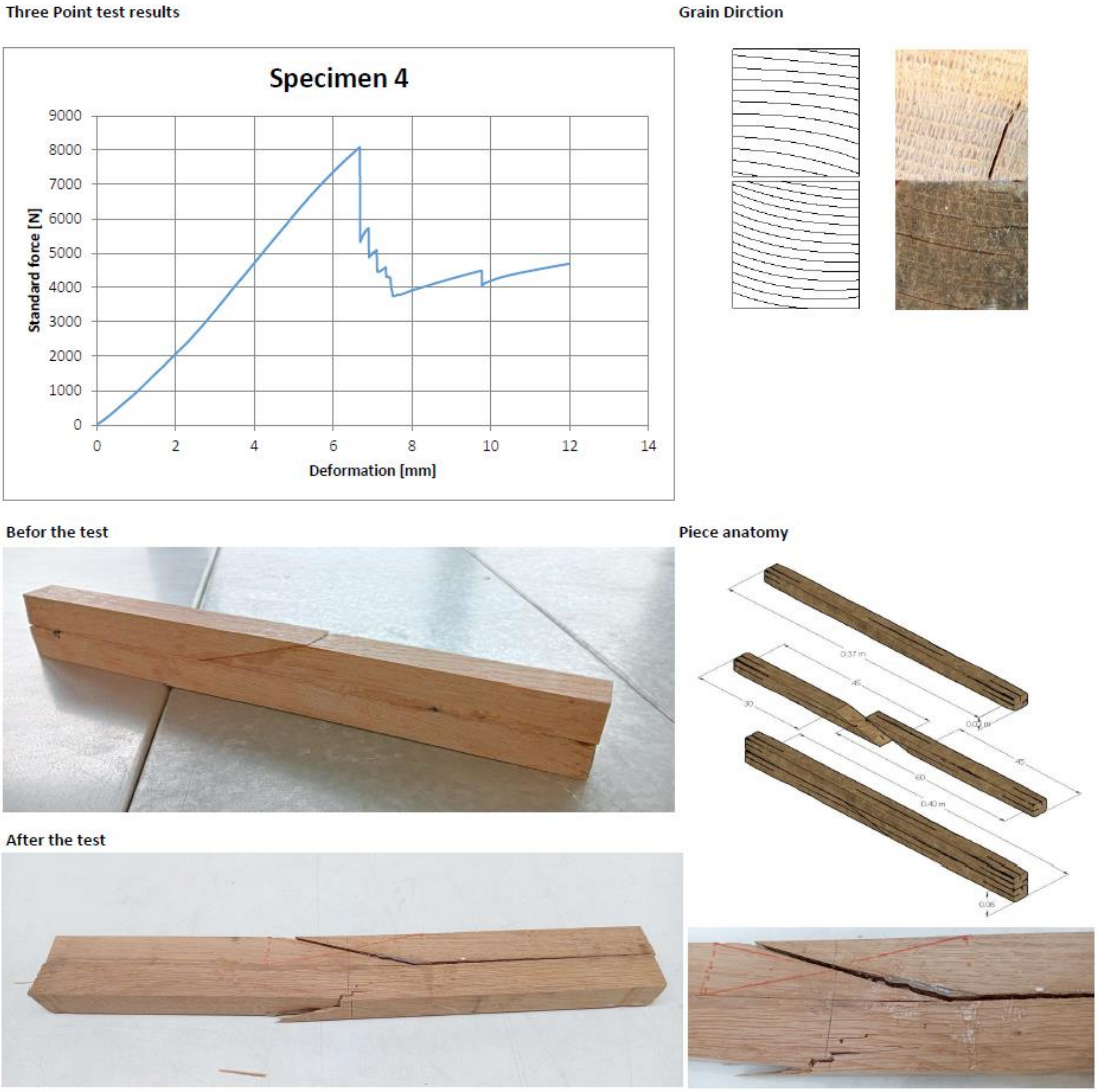



**FIGURE 56: SPECIMEN 4 REPORT (OWN WORK)**

Types of failure description:

The piece took a lower load until it broke (8088.012 N), which is 2 KN less than specimen 3.

The crack originated in the middle of the specimen in the same region as the slope cut. The crack followed a path with almost the same angle as the slope cut but flipped. After the head machine released it, it became apparent that part of the upper lamella

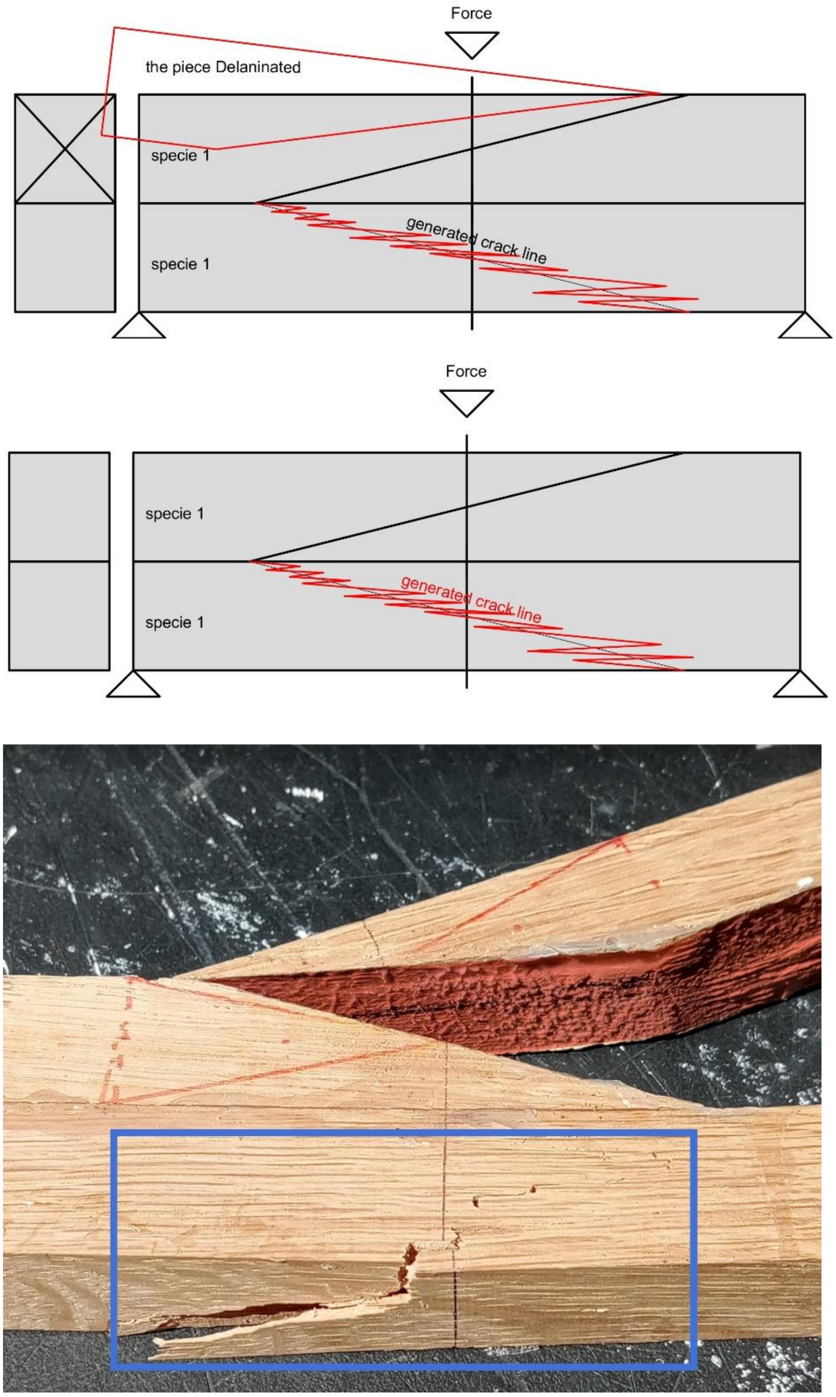



**FIGURE 57**

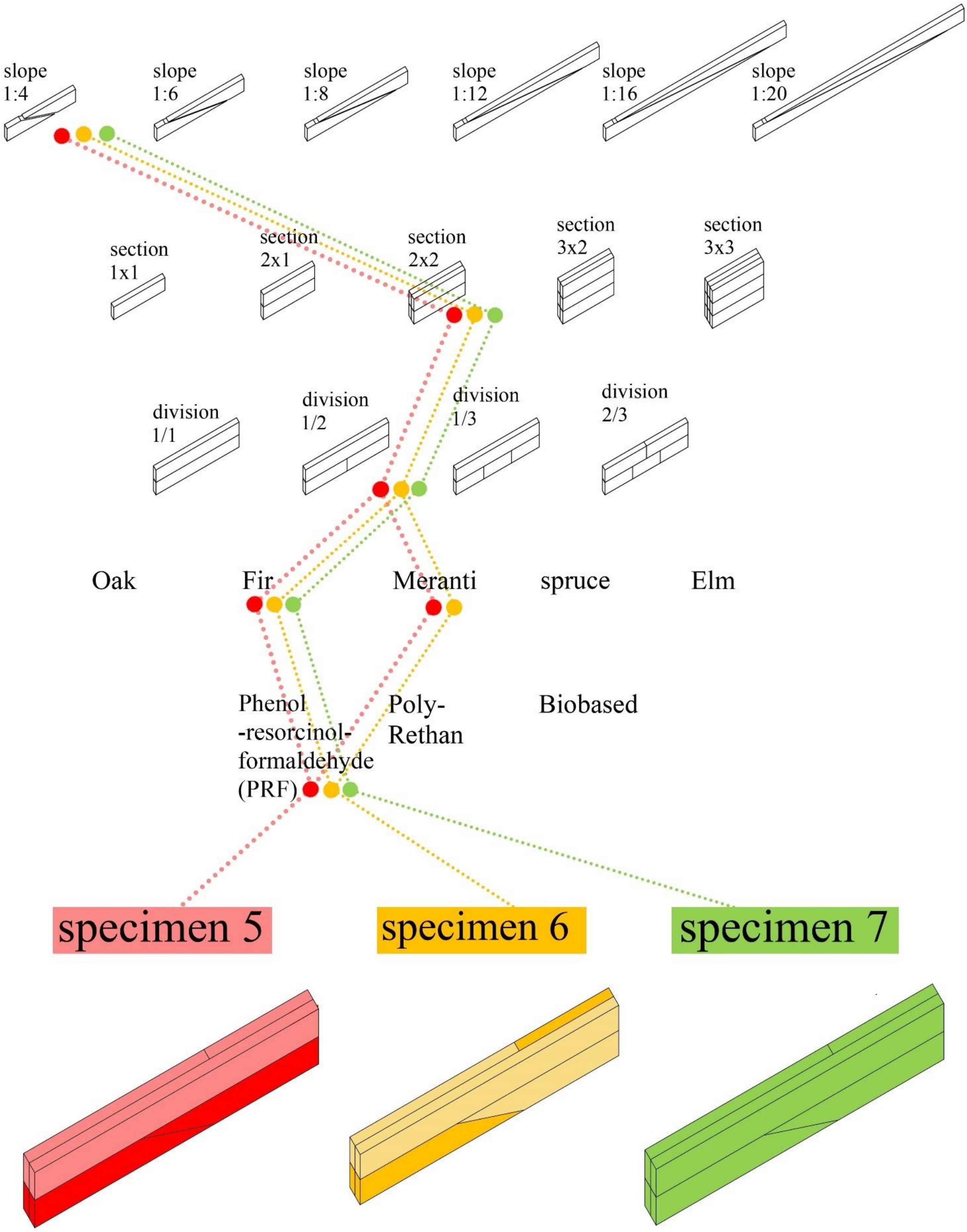



**FIGURE 58: SPECIMEN CONFIGURATION CRITERIA (OWN WORK )**

## 4.8.3 Specimen 5: 4 interlocking lamellas from Fir and Meranti

The piece is made of reclaimed Fir and Meranti, with the same grain composition illustrated below. It consists of 4 lamellas, with the lower two lamellas made of hard timber (Meranti) and the upper two lamellas made of fir (softwood).

The length of the piece is 57 cm, with a height of 5.2 cm and a depth of 4.1 cm.

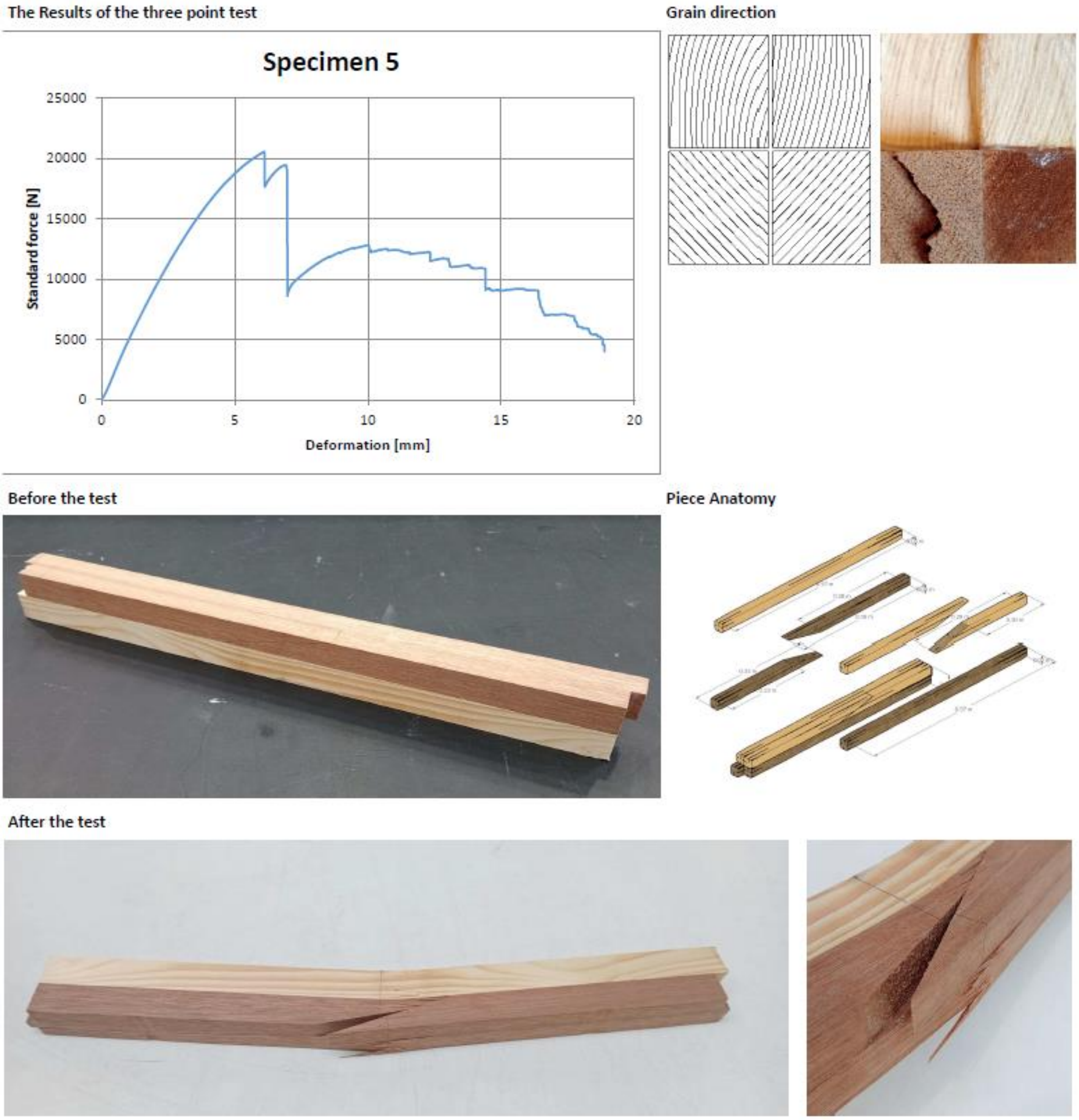


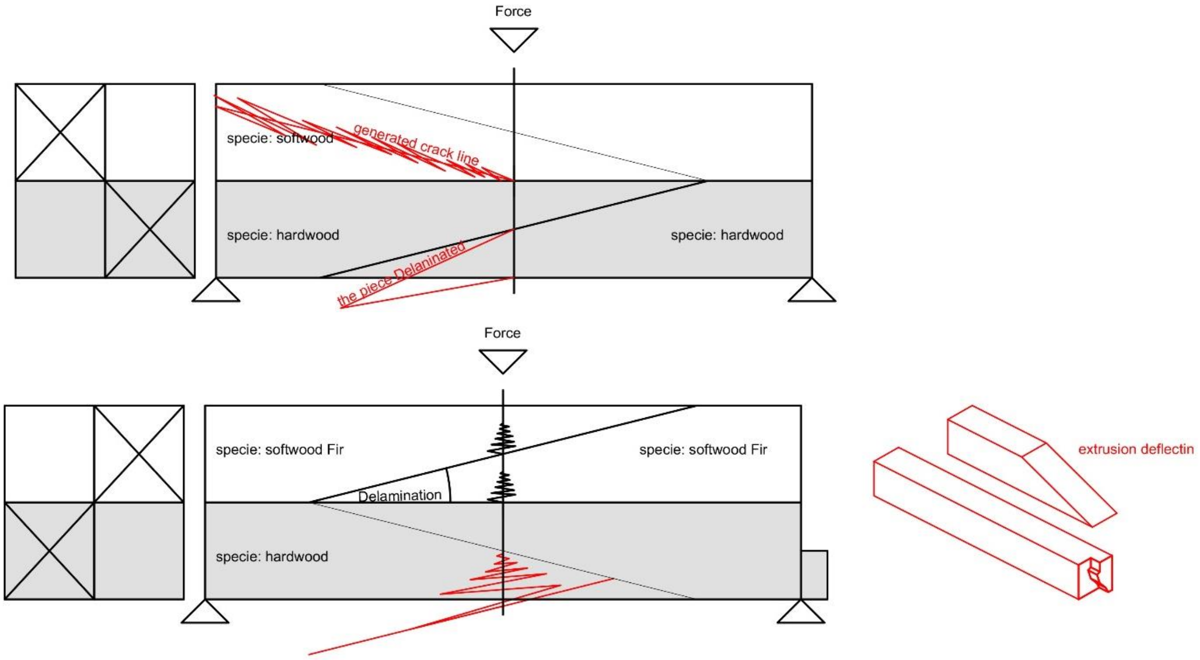

**FIGURE 59**

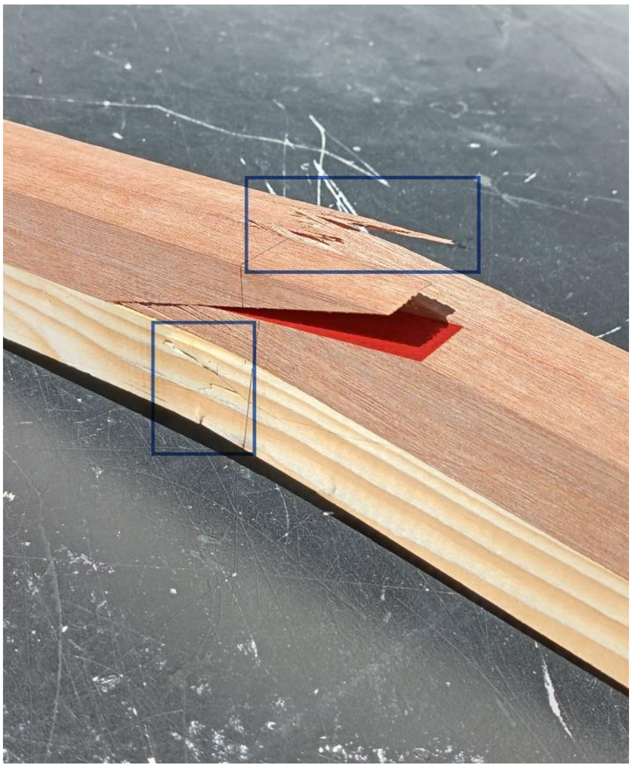
types of failures description

- The piece experienced a maximum force of 20574.39 N.

- A sudden drop in force is observed in the graph, indicating the transformation of tension from the lower lamellas to the upper one, as depicted in the drawing below.

- Delamination occurred in the lower lamellas at the slope cut, while the rest of the lower lamella is cracked in the middle along a path with the same angle as the slope cut.



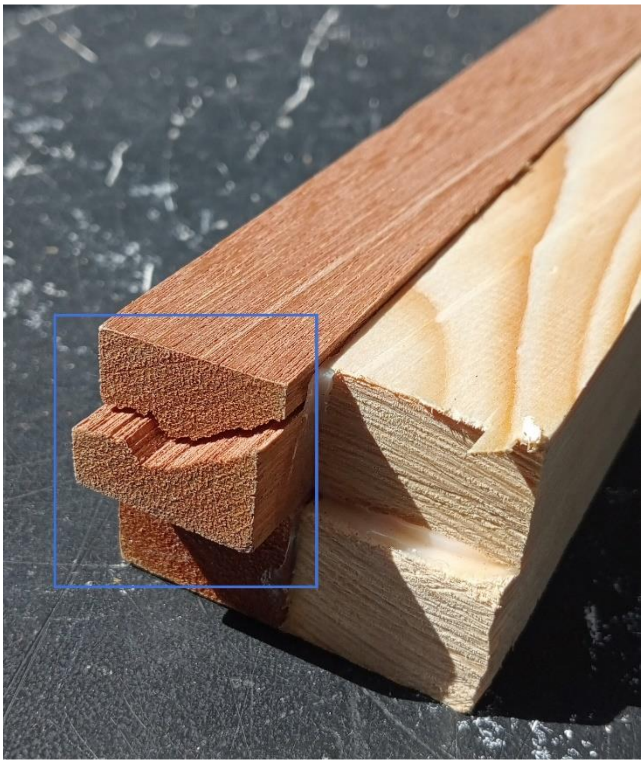


**FIGURE 60**

- Regarding the upper lamellas, bending deformation of the fibres occurred at the end of the slope cut, with partial delamination at the corner. Cracks also formed along a path in the middle of the piece aligned with the pushing force path.

- For the continuous softwood piece, cracks followed a path with the same angle and direction as its adjacent lamella but with an offset. The crack originated from the middle part of the specimen, as illustrated in the diagram.

- Another observed deformation is when a bundle of fibres from the lower lamella is extruded from the end due to tension in the lower middle part being transferred as compression force at the end of the lamella.

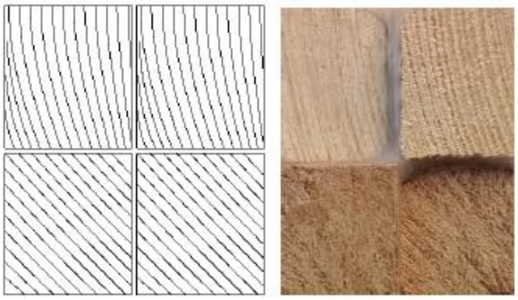
## 4.8.4 Specimen 6: 4 interlocking lamellas from fir and meranti

Similar to Specimen 5, this model is constructed from a mixture of meranti and fir. However, the difference lies in the redistribution of hard wood from the lower lamellas to the upper lamella, with meranti serving as the replacement. Consequently, the lower lamella comprises 25% softwood and 75% hardwood, while the upper lamella consists of 25% hardwood and 75% softwood, maintaining the same design layout as previously explained.

Types of failure discription:

Three point test results


Grain direction



Before the test

the piece anatomy

After the test

**Figure 61**

- The lowest continuous lamella experienced a crack in the middle, following a path parallel to the slope cut in its adjacent lamella.

- The other hardwood in the adjacent lamella experienced partial delamination at the corner.

- The softwood part of the adjacent lamella started to crack parallel to the cut in the upper lamella, which continues to cross its upper adjacent softwood lamella.

- Additionally, an extrusion on the outside at one end of the lower lamella's hardwood is spotted, resembling the position observed in Specimen 5

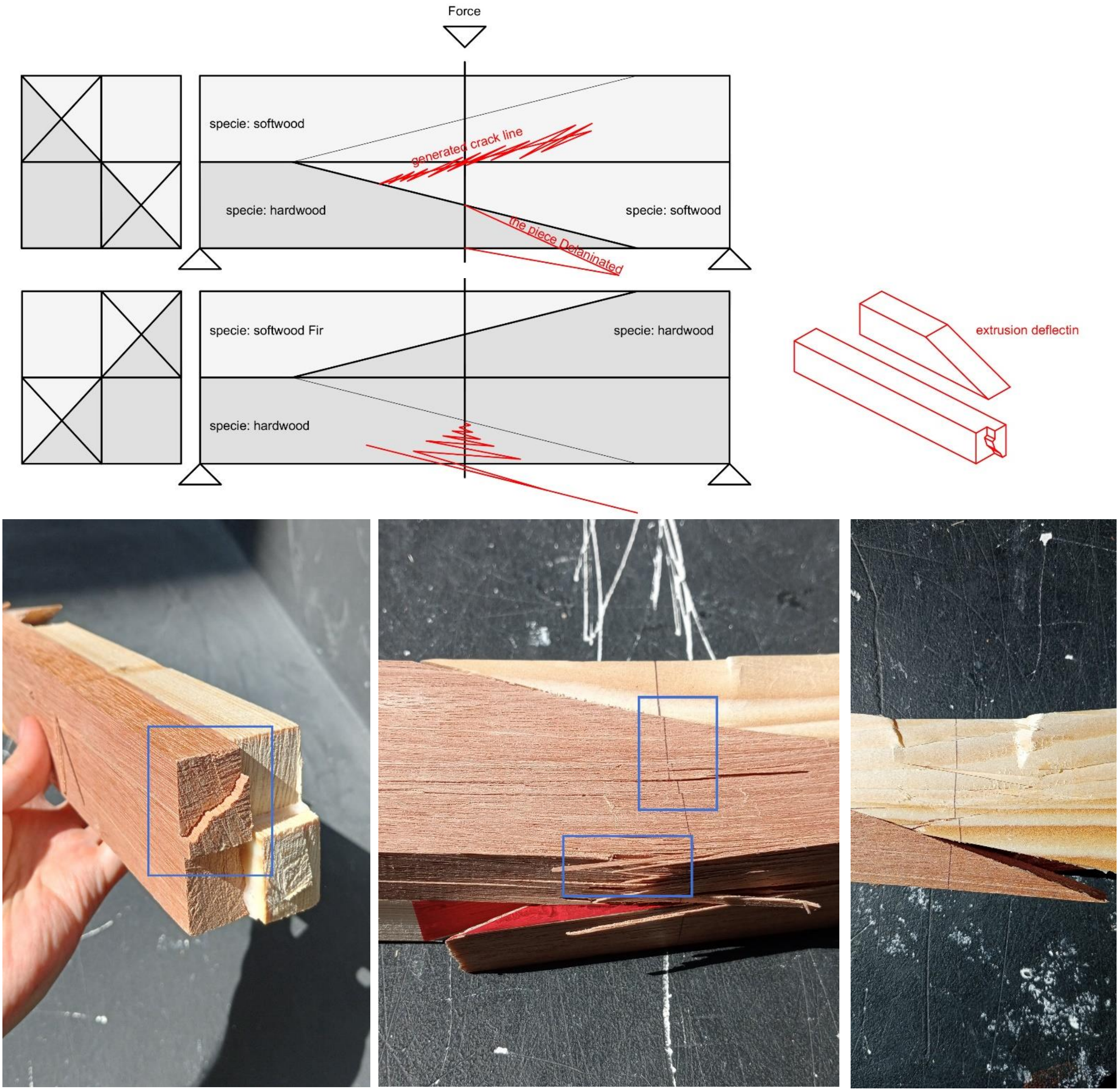



**FIGURE 62**

## 4.8.5 Specimen 7: 4 interlocking lamella from fir

made up completely from Fir (softwood) with the same interlocking 4 lamellas layout

The length of the piece is 57 cm, with a height of 5.2 cm and a depth of 4.1 cm.

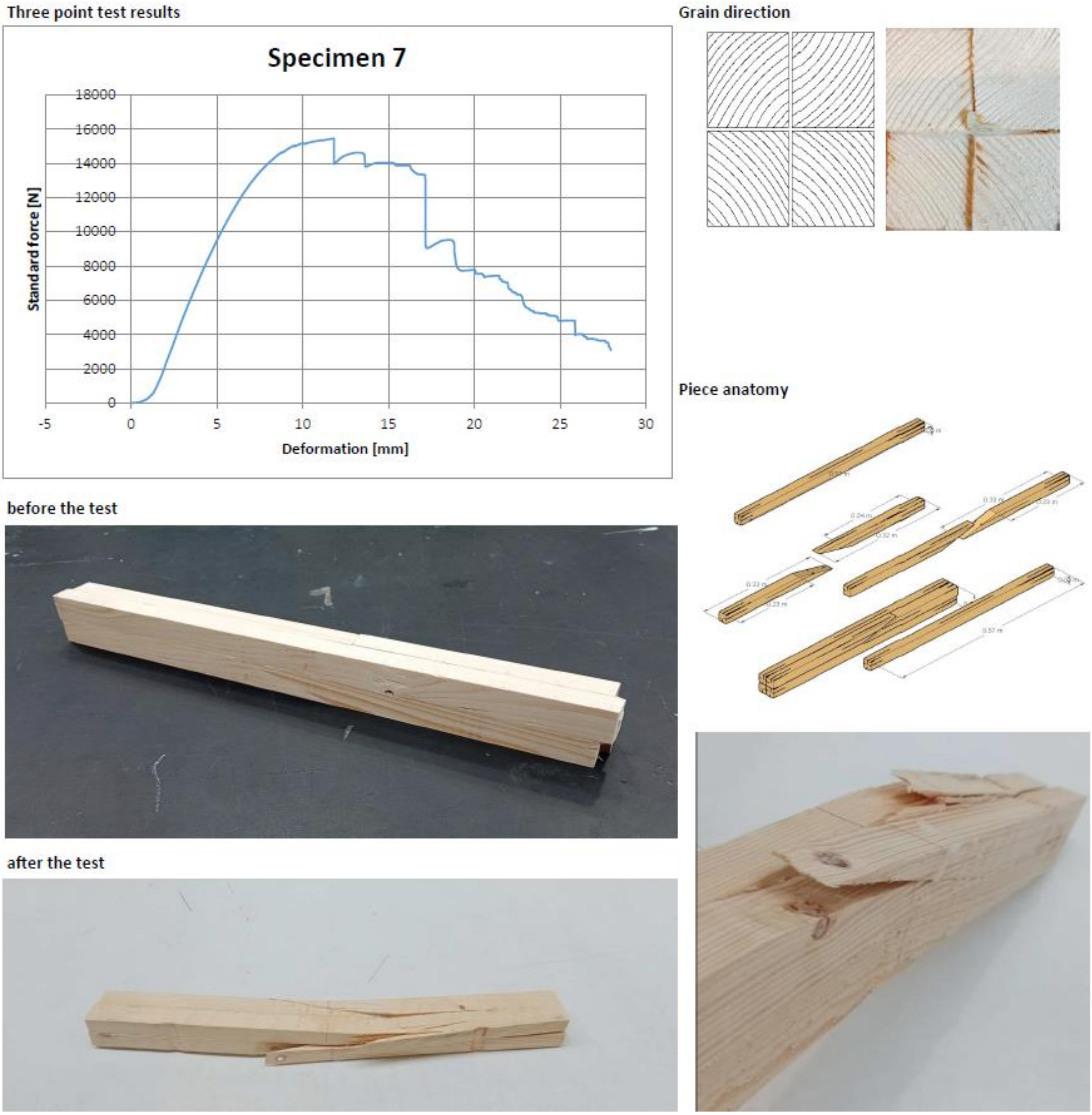



**FIGURE 63**

Types of failures description:

- In the graph, the specimen reached 15.4 kN and a deflection of 11.8 mm, the highest among the tested specimens.
- Similar to previous specimens, the lower lamella containing the slope cut experienced partial delamination at the edge of the cut corner. Meanwhile, its adjacent neighbour, the continuous lower lamella, experienced a crack propagated along a path parallel to the 1:4 slope in the lower lamella. The upper part didn't suffer from any rupture, but the corner between the three pieces was delaminated.
- Considering the compression force generated at the end of the specimen, a split is noticed in the lower continuous lamella (at the same position as the fibre extrusion in specimens 5 and 6), accompanied by vertical side delamination from its adjacent member.

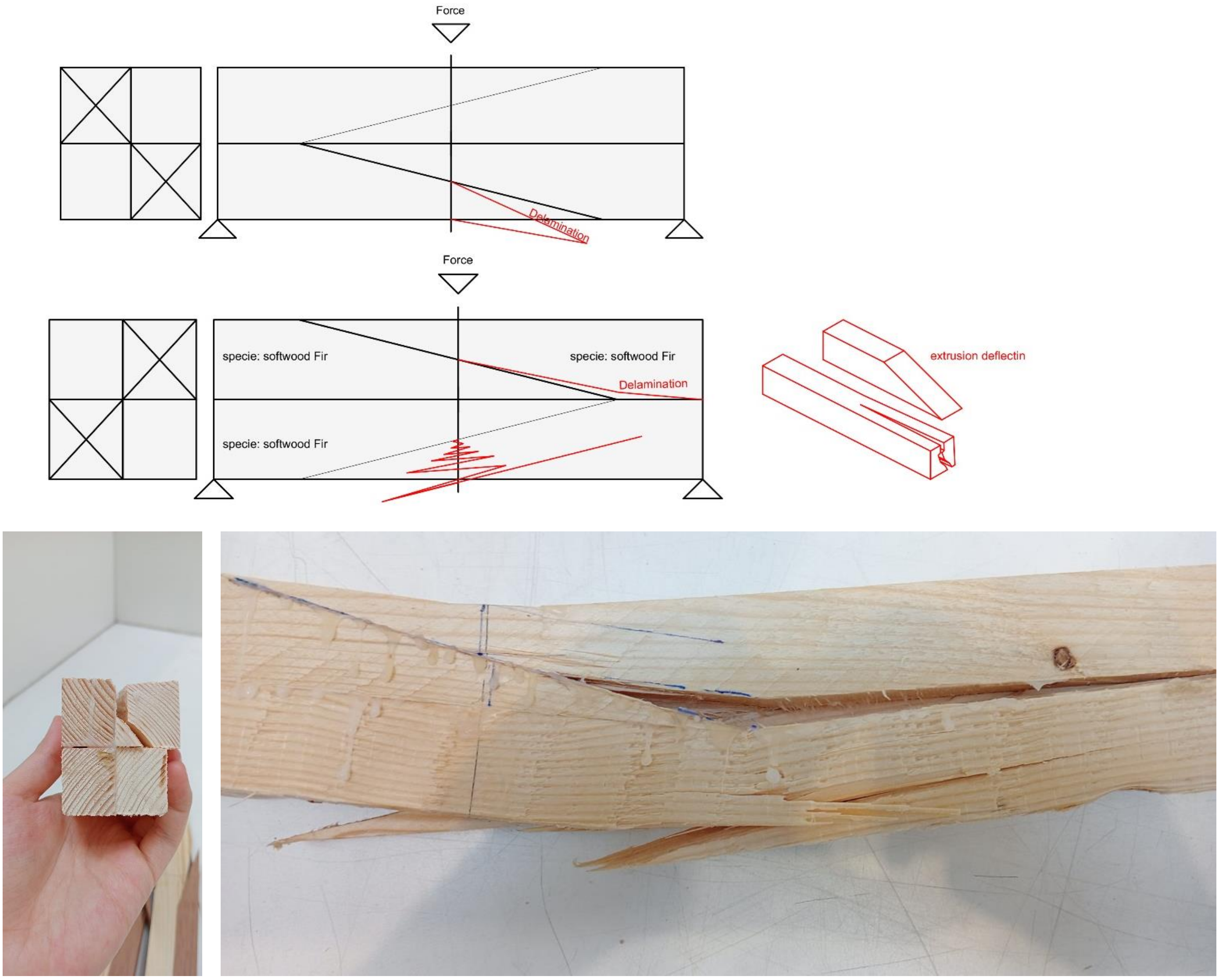



**FIGURE 64**

## 4.9 Conclusion

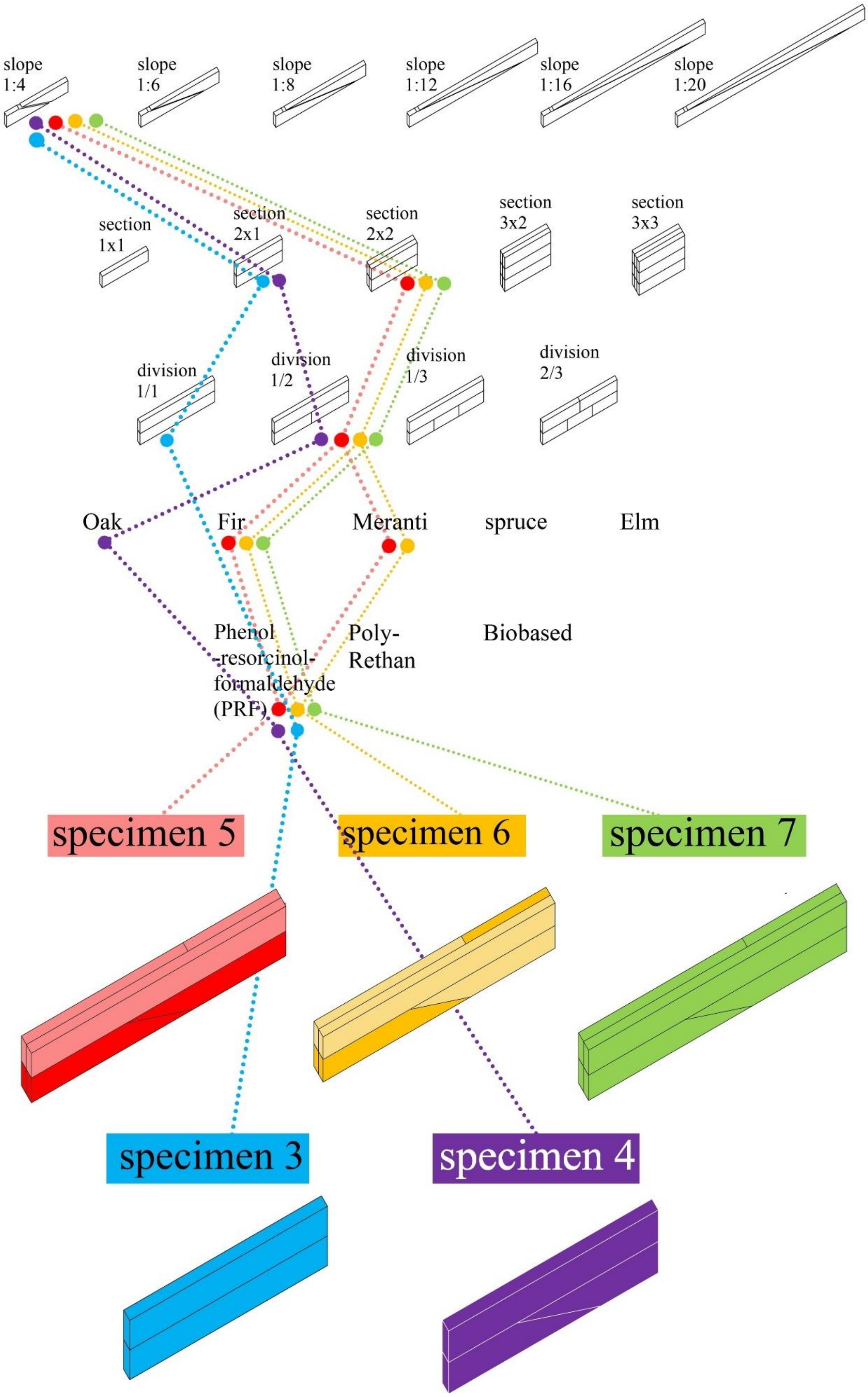



**FIGURE 65: SPECIMEN CHOOSING CRITERIA (OWN WORK )**

| **TABLE 8** | $F_{max}$ | dL at $F_{max}$ | $F_{Break}$ | dL at break | $a_0$ | $b_0$ | $S_0$ |
|---|---|---|---|---|---|---|---|
| | N | mm | N | mm | mm | mm | mm² |
| Specimen 3 | 10739.19 | 7.363589 | 10363.42 | 7.445922 | 100 | 100 | 10000 |
| Specimen 4 | 8088.012 | 6.674073 | 4688.503 | 11.99171 | 100 | 100 | 10000 |
| Specimen 5 | 20574.39 | 6.110257 | 3984.609 | 18.87277 | 100 | 100 | 10000 |
| Specimen 6 | 19697.14 | 9.479986 | 3933.534 | 26.73088 | 100 | 100 | 10000 |
| Specimen 7 | 15463.81 | 11.81508 | 3092.065 | 27.96162 | 100 | 100 | 10000 |

### 4.9.1 Comparative study and findings from the previous test

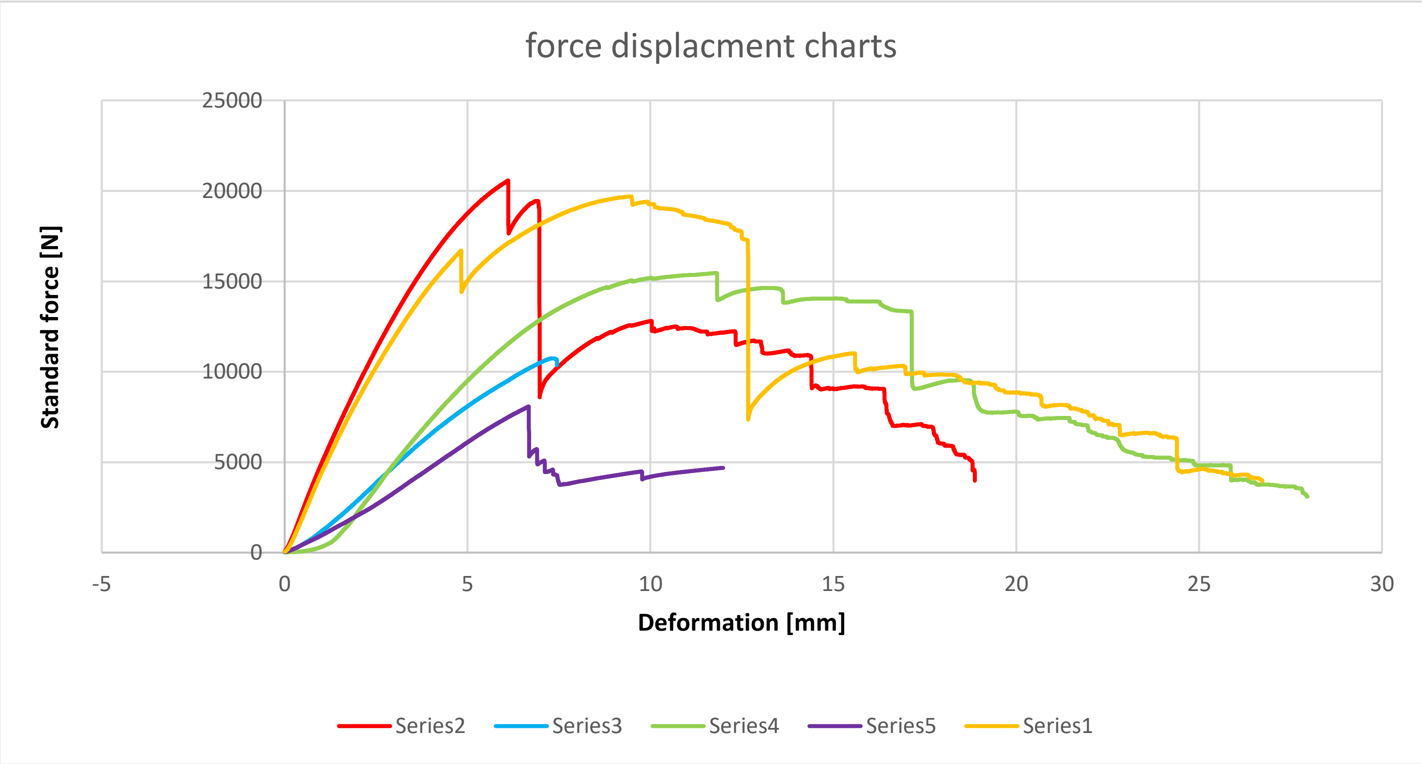



**FIGURE 66: FORCE DISPLACEMENT CHART(OWN WORK )**

By combing the graphs for all the specimen, we can see the difference in stiffness and flexibility for each piece:

1- Due to lamination issues and the anatomy of the specimens, all except for specimen 3 experience a sudden drop in the applied force after the lower lamella breaks.
2- After the drop, the pieces exhibit a non-linear elastic behaviour as strain transitions from the lower lamella to the upper one. This increase is evident in specimens 5 and 6, where the lower lamella is mostly made of hardwood, and less clear in specimen 4. Specimen 7, made of a single piece of timber with uniform stiffness, does not exhibit a prominent increase in non-linear elastic behaviour. Minor drops in force are observed, indicating the gradual collapse of the pieces forming the joist.
3- Specimen 5 has the highest stiffness among the tested pieces, withstanding more than two tons before breaking. Specimen 6 exhibits similar behaviour, remaining in the elastic range for a longer period despite reaching higher deformation values before failure.
4- Specimen 7 undergoes the longest period of plastic deformation before failure.

### 4.9.2 Optimizing Strength in Interlocking Glued Solid Timber from Reclaimed Sources: Key Considerations

To enhance the strength of interlocking glued solid timber (IGST) derived from reclaimed timber, several key considerations should be addressed:

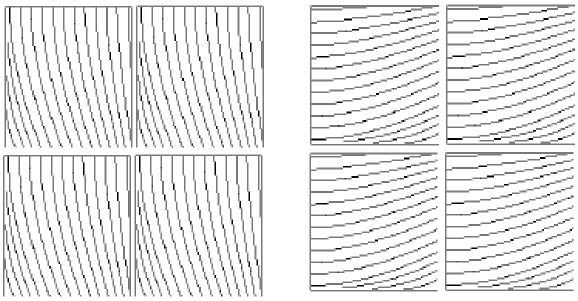
1. Glue Selection and Application: Significant attention must be devoted to the type and quantity of adhesive utilized in the lamination process. Additionally, the positioning of clamps and surface treatment techniques are crucial factors that impact the performance of specimens. Addressing these aspects meticulously during lamination is essential for optimizing specimen strength and durability.


he type of glue
sed for the pre-
ious experi-
ıent


The proposed glue for future experiments

**2. Grain Orientation:** While aligning the grain perpendicular to the applied force is essential, it may not always suffice, especially in specimens composed of four lamellas. Observations indicate that the fibres of the lower lamella may experience tearing due to compression forces at the joist's end. To mitigate this issue, further exploration of grain direction within this lamella is recommended. This may involve:

- Avoiding diagonal grain orientation in the lower lamella.
- Striving for uniform grain direction across all lamellas to promote structural integrity.



**3- Scarf Joint Enhancement:** In addressing the slope cut, also known as a scarf joint, efforts should be made to minimize delamination at the joint's end. One potential approach is to enhance the connection method, such as utilizing a nipped scarf joint instead of a plane scarf joint. This modification can bolster the integrity of the joint and reduce the likelihood of delaminateon, thus contributing to overall

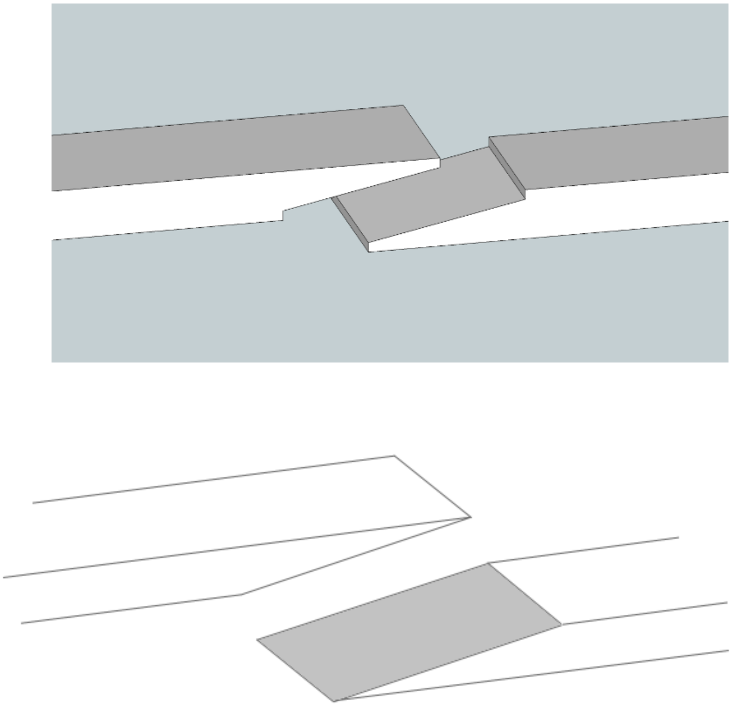


**FIGURE 67: PLANE VS NIBBED SCARF JOINT (OWNWORK )**

# SECOND PHASE OF EXPERIMENTS: 4 POINTS BENDING TEST OF FULL-SCALE SPECIMEN

# المرحلة الثانية من التجارب اختبار انحناء 4 نقاط لعينة كاملة الحجم

# 5. Second phase of tests

## 5.1 Introduction:

The previous experiments provided initial insights into the behaviour of interlocking glued solid timber (IGST) under bending forces, but practical applications involve additional considerations beyond the lab setting. These include scaling elements to real-world sizes, on-site assembly challenges, feasibility assessments, structural adhesion, logistics, and validation processes.

Our initial experiments, conducted domestically at the TU Delft campus using limited waste timber pieces, were conducted without the involvement of a skilled carpenter. However, they still provided valuable insights into the topic. To further explore this area within the wood industry context, we are fortunate to collaborate with Lorin Brasser, a carpenter specializing in timber demolition and cultivation near Amsterdam.

During a visit to Lorin's workshop and subsequent discussions, several key observations were made:

- Spruce is the predominant wood species used in construction, with additional availability of two types of hardwood: Meranti, imported from Indonesia and historically used for window frames, and Elm, sourced locally around Amsterdam and commonly used for furniture and tools.

- Including these wood species in further experiments ensures alignment with real-world waste materials.

Considering span requirements, typical single timber sections with a length of 2.4 meters can span spaces adequately without glued laminated timber (glulam). However, IGST becomes advantageous for spans exceeding 3 meters, necessitating the use of multiple pieces. Thus, we aimed to test the concept with a 3.6-meter span.

Another critical aspect affecting the sustainability of glulam products is the type and quantity of glue used. Many industry-standard glues may contain additives that emit potentially harmful chemicals during curing and contribute to environmental waste. Therefore, conducting experiments with various glue types, including both conventional and environmentally friendly options, will provide valuable insights into sustainable IGST production.

## 5.2 Aim of the experiments

To explore the limitation of the products of the proposed workflows, from stocks to a design, those limitations can be structural, or the workflow need to be enhanced to give better results

## 5.3 Objective of the experiments

To measure the strength of specimens that represent the proposed parameters in the parametric workflow.

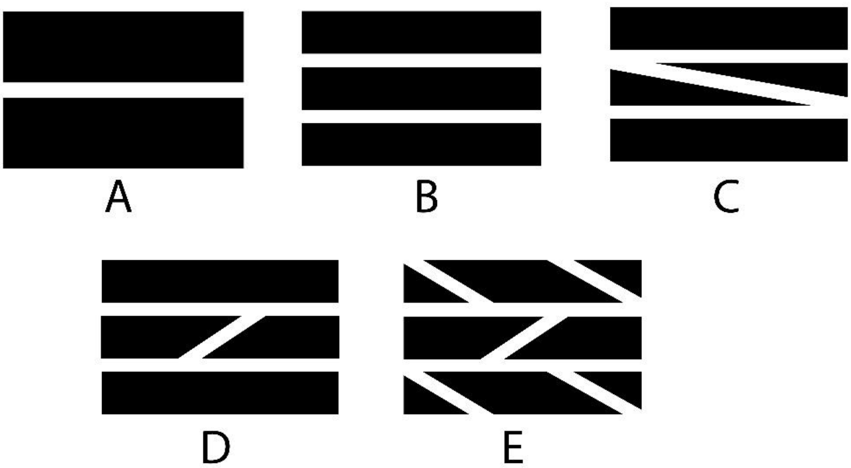
## 5.4 Hypothesis

We hypothesize that interlocking solid glued timber beams, produced through our workflow, will exhibit reduced strength as the number of lamellas and joints increases, despite having the same length and cross-sectional size. Each additional lamella and joint introduce potential weaknesses, potentially compromising structural integrity. By testing these beams, we aim to examine how these features affect beam strength,

## 5.5 Experimental questions

- How does the number of lamellas affect the strength of interlocking solid glued timber beams produced from reclaimed stocks?
- How do the quantity and placement of joints influence the overall strength of these beams?
- How does the slope ratio of the joints impact the performance and strength of the beams?

## 5.6 Methodology




Due to availability, the results of the matching algorithm can lead to different scenarios, each potentially affecting the performance of the beam. To explore these effects, specific availability challenges were highlighted, each represented by a distinct specimen layout. These layouts also explore the expected topologies from the matching algorithm. The highlighted scenarios are:

- Scenario A: A parallel joist made of 6 lamellas. The aim is to compare the performance of a 6-lamella joist with a solid joist and a 4-lamella parallel joist, to assess the effect of cross-sectional layout on beam performance.

- Scenario B: A 6-lamella IGST with 1:2 and 1:1 interlocking division ratios and an 8:1 scarf joint slope. The aim is to check the effect of increasing the slope ratio on beam performance.

- Scenario C: A 6-lamella IGST with 1:2 and 1:3 interlocking division ratios and a 8:1 scarf joint slope. The aim is to check the effect of dividing the length of the lamellas on beam performance.

To explore the effects of these scenarios, an in-situ test has been planned by conducting four-point bending tests for the four different specimens. Each specimen has a fixed cross-section, length, and wood species to highlight the effect of the proposed topologies on design strength. To validate the results of the mechanical tests, an FEA analysis was developed for a four-point bending test on an equivalent solid joist specimen. This allows for comparison of each beam's performance with an ideal scenario. The FEA was designed to match the boundary conditions of the planned test, with the same tested span of 3.20 meters, the same span between loading points of 1.6 cm, and the same discrete loading condition.

### 5.6.1 Fixed boundary conditions:

- Size of the beam (Length and cross section)
- Fixed timber size specie
- Fixed type of glue
- Fixed grain direction
- Fixed testing span (support and load)

**- The Beam Design:** The design of this test focuses on checking the applicability of concepts in real-life scenarios and anticipating expected problems during the manufacturing process to achieve that goal.

**- The length:** was chosen to cover a 3.6-meter space where it is hard to span this space with a single reclaimed joist.

**- The height of the Beam:** According to the rules of thumb, the ratio 1:20 was chosen to determine the height of the beam.

**- The timber species:** Spruce is a softwood commonly used for mass timber structures, and it is prominently available in reclaimed stocks.

**- Type of Glue:** Phenol-resorcinol-formaldehyde (PRF) adhesive will be used. PRF is strong, moisture-resistant, and ensures accurate, reliable test results. It also meets European standards, making it a dependable choice for testing.

## 5.6.2 Validating the results

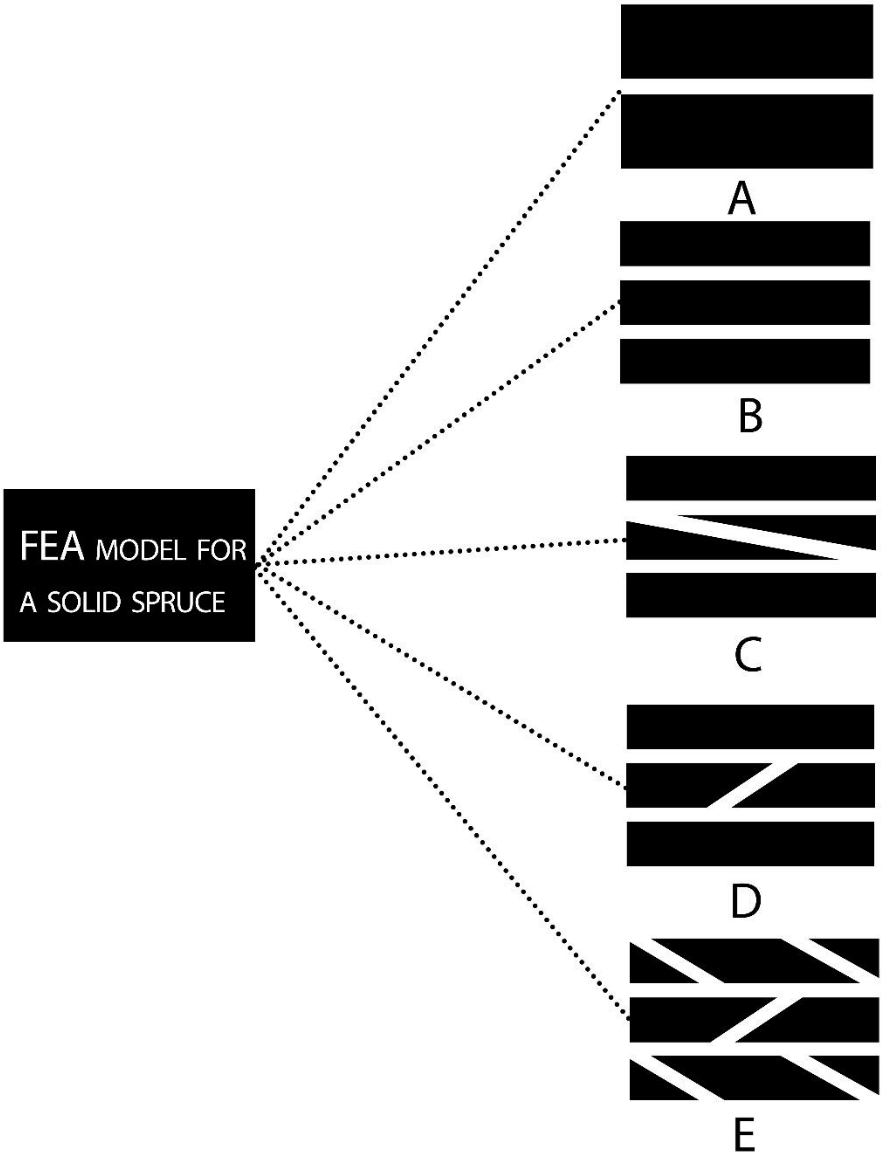



**FIGURE 68**

# 5.7 SECOND PHASE TEST SPECIMEN CONFIGURATIONS:

## 5.7.1 Specimen A,B:

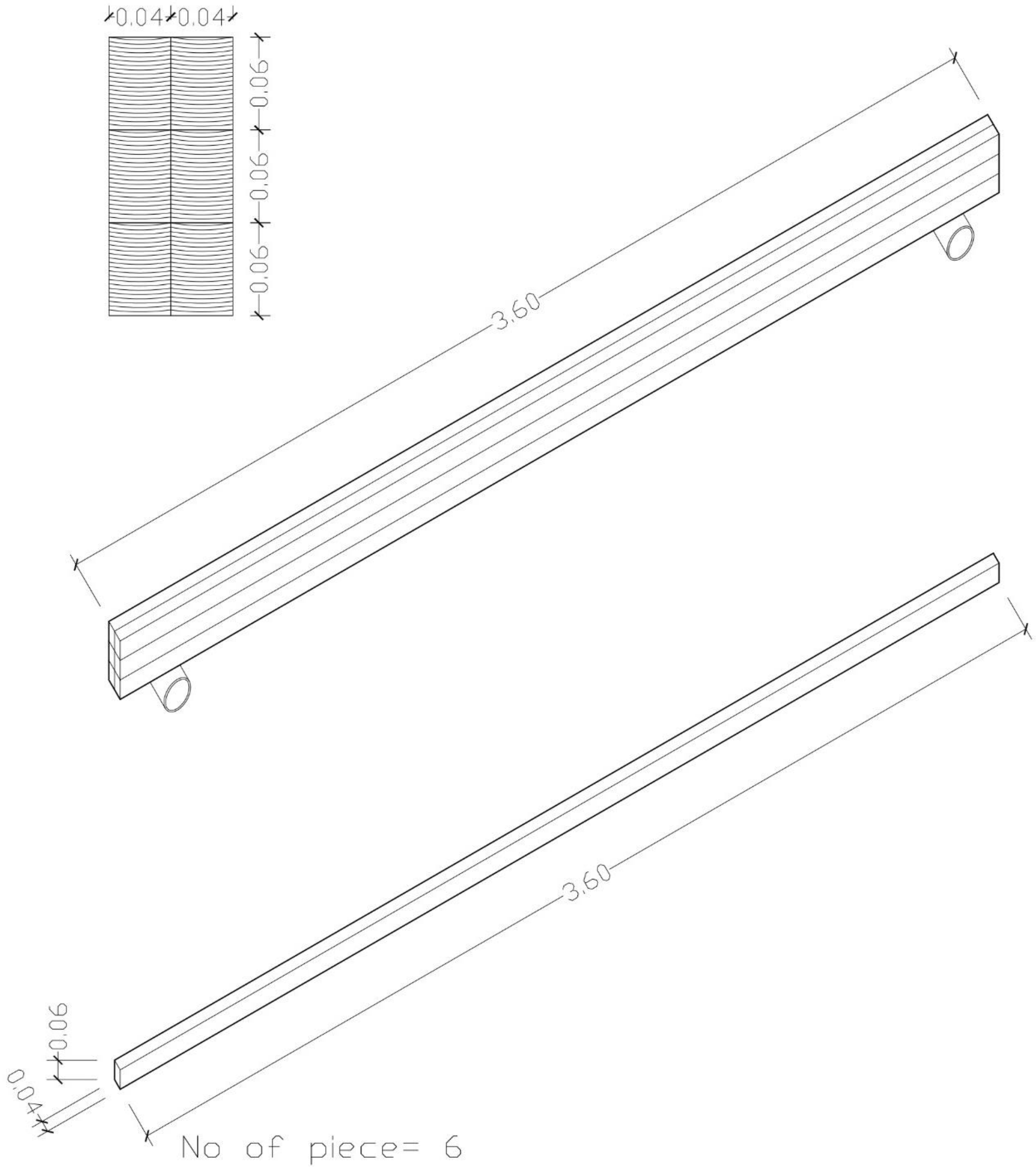



**FIGURE 69: SPECIMEN A,B CUT LIST (OWN WORK )**

## 5.7.2 Specimen C

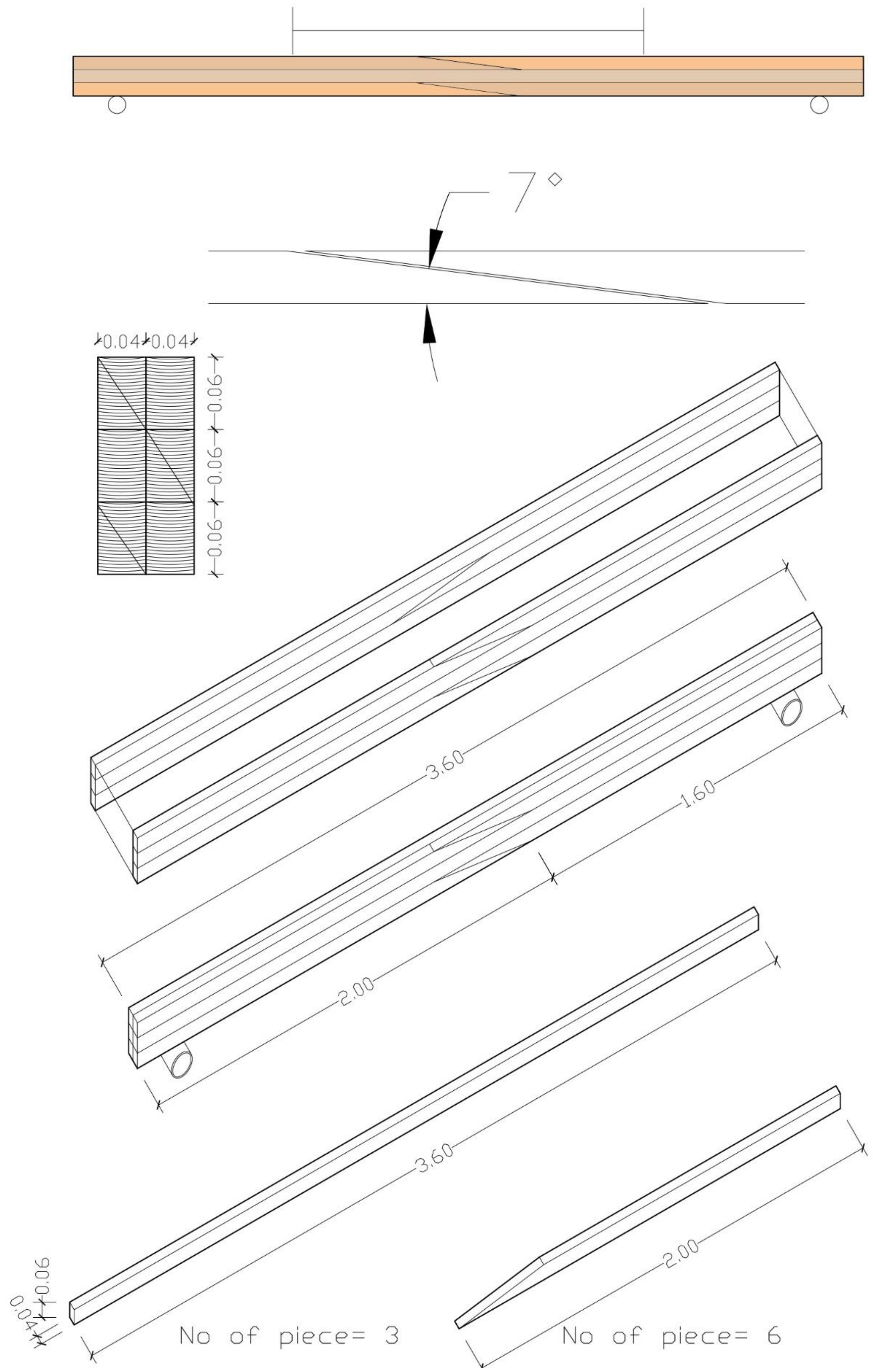



**FIGURE 70; SPECIMEN C CUT LIST (OWN WORK )**

## 5.7.3 Specimen D

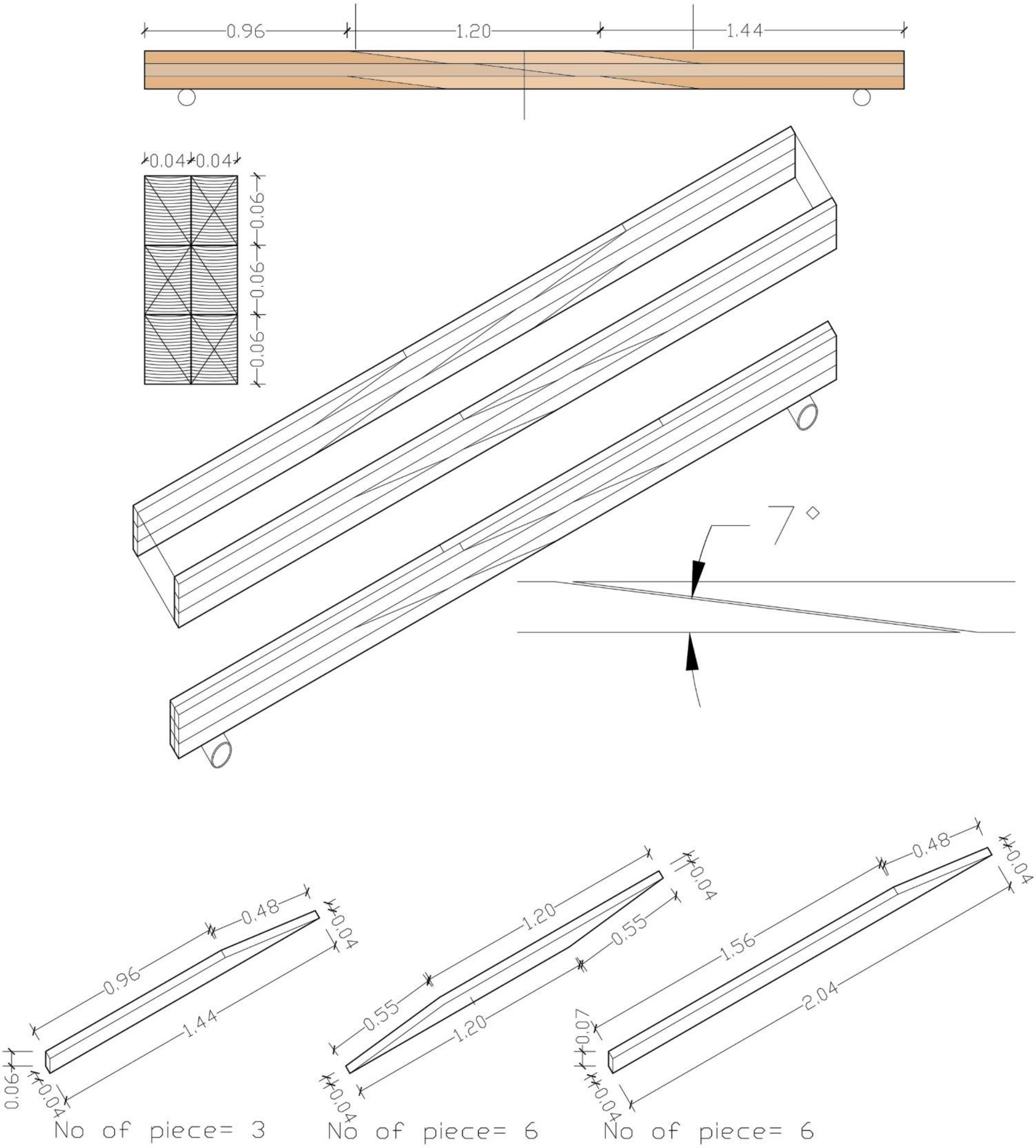



**FIGURE 71: SPECIMEN D CUT LIST (OWN WORK)**

# 5.8 Test preparation and samples manufacturing

### 5.8.1 Sourcing the pieces:

In a salvaged material warehouse 10 km away from the wood workshop, piles of used solid spruce joists with lengths between 3.8 to 4.2 m, mostly graded C24, were selected for the experiments through a quick visual grading process. This process can be summarized as follows:

- **Avoid Fungi and Rot**: This is easy to spot by checking for any change in color or decay.
- **Check the Moisture Content**: Most pieces were dry to touch; ideally, a moisture content measurement device is recommended during this process.
- **Focus on Continuous Grain**: Select pieces with continuous grain along the length and avoid pieces where wooden fibers are interrupted by large knots.
- **Avoid Heavily Damaged Pieces**: Exclude pieces that are heavily damaged either during their previous lifespan or due to demolition.

CONTINIOUS GRAIN (PREFERED)

RAIN INTEREPTED BY BIG KNOTS (AVOIDED)

AVOIDED ROT

SEPERATING THE CHOSEN PIECES FROM THE VISUAL FIELD-GRADING

**FIGURE 72 CHOOSING AND VISUAL REGRADING FOR RECLAIMED TIMBER (OWN PHOTOS )**

### 5.8.2 Transferring the Pieces to the Wood Workshop

To transfer the pieces from the warehouse to the wood workshop, they were manually lifted onto the top of a van and brought to the workshop. There, they were hoisted by crane onto the working table.

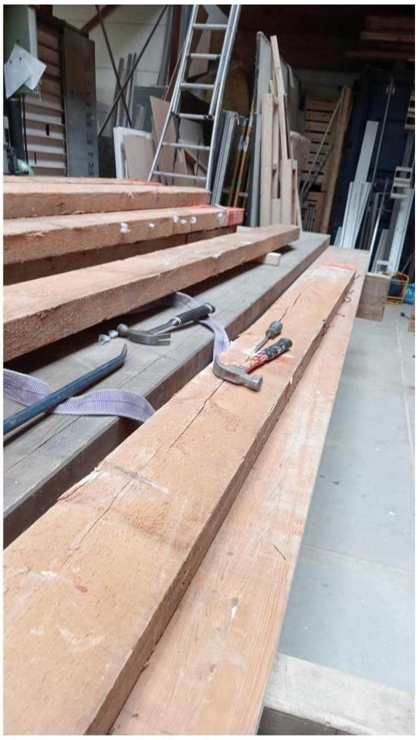
**FIGURE 73: USING SMALL VAN FOR TRANSPORTATION (OWN PHOTO)**

Primary calculation were done to figure out the amount of timber needed to do the samples which was around 5 beams, however to be in the safe side, an extra 5 beams where collected to avoid any material shortage.

### 5.8.3 Cleaning the preparing the piece:

The reclaimed pieces were placed on the table and cleaned of nails, screws, hooks, and any metal objects that might cause problems during sawing and planning. This process took around one day to clean the 10 beams. It is important to note that most of the metal elements were removed easily, but some rusty nails were stuck inside the fibres. Fortunately, these were located at the ends of the beams, so they were chopped off to bring the pieces to the design length.

RUSTY SCREWS STUCK INSIDE THE FIBERS

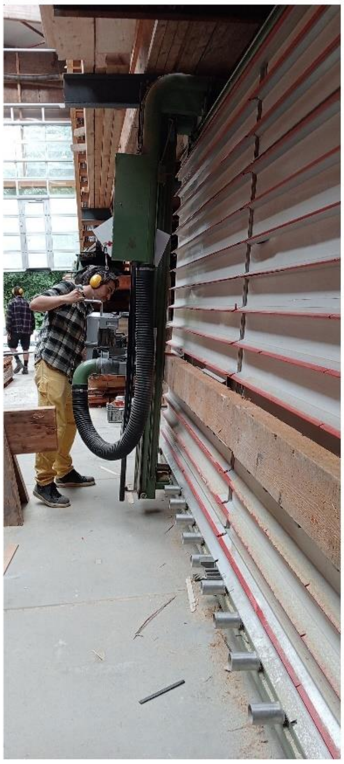


DURING THE PROCESS OF CLEANING

**FIGURE 74: CLEANING RECLAIMED ELEMENTS (OWN PHOTOS)**

### 5.8.4 Planning and cutting the pieces in size:

- After the cleaning the piece were planed from both sides to ensure a right-angle corner
- Then the pieces were sewn using the table saw and vertical wall saw, in order to bring the pieces roughly to the required Lamella size, with 9-millimetre tolerance
- The last step was to plane the lamella to have exactly the required section 6 x4 cm



USING THE VERTICAL WALL SAWY TO CUT THE PIECES

USING THE PLANNER TO PLAIN THE PIECES IN SHAPE



USING TH TABLE SAW TO CUT THE BIGGER PIECES

BUNNDLE OF LAMELLA READY FOR LAMINATING

**FIGURE 75: CUTTING PROCESS (OWN WORK )**

## 5.8.5 Assemble the pieces:

- Before laminating, all beams were double-checked, dry-fitted, and clamped to identify any cutting issues.
- The pieces were numbered to ease the assembly process.
- After checking, the workbench was prepared for lamination by cleaning the table, covering it with foil, and setting up timber sticks to lift the pieces.
- Clamps were collected and prepared for immediate use after lamination


CHECKING THE MOISTURE CONTENT BEFORE LAMINATING

DRY FITTING , AND DOUBLE CHECL THE SIZE OF THE PIECES

AGGREGATE THE DRY FITTED PIECES CLAMPS TO MOVE IT TO THE WORKING BENCH

PLACING THE PIECES ON THE WORKING BENCHES AND PLANNING THE THE CUT

**FIGURE 76: DRY FITTING (OWN WORK )**

### 5.8.6 Glueing the pieces:

- As we mentioned the used glue is epoxy based RS80 billiard , which consists of two component, a powder (hardener)and resin liquid , this type of glue is commonly used in laminating structural timber, even though it's not environmentally friendly.
- According the manual to laminate for each 5 portions of liquid in potion of hardener, and 1 kg for 2.5 to 3 meters, so to do the mixing also a pair of buckets and scale where prepared on the spot, specially that the process of applying the glue should not extend more than 10 minutes which required to plan using the mixture in periods to not spoil it.


**FIGURE 77**

**FIGURE 78: MIXING THE TWO COMPONENT OF THE GLUE (OWN PHOTO)**

**FIGURE 79:CLAMPING AFTER GLUEING (OWN WORK )**

Glueing sequence

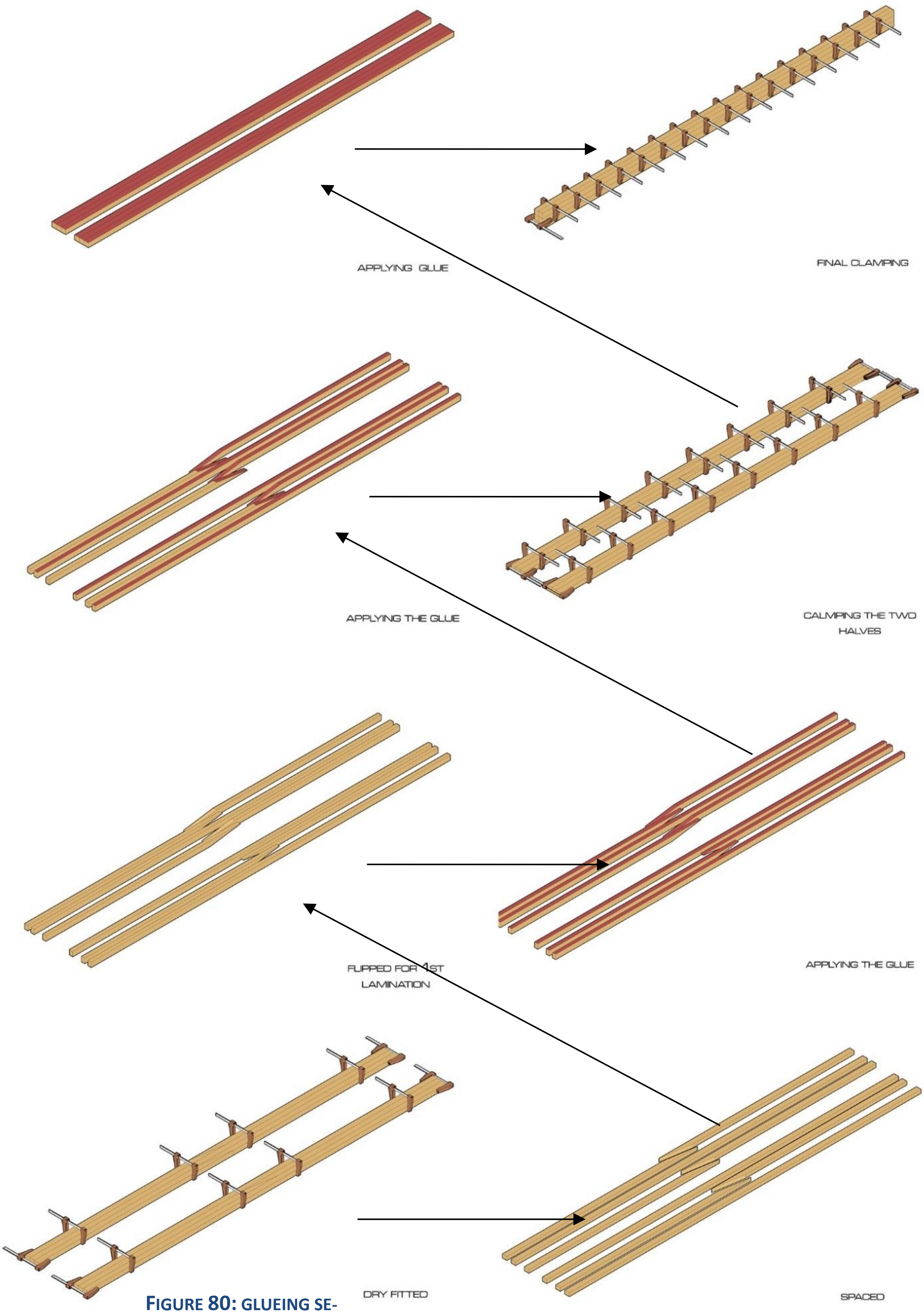



**FIGURE 80: GLUEING SEQUENCE (OWN WORK )**

## 5.9 Test Procedure:

1- Firstly, determine the positions of the two loading points on the beam, each located at L/3=120L/3 = 120L/3=120 units away from the rear support.

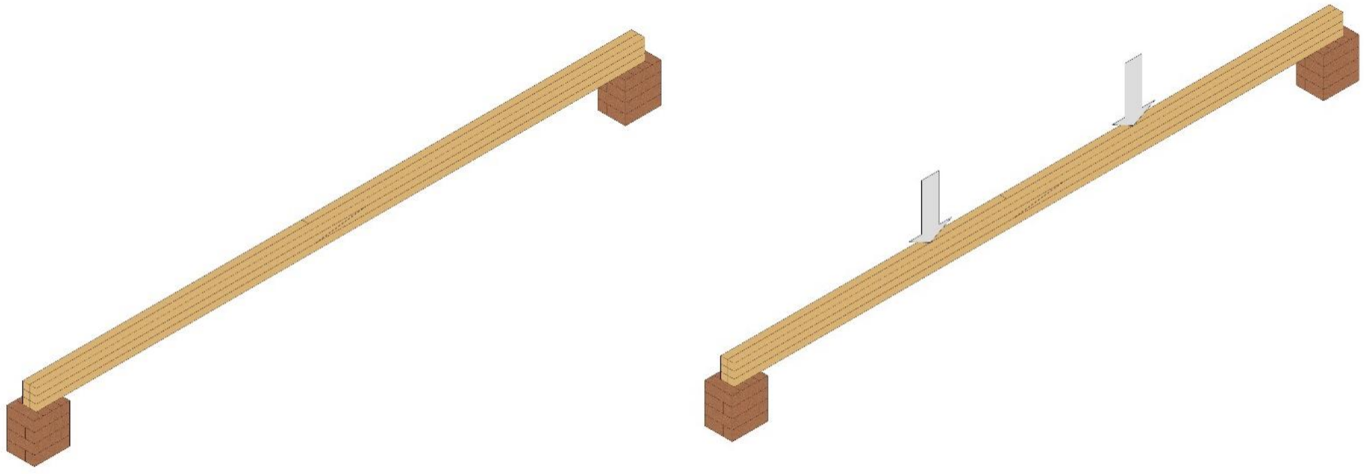


**FIGURE 81: ISOMETRIC TO SHOW THE LOADING SPAN (OWN WORK )**

2- Secondly, identify the components necessary to distribute the load and transfer it to the two designated points on the beam at the aforementioned locations.

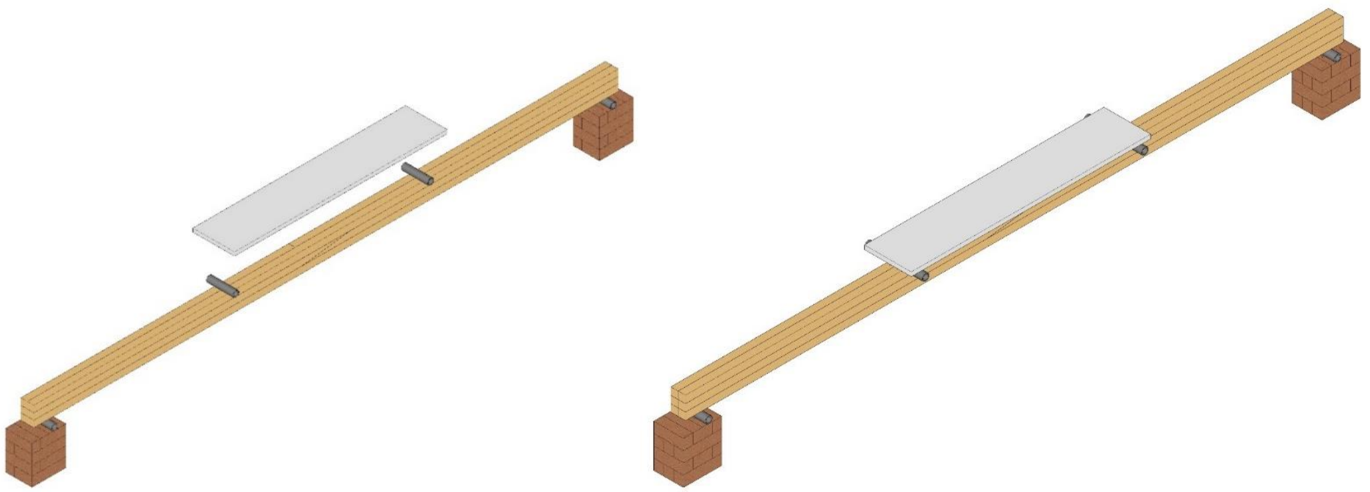


**FIGURE 82: ISOMETRIC FOR THE COCNPET OF THE TEST (OWN WORK )**

3- To achieve this, four steel round hollow sections with a diameter of 7.5 were employed as pivoting connections. These sections facilitated simple support and allowed deflection in response to the load at the points of contact and the reaction forces at the supports.

4- To prevent the section from moving away from its designated points, screws were installed into a CLT block (two blocks used to elevate the specimens from the ground). Additionally, clamps were positioned to secure the beam and prevent it from tipping

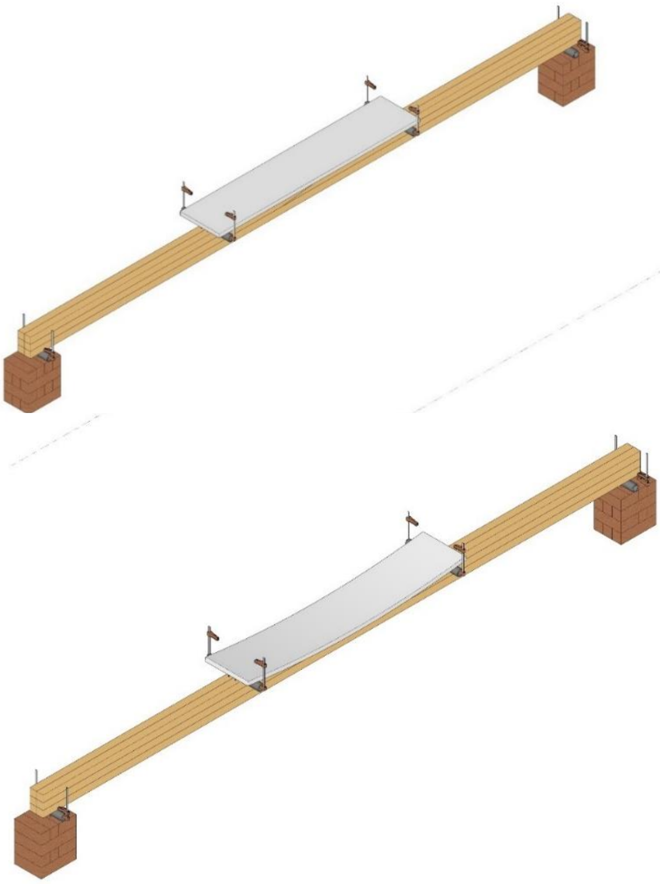
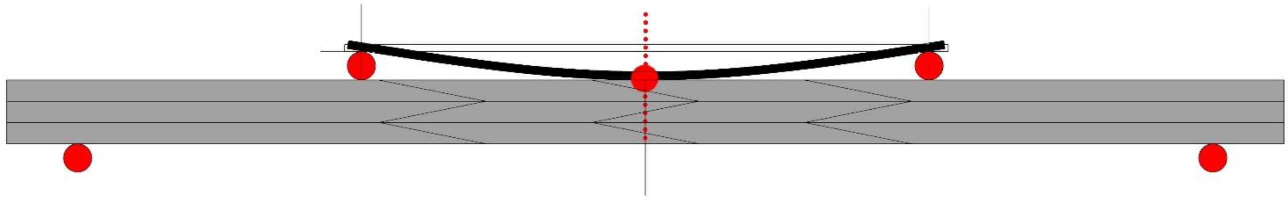


**FIGURE 84: USING CLAMPS TO RESTRICT MOVOMENT(OWN OHOTO )**



over the steel sections, as shown in the photograph.

**FIGURE 83: LOADING BOARD DEFLECTING ADDING EXTRA LOADING POINT ON THE SPECIMEN (OWN WORK )**

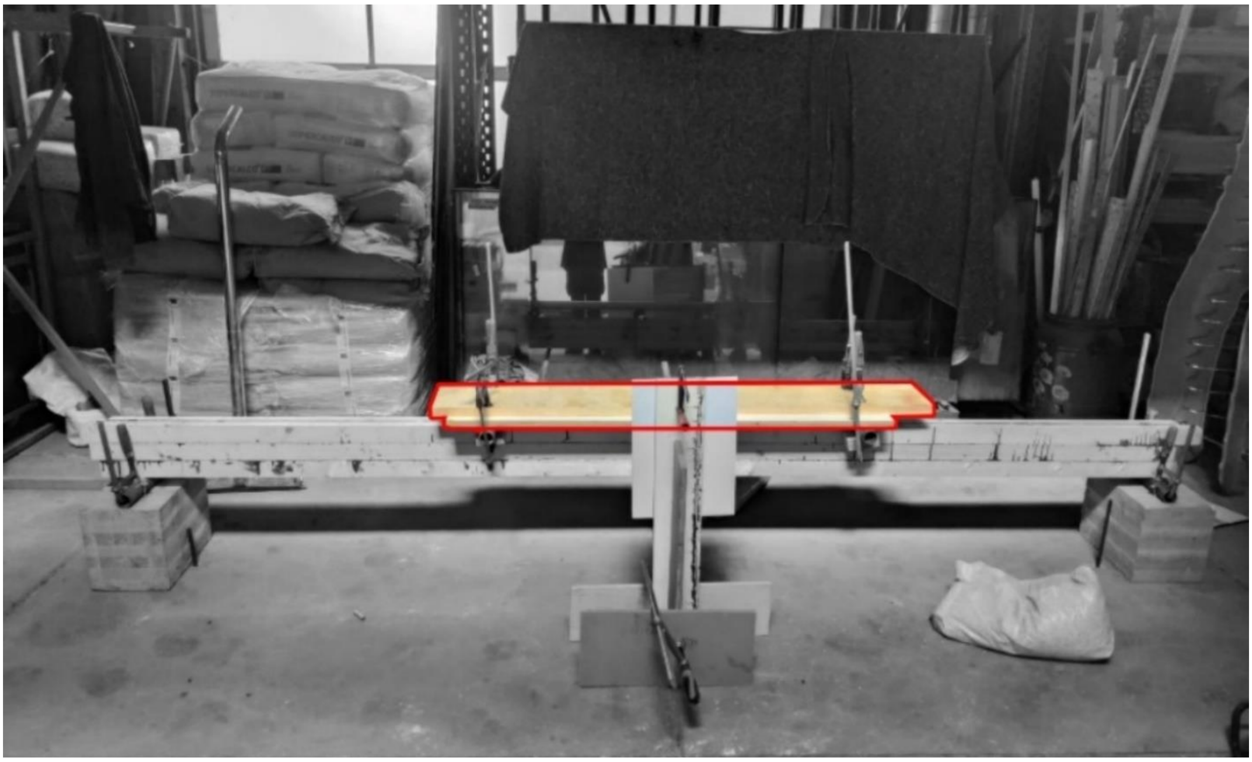


FIGURE 85: INCREASING THE THICKNESS OF THE LOADING BOARD (OWN PHOTO )

5- One potential issue anticipated was the sagging of the loading board to the extent that it could touch the specimen, introducing an unintended additional loading point. To prevent this, we calculated the theoretical deflection of the board based on the applied load. Subsequently, we selected a board that could withstand the desired load without failing due to excessive deflection, a board of Elm hard wood with 2.5 cm thickness

6- Furthermore, we accounted for the maximum allowable sagging by providing buffer space, ensuring that the board can deflect sufficiently without making contact with the specimen.

**FIGURE 86: ELEVATING THE LOADING BOARD(OWN PHOTO)**

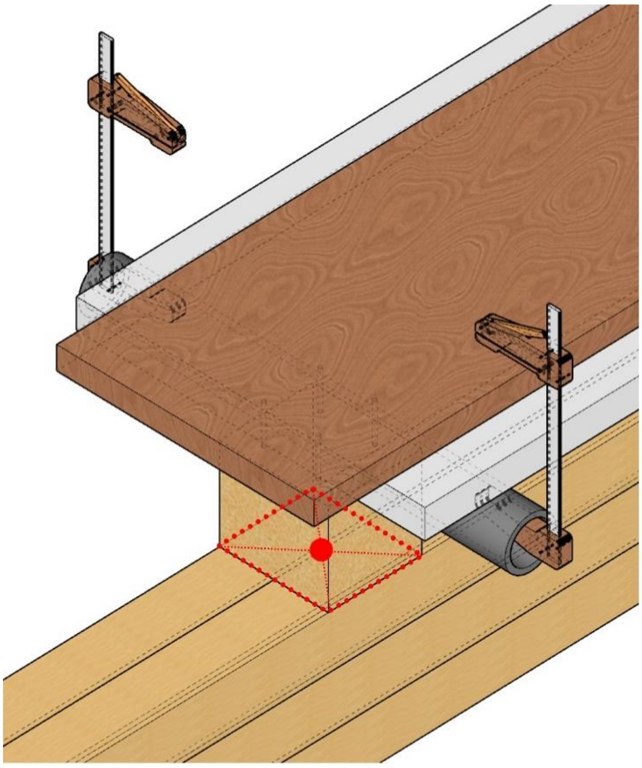


**FIGURE 87**

7- In conducting this experiment, it is crucial to ensure the specimen receives the load at the intended point. The steel section is ideal for this purpose as the specimen will only contact it tangentially. When elevating the loading board, it is important to

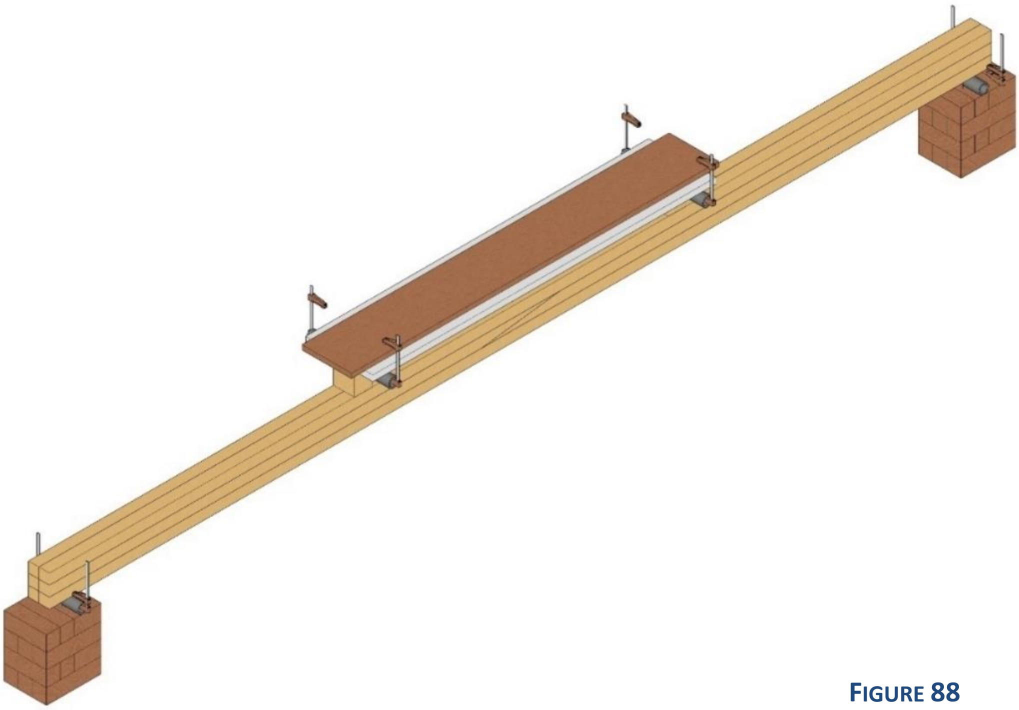
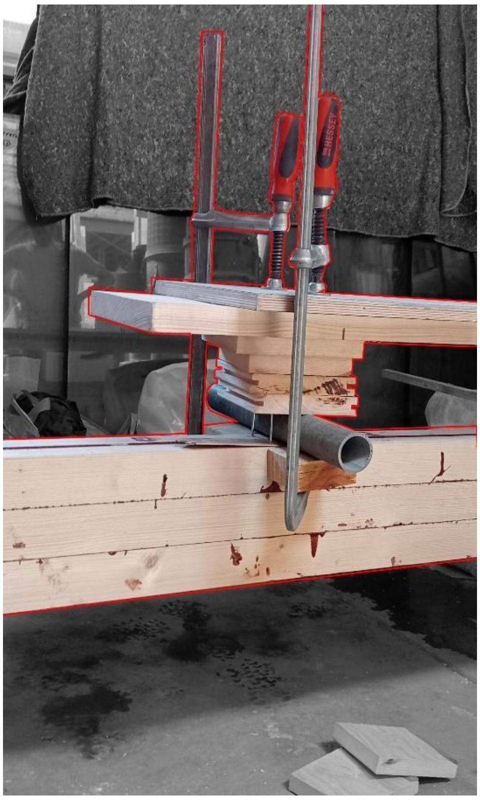


**FIGURE 88**

prevent the block from touching the specimen. To achieve this, the component was flipped upside down.



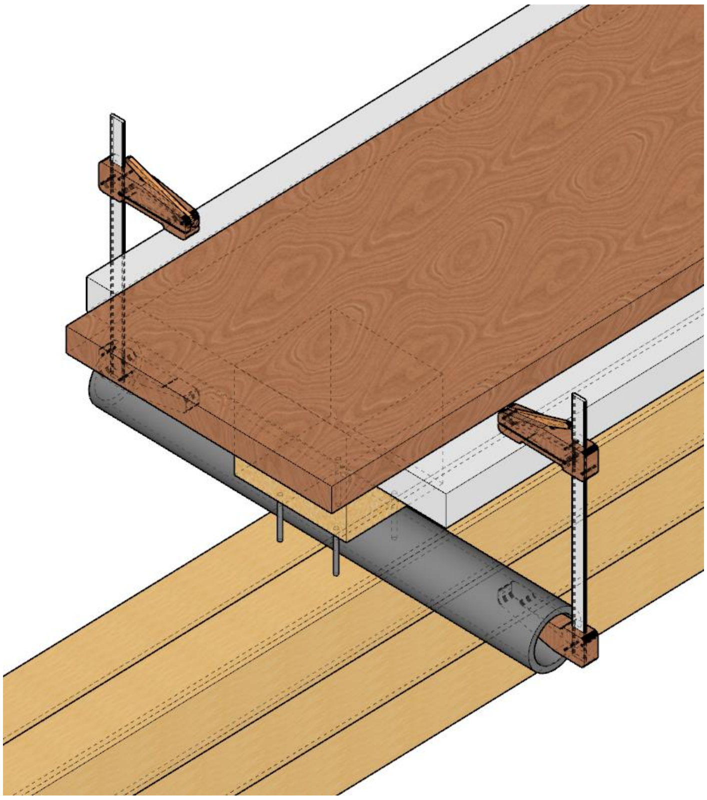


**FIGURE 91: (OWN PHOTO)**

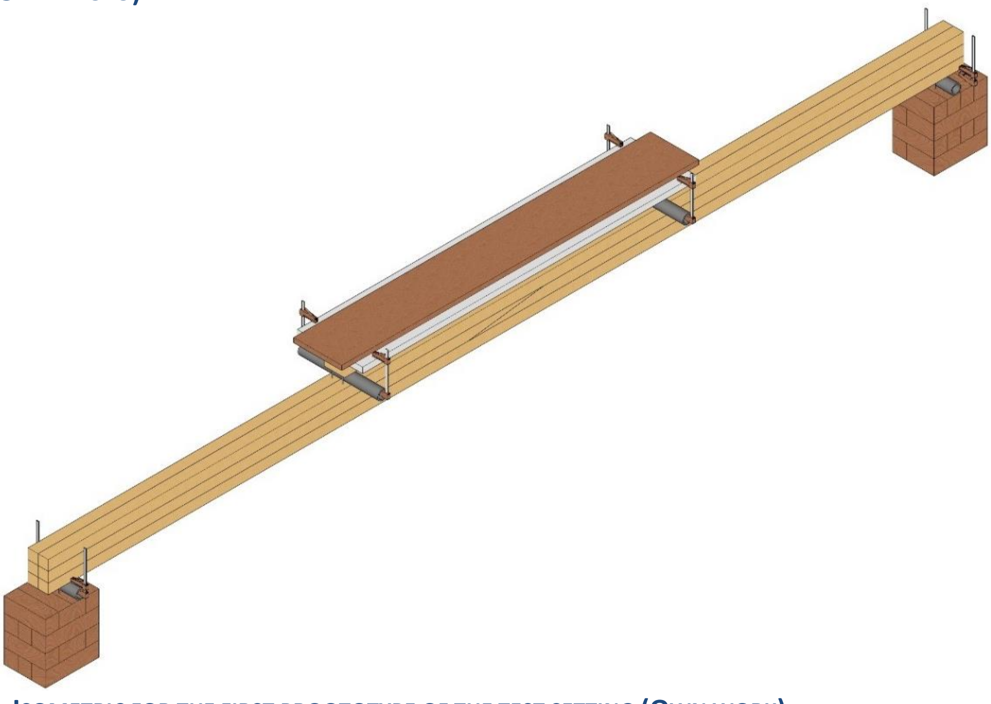


**FIGURE 89: ISOMETRIC FOR THE FIRST PROOTOTYPE OF THE TEST SETTING (OWN WORK)**

8- With the beam ready to receive the desired load, the challenge was balancing the steel connections' overhangs to prevent toppling. Adding more clamping force along the beam's ZX axis could affect the section's inertia at the clamping point. Therefore, two pieces of timber were clamped in the XY orientation to support the section from underneath.

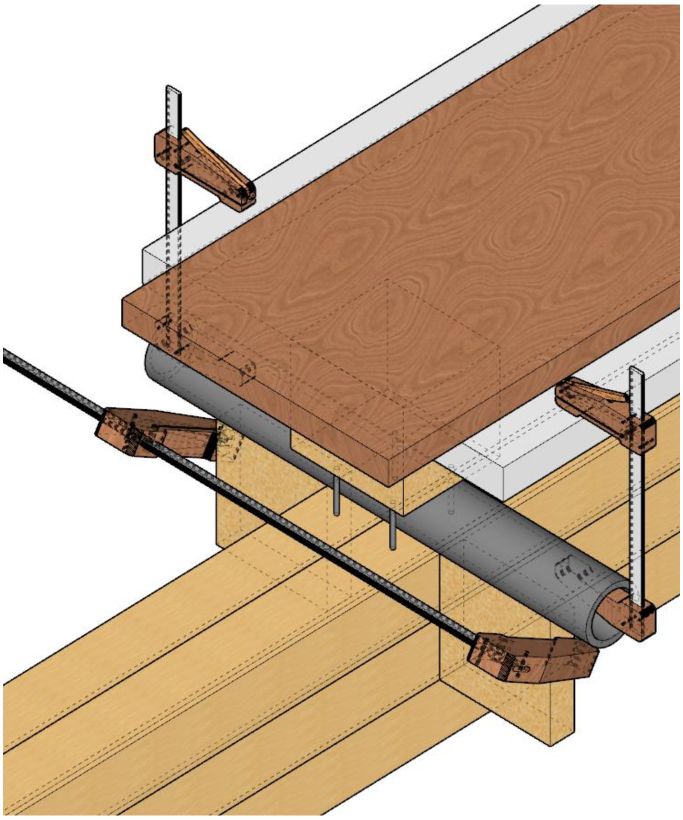


**FIGURE 92: CLAMPING FLANGS TO SUPPORT THE STEEL SECTION (OWN WORK)**

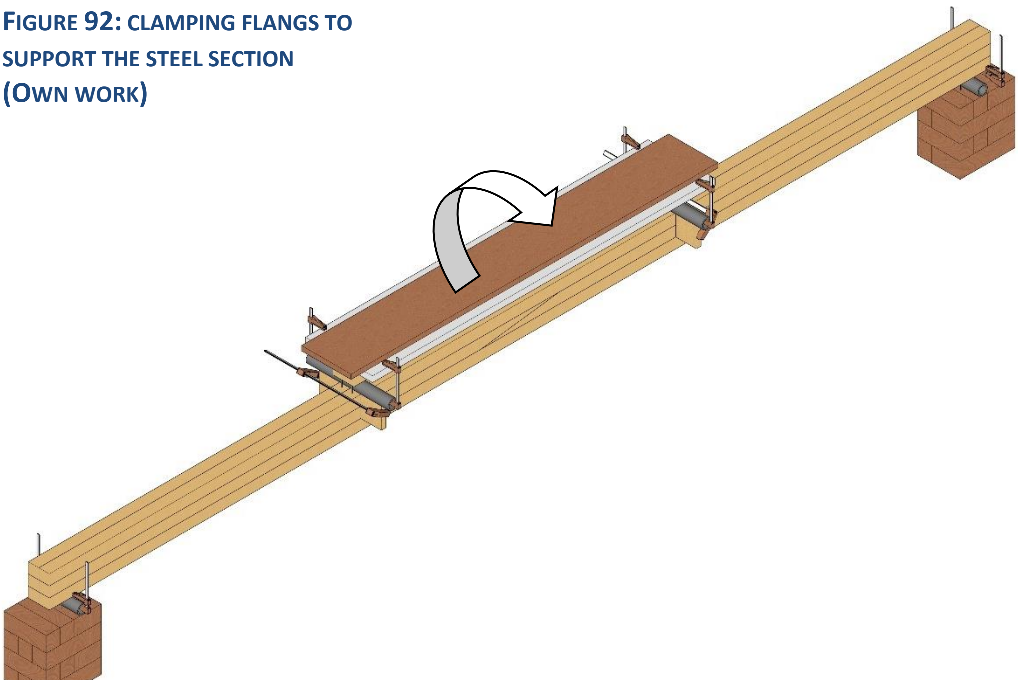
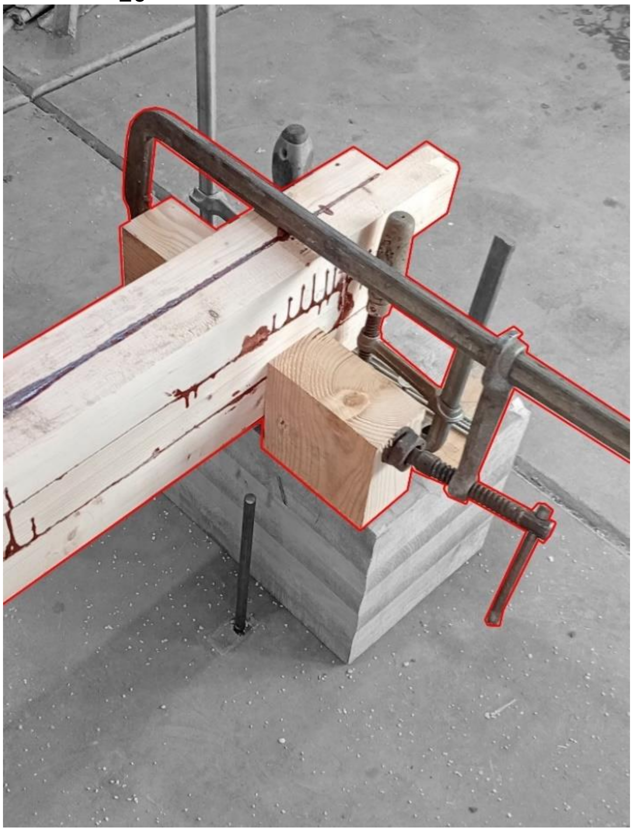


**FIGURE 93: ISOMETRIC FOR TEST SETTING (OWNWORK)**

9- A similar issue was noticed near the support, where preventing the beam from toppling over the rear support became critical as the load increased. To address this, two blocks of timber were clamped to both ends of the beam to prevent rotation on the XZ axis. Additionally, the clamps were positioned along the same axis for stability.

10-



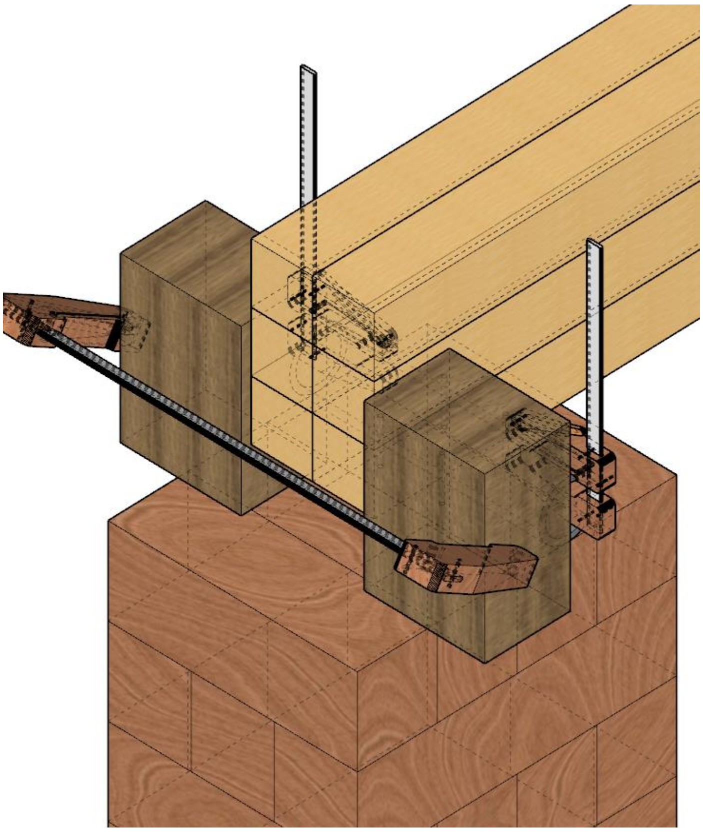


**FIGURE 95(CLAMPING THE END OF THE BEAM (OWN PHOTO)**

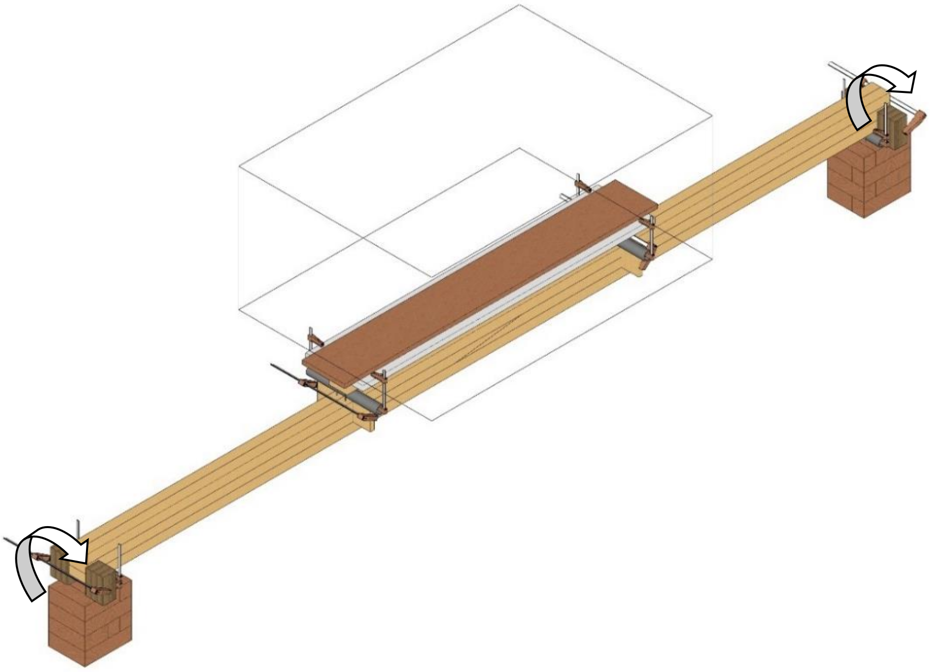


**FIGURE 94: ISOMETRIC OF THE TEST SETTING (OWN WORK )**

Sandbags were planned to be used as a load to test the beam's capacity. However, the required load exceeded the space available on the loading board. To extend the loading area, a wooden pallet was clamped on top of the loading board.

**FIGURE 96: LOADING USING SANDBAG(OWN PHOTO)**

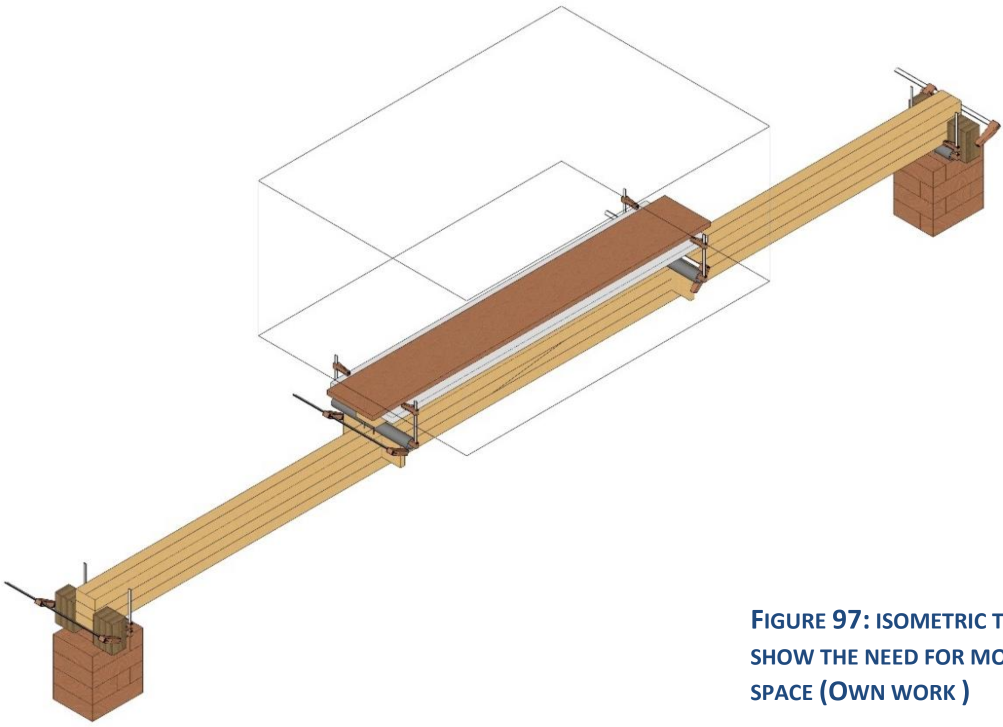


**FIGURE 97: ISOMETRIC THAT SHOW THE NEED FOR MORE SPACE (OWN WORK )**

11- Due to frequent movement and nails in the pallet, some sandbags were scratched and their contents spilled. The more the sandbags moved, the greater the damage. To prevent this hazard, a plastic blanket was placed between the sandbags and the pallet, but the bags continued to be damaged.

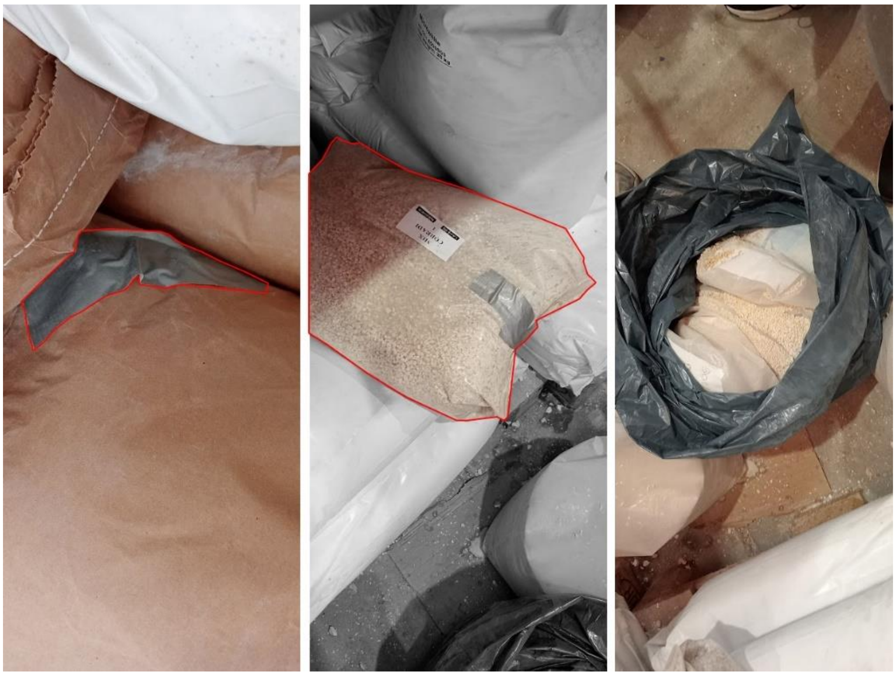


**FIGURE 98: TORN SAND BAGS (OWN PHOTO )**

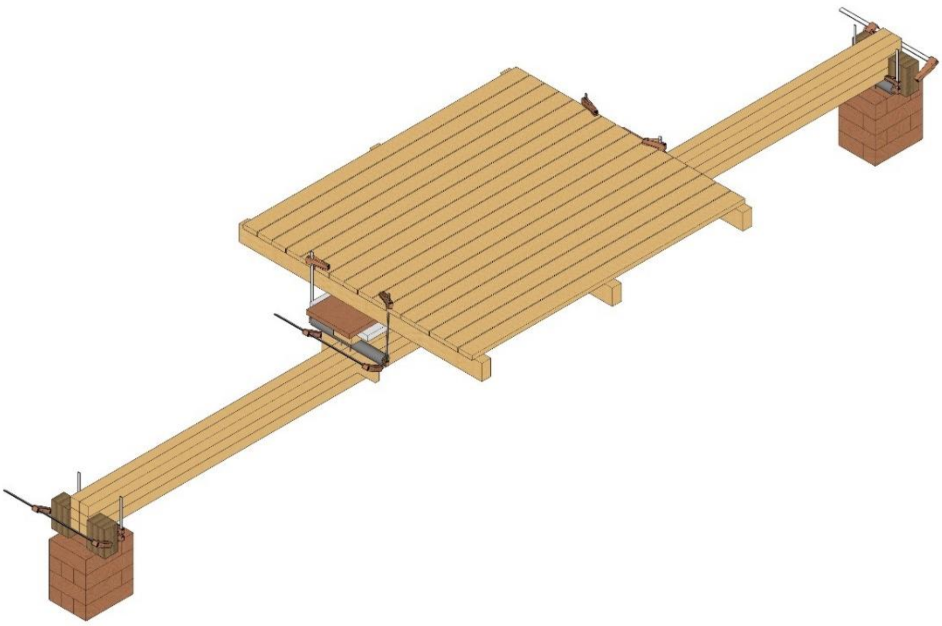
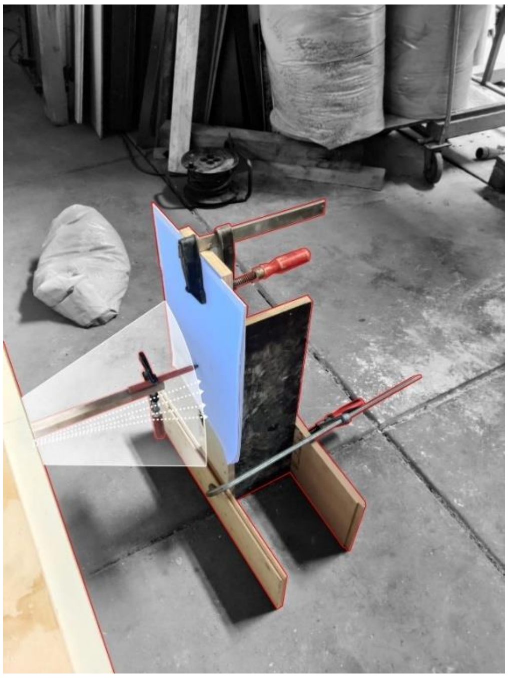


**FIGURE 99: ISOMETRIC VIEW FOR TESTING SETTING (OWN WORK )**

12- In addition, balancing the sandbags on the loading board was cumbersome, causing uneven load distribution and minor movements among the test elements. As a result, it was difficult to stabilize the weight for accurate readings on the recording boards.



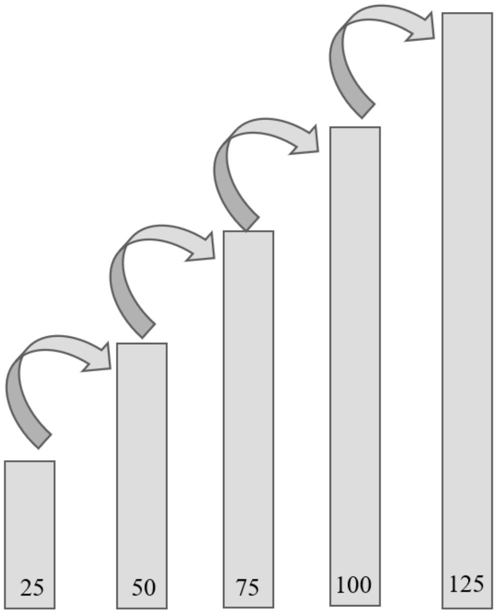
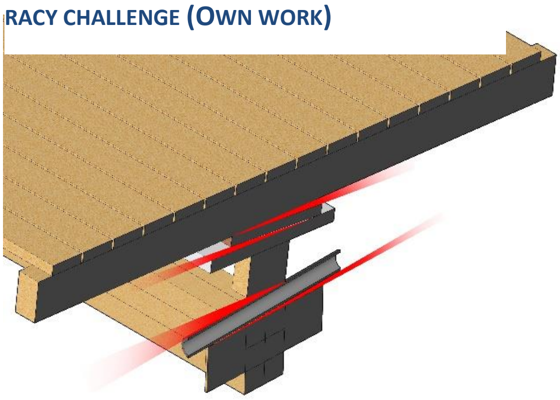



**FIGURE 100: RECORDING DEFLECTION ACCURACY CHALLENGE (OWN WORK)**



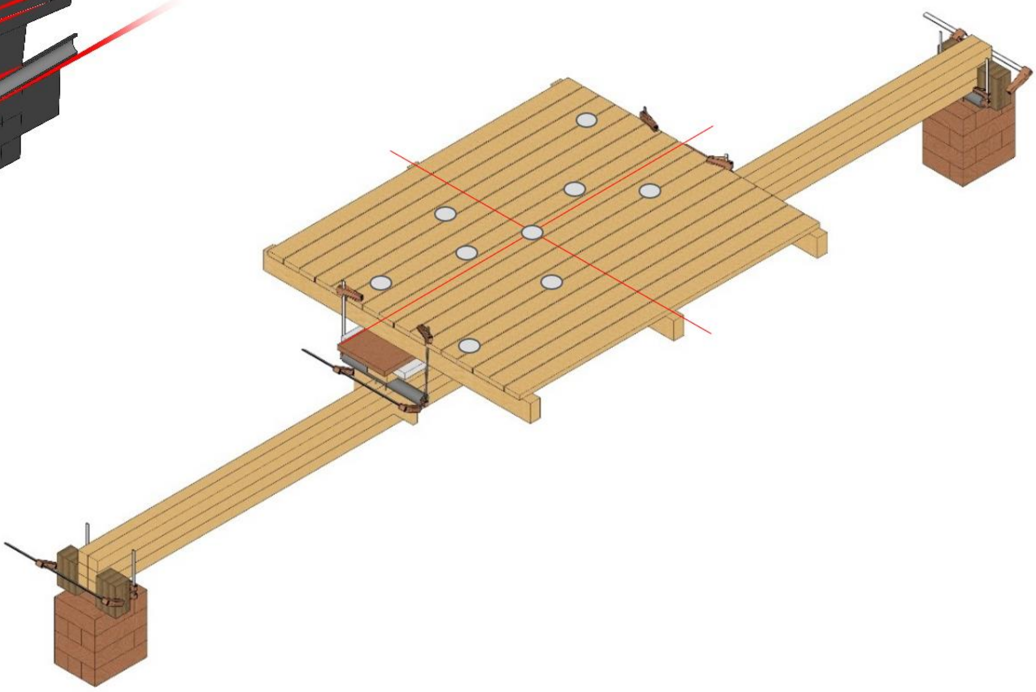


**FIGURE 101: UN EVEN LOAD DISTRIBUTION ()OWN WORK**

13- To overcome the aforementioned loading problem, an alternative method was used to ensure more equal load distribution on the loading board and minimize minor movements within the test pieces. A 1-ton plastic water tank available in the workshop was used, hung from a crane, and filled with water using the emergency fire hose.

**FIGURE 102: MEASURING THE LOAD FROM WATER LEVEL (OWN WORK)**

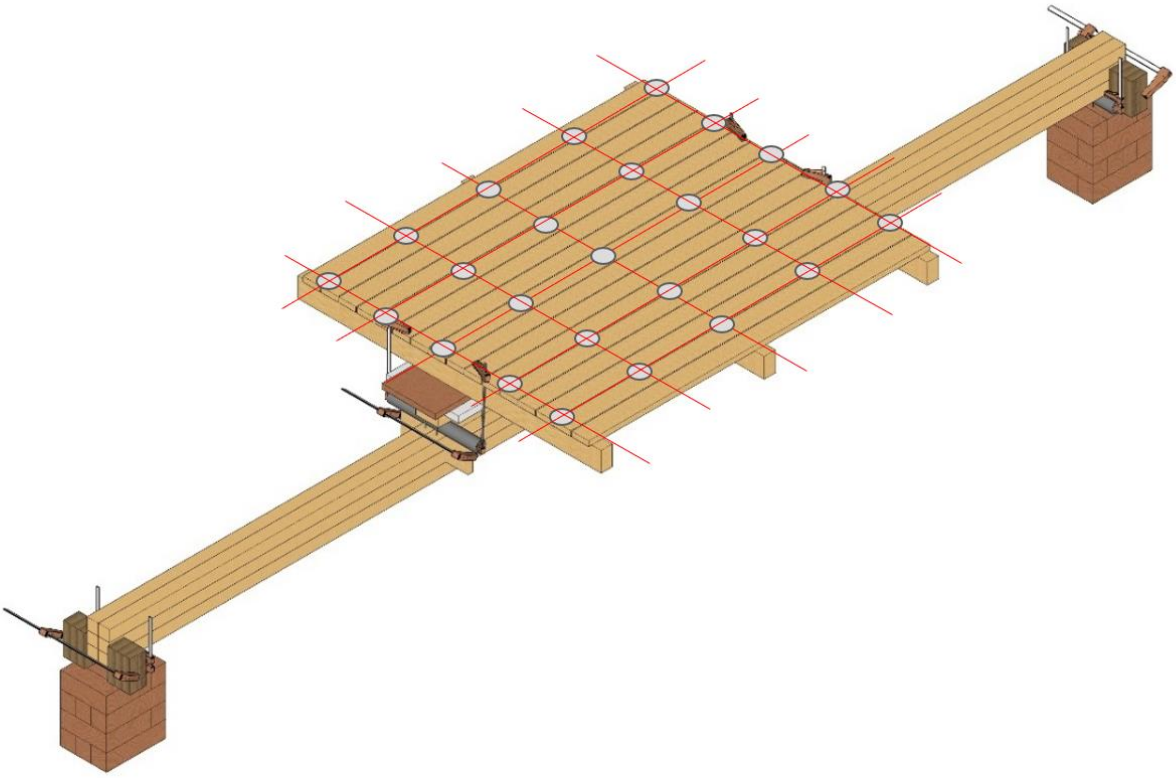


**FIGURE 103: ILLUSTRATION THAT SHOW THE LOAD (OWN WORK)**

14- Although the water tank loading method was more balanced than using sandbags, it required additional lateral support. Two large wooden stands were placed on either side of the loading board, creating a slot with tolerances that allowed vertical movement while preventing the load from tipping over. This setup helped avoid significant damage to the timber pieces in the workshop.

**FIGURE 104: PHOTO FROM TESTING BEAM B (OWN WORK )**

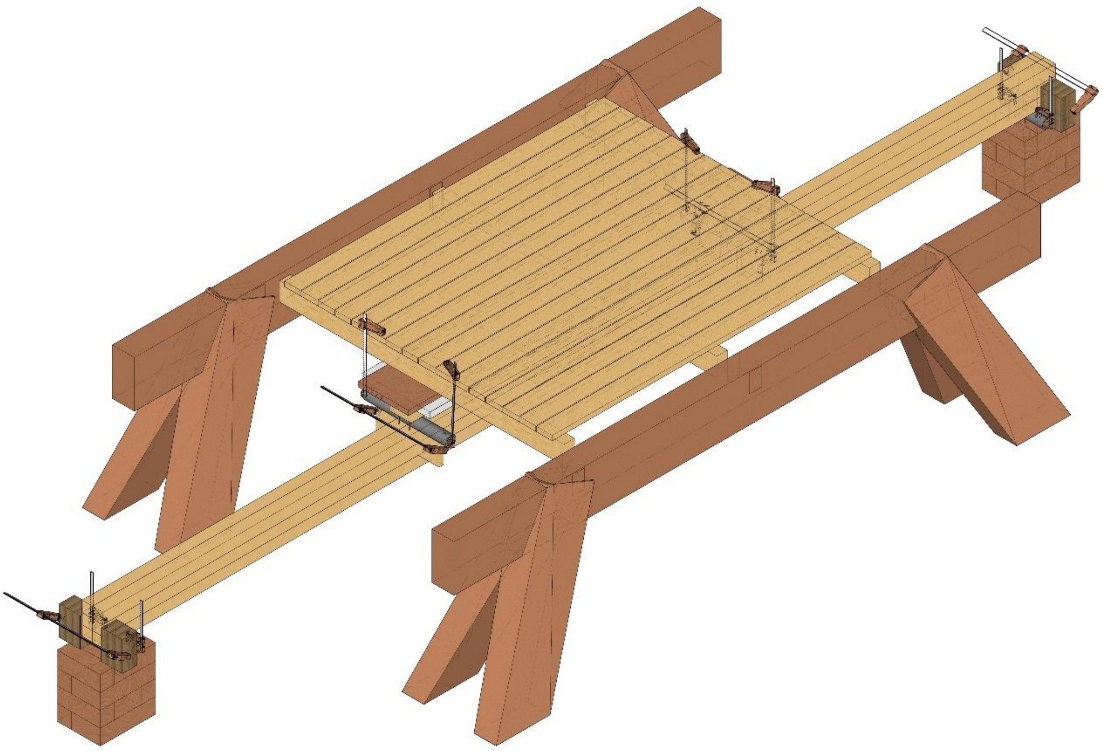


**FIGURE 105: ILLUSTRATION FOR THE SETTING OWN WORK**

FIGURE 106: USING WATER TANK AS A LOAD (OWN WORK )

## 5.9 Second phase mechanical test results:

Due to time and situational constraints, we were unable to continue the experiments using the 1000 kg water tank for the following reasons:

1. The plastic container deformed significantly under the pressure of the large amount of water inside, causing considerable tension at some points, which could potentially lead to the container bursting and causing extensive moisture damage in the wood workshop.

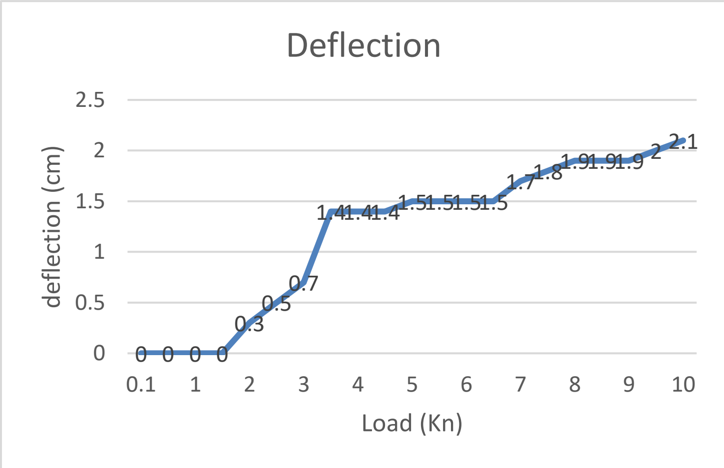
2. Emptying and refilling the plastic container was cumbersome and required another water tank and a pump to transfer the water, which the workshop lacked.

3. If we needed to dispose of the water and refill the tank, the process would be time-consuming. It takes approximately one hour and 15 minutes to fill the tank and over 20 minutes to extract the water, plus 20 minutes to set up the experiment. Thus, each specimen would require around two hours, totaling eight hours for all the beams, exceeding the allocated time for conducting and documenting the experiments.

4. Conducting the experiments with the four beams would require four cubic meters of water, which would be wasted, conflicting with the main purpose of the research.

**TABLE 9**

| load Liter | Load K.n | Deflections |
|---|---|---|
| 10 | 0.1 | **0** |
| 50 | 0.5 | **0** |
| 100 | 1 | **0** |
| 150 | 1.5 | **0** |
| 200 | 2 | **0.3** |
| 250 | 2.5 | **0.5** |
| 300 | 3 | **0.7** |
| 350 | 3.5 | 1.4 |
| 400 | 4 | **1.4** |
| 450 | 4.5 | **1.4** |
| 500 | 5 | **1.5** |
| 550 | 5.5 | **1.5** |
| 600 | 6 | **1.5** |
| 650 | 6.5 | **1.5** |
| 700 | 7 | **1.7** |
| 750 | 7.5 | **1.8** |
| 800 | 8 | **1.9** |
| 850 | 8.5 | **1.9** |
| 900 | 9 | **1.9** |
| 950 | 9.5 | **2** |
| 1000 | 10 | **2.1** |



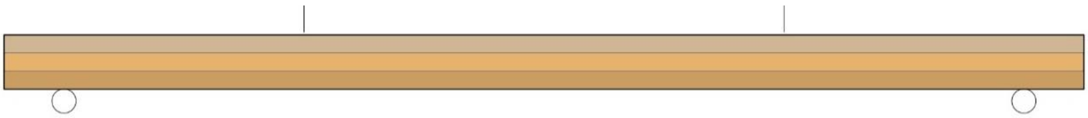



**FIGURE 107**

An alternative uproach was to use the already hanged filled water tank to test the rest of the specimens for SLS:

We continued conducting the mechanical test using the suspended water tanks as an instantaneous load to measure the deflection. After placing the load for 10 seconds, specimen D showed a deflection of 1.5 cm. According to SLS validation, the deflection should not exceed L/500=0.72L/500 = 0.72L/500=0.72 cm. Therefore, the deflection exceeded the required SLS limits for an instantaneous load.

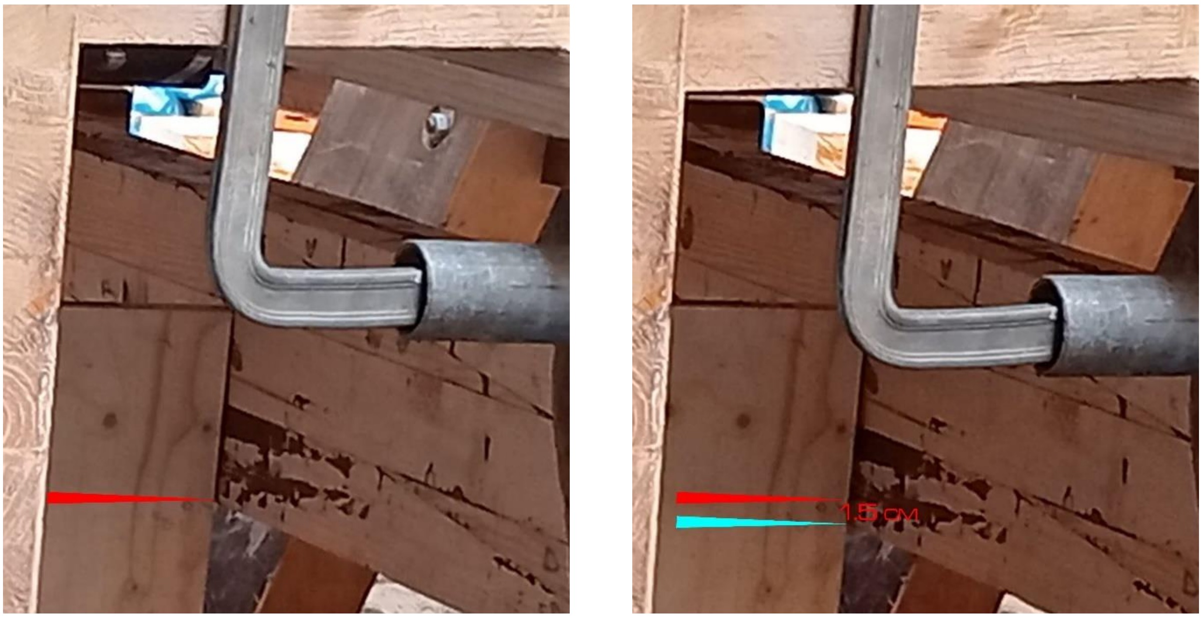



**FIGURE 108 : DEFLECTION OF BEAM D**

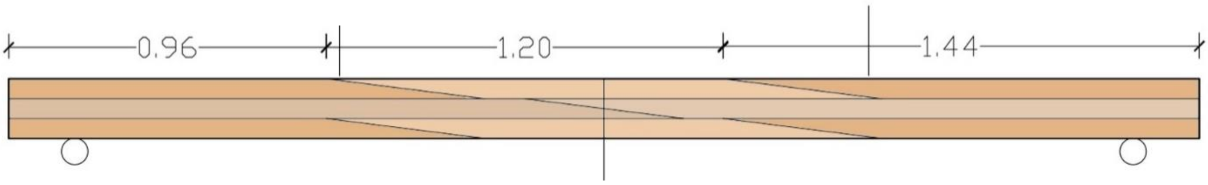


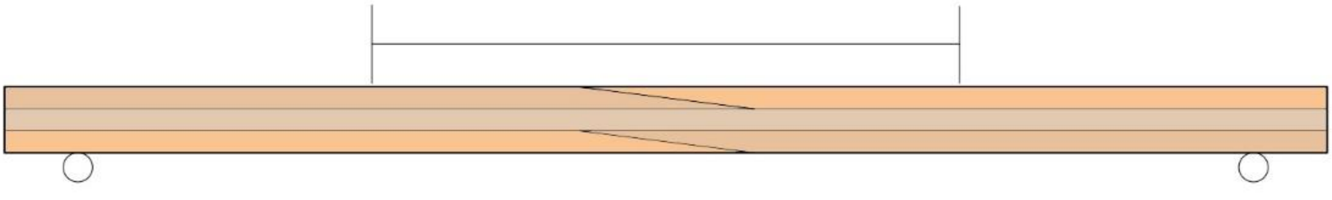

**FIGURE 109 : BEAM D**

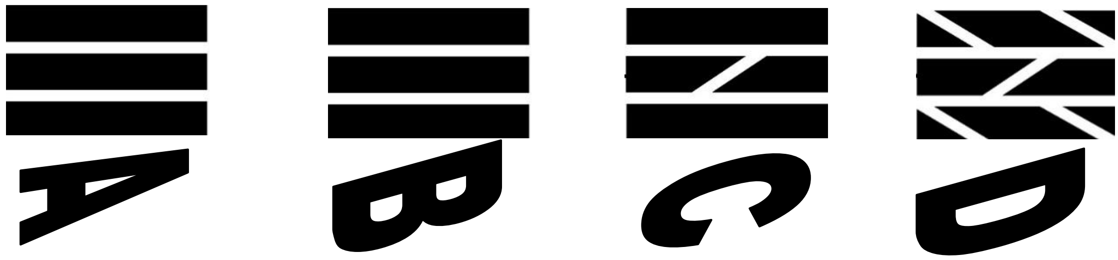
We continued conducting the mechanical test using the suspended water tanks as an instantaneous load to measure the deflection. After placing the load for 10 seconds, specimen D showed a deflection of 1.6 cm. According to SLS validation, the deflection should not exceed L/500=0.72L/500 = 0.72L/500=0.72 cm. Therefore, the deflection exceeded the required SLS limits for an instantaneous load.

**FIGURE 110: PHOTAGE OF WATER PLACING WATER TANK ON TOP OF THE BEAM (OWN WORK )**

## 5.9.1 Results:

- The three pieces in the table exceed the serviceability limit under the applied load.
- Despite exceeding the serviceability limits, they exhibit less deflection compared to theoretical calculations based on the deflection formula.
- Given the uncontrolled conditions of the mechanical test, it is crucial to specify whether the load application was static or instantaneous. Each method follows different guidelines. For instance, Specimen D shows slightly less deflection than Specimen C, with a difference of 2 to 3 mm. In contrast, the parallel joist deflects the most, with a difference of half a centimetre compared to Specimen C and 7 millimetres compared to Specimen D





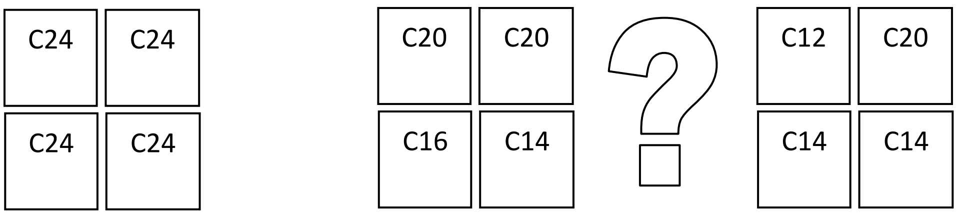

Specimen A was partially manufactured using a casein bio-based glue. Due to time constraints, it has not yet been tested, but it will be tested in the near future.

| Speci-men | P | a | E | I | L | #DIV/0! | Inst SLS | Stat SLS | Max meas-ured def |
|---|---|---|---|---|---|---|---|---|---|
| D | 10000 | 1.2 | 11000000000 | 0.000038 | 3.6 | 0.039617225 | 0.0072 | 0.012 | **0.015** |
| | 4000 | 1.2 | 11000000000 | 0.000038 | 3.6 | 0.01584689 | 0.0072 | 0.012 | **none** |
| | | | | | | | | | |
| C | 10000 | 1.2 | 11000000000 | 0.000038 | 3.6 | 0.039617225 | 0.0072 | 0.012 | **0.016** |
| | 4200 | 1.2 | 11000000000 | 0.000038 | 3.6 | 0.016639234 | 0.0072 | 0.012 | |
| | | | | | | | | | |
| A | 10000 | 1.2 | 11000000000 | 0.000038 | 3.6 | 0.039617225 | 0.0072 | 0.012 | **0.021** |
| | 5200 | 1.2 | 11000000000 | 0.000038 | 3.6 | 0.020600957 | 0.0072 | 0.012 | **0.015** |

TABLE 10: DEFLECTION WITH SLS LIMITS

**The difference in performance, along with the effectiveness of the IGST, can be attributed to the following factors:**

- Re-Grading: Despite using strong, healthy pieces for the lower lamellas, the actual strength of these pieces should be investigated further. A regrading workflow can help determine the precise grade of all lamella pieces.



- Structural Glue: Specimen D has more scarf joints, meaning more timber fiber is reinforced with epoxy resin along the xz axis, increasing the overall stiffness of the joist.

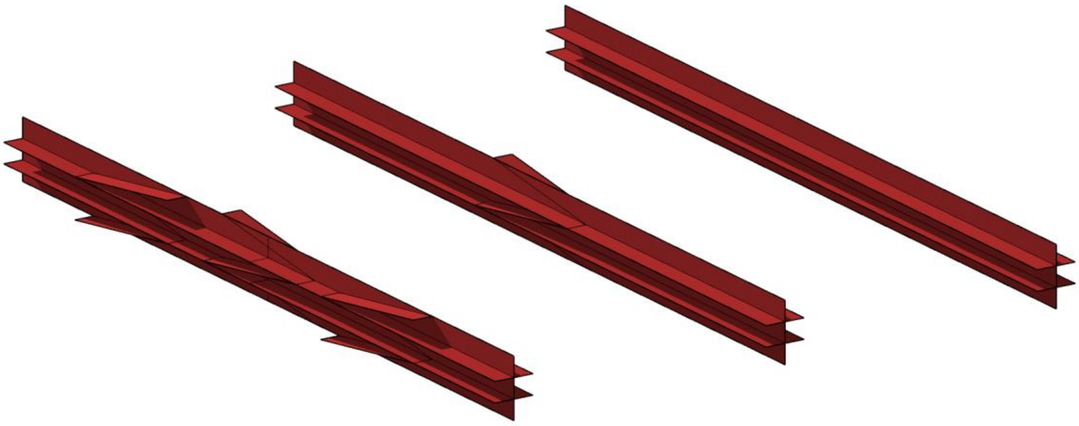


**FIGURE 111: GLUE STRUCTUE**

### 5.9.2 Key considerations:

- These results require more robust validation, where load and deflection are simultaneously and accurately recorded using an LDTV device under controlled conditions with consistent loading speeds. Improving these conditions could significantly alter results, enhancing reliability for future research.
- The test objective, as discussed earlier, led us to select a 3.6-meter span to observe full-scale application, particularly since larger spans are more suitable for IGST. However, it's important to note that manufacturing these pieces requires skilled carpenters due to their size and weight. Handling such large specimens often leads to extended manufacturing times and increased material and labour costs. Scaling down specimens would streamline production, making them easier to manufacture, manoeuvre, and test for ultimate and serviceability limit states (ULS and SLS).

# 5.10 Environmental impact:

## 5.10.1 Methodology

Previously, we mentioned the ReCiPe method for LCA, illustrating how it can be used to determine the environmental impact of a product due to its comprehensive and standardized assessment. However, while sourcing material for the second phase test, a simpler approach was easier to spot the difference.

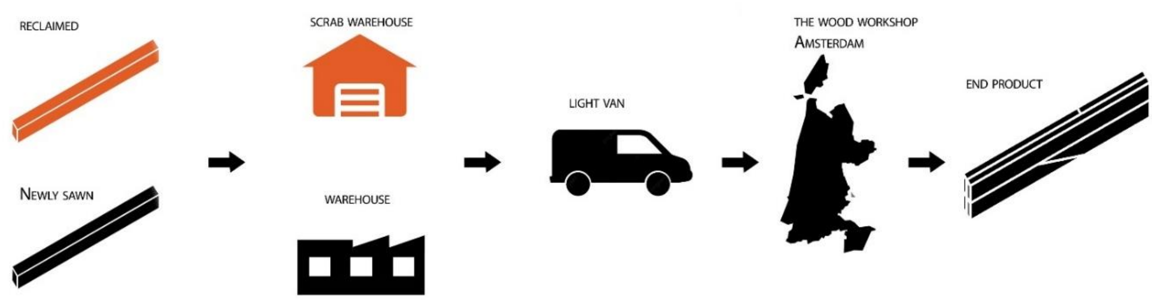
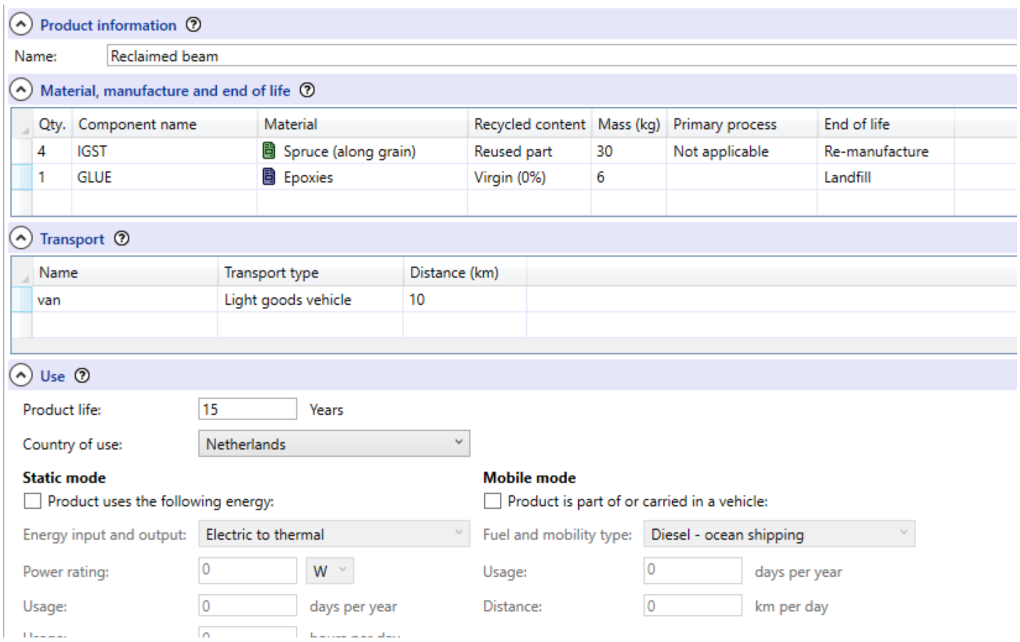



**FIGURE 112: SOURCING SCENARIO**

The scenario is as follows: If the distance between the reclaimed material warehouse and the new materials warehouse is almost the same, and we use the same means of transportation to deliver the timber to the workshop in Heineg, Amsterdam, to make the product, the only difference in the process will be the source of the timber. By using the EduPack Eco Audit tool, we can estimate the carbon footprint and the energy used in making the product.

Noting that in both scenarios, the same type of the structural glue has been used, and the same product life of 15 years, and the energy usage was avoided


Product information

Name: Reclaimed beam

Material, manufacture and end of life

| Qty. | Component name | Material | Recycled content | Mass (kg) | Primary process | End of life |
|---|---|---|---|---|---|---|
| 4 | IGST | Spruce (along grain) | Reused part | 30 | Not applicable | Re-manufacture |
| 1 | GLUE | Epoxies | Virgin (0%) | 6 | | Landfill |

Transport

| Name | Transport type | Distance (km) |
|---|---|---|
| van | Light goods vehicle | 10 |

Use

Product life: 15 Years

Country of use: Netherlands

**Static mode**

Product uses the following energy:

Energy input and output: Electric to thermal

Power rating: 0 W

Usage: 0 days per year

**Mobile mode**

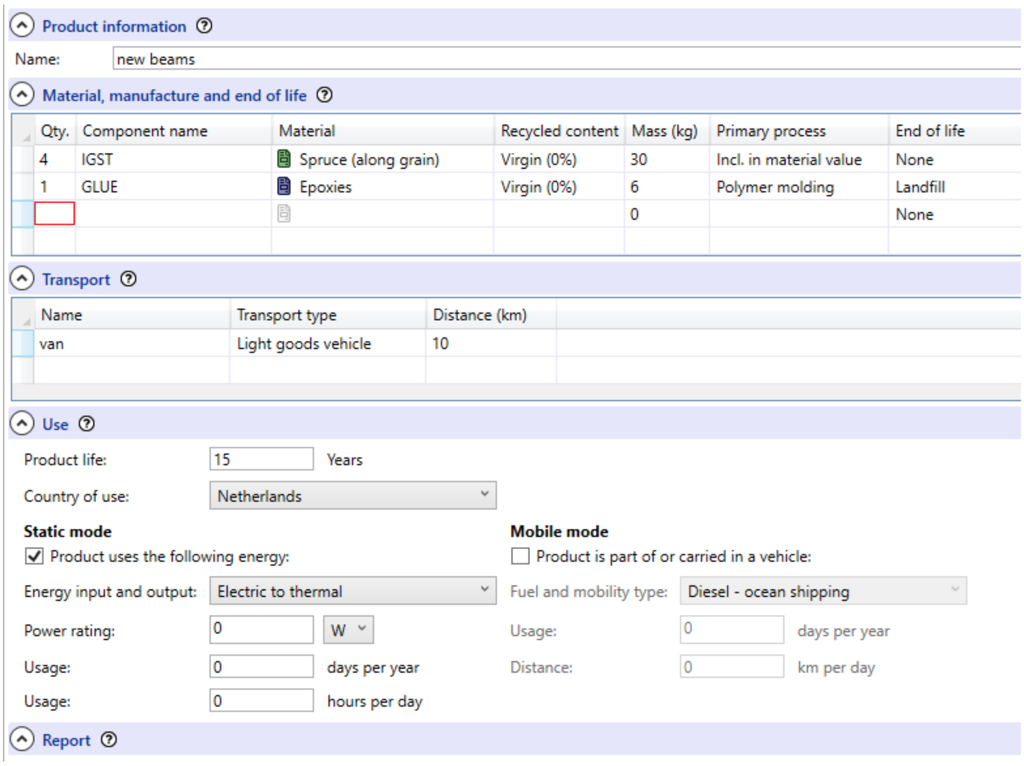
Product is part of or carried in a vehicle:

Fuel and mobility type: Diesel - ocean shipping

Usage: 0 days per year

Distance: 0 km per day

**FIGURE 113: A SNIPPET FROM THE EDUPACK ECO AUDIT TOOL**




### 5.10.2 Results:

- As seen in the results, the difference between reclaimed spruce and newly sawn spruce is significant. Reclaimed timber requires around 700 MJ of energy, while newly sawn timber requires more than 2500 MJ of energy. This means reclaimed timber consumes about three times less energy to make the same four beams presented in the research.
- Regarding the CO2 carbon footprint, manufacturing the four beams produces 65 kg of CO2 when new timber is used, compared to 35 kg of CO2 in the reclaimed timber scenario, which is about half the carbon emissions of new timber.

### 5.10.3 Conclusion:

- Even though we fixed some parameters regarding transportation, glue, and lifetime, which were considered in Favor of the newly sawn timber, we still observe a clear difference in energy consumption and CO2 footprint.
- Ideally, the closer the warehouse of reclaimed timber is to the construction site, the better the environmental result. Fortunately, this was the case when we manufactured the test beams.
- The glue used in the construction is phenol-resorcinol based, which hinders the end-of-life (EoL) potential for both scenarios. Ideally, using a bio-based glue or other mechanical stacking methods like nails and dowels would be crucial additions to reduce the environmental impact of any structural timber product.

- It is also important to note that working with reclaimed timber requires extra work before its ready to be used, mainly regrading, cleaning and planning the pieces to avoid any deformation during the lamination, and in case of high moisture content, a well-ventilated space is needed to extract the moisture all of these aspects are vital to figure out the environmental impact noting that, using the method described in the literature is more valid in our case but still the following simplified method can also shows the clear difference material wise.

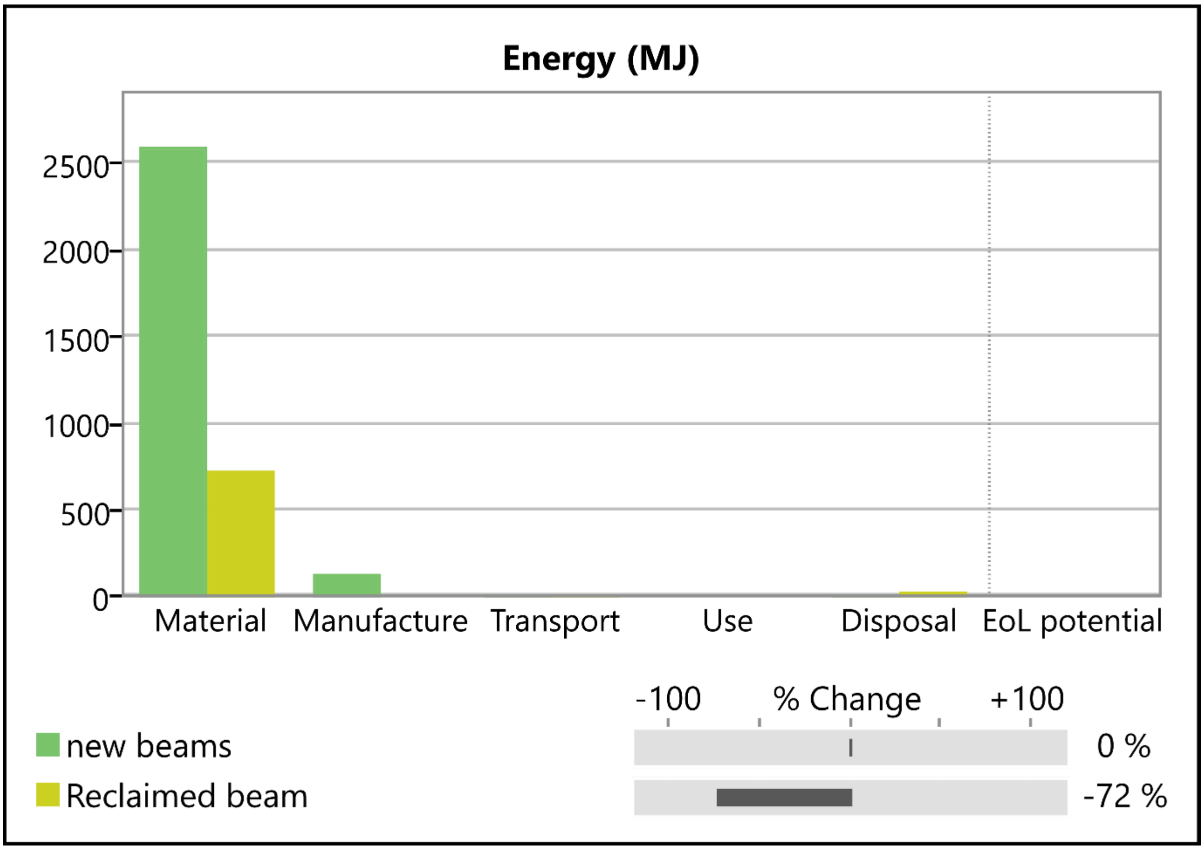



**FIGURE 114: ENERGY CONSUMPTION COMPARISON BETWEEN RECLAIMED AND NEW ELEMENTS**

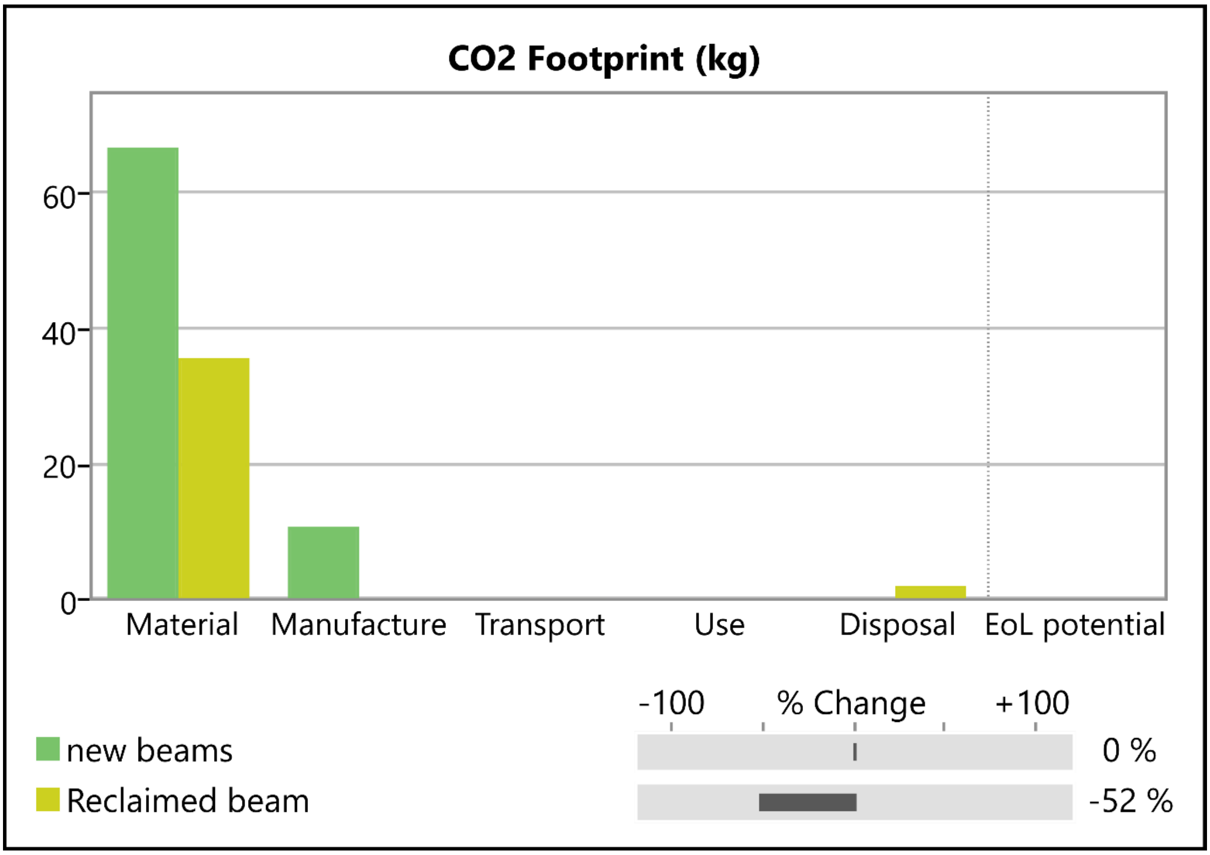

CO2 Footprint (kg)
60
40
20
0
Material
Manufacture
Transport
Use
Disposal
EoL potential
-100
% Change
+100
new beams
0 %
Reclaimed beam
-52 %

**FIGURE 115**

# 6. Conclusions

## 6.1Literature review:

1- Laws are changing, more need for biobased construction, product from reclaimed timber need to be verified to comply with the industry norms

2- The market has a considerable percentage of uncertified timber specially tropical hardwood imported from Indonesia and Congo, this uncertified timber like the meranti wooden frame used 15 years ago which community found in the reclaimed material stocks, those timber species should be managed wisely because its value goes beyond the border of the European content

3- The industry moved from visual grading, timber is being used with the limit of its capacity, so percentage of fatigue is expected, using a single joist might not satisfy the structural need for its span, however using a bundle of reclaimed element to make a wide span product can provide a sustainable cost-efficient engineered timber product

4- Grading is a critical process, refiguring out the grade of reclaimed timber is quite a challenge which urged researches to develop processes to do that, this processes contains basic physical characteristic measurements, as well as the use of some equipment's, like moisture meter and doppler vibrometer, in addition to that more computational tool are being used along side machine learning models to define some important timber characteristics, it will be interesting in the future to see a software or platform that integrate all of this techniques and make them ready to assist carpenters working on reclaimed timber.

5- the state of art of EPW has been briefly explored, previous experiments tried to make a glulam from reclaimed timber, which satisfy the structural need, but when the span expand more than 12 meter, more finger joint are needed to link the pieces at the same more weaker point in the joist, while using IGST proof that it give better performance with simpler technique, which at the same time might be the perfect function for reclaimed timber, where salvaged solid joist harvested from scrab yard of demolition sites can be checked cleaned and aggregated in in wide span IGST, by using simple carpentry techniques

6- IGST can be explained as a big section glulam beam with splayed scarf joint, based on that rule of thumbs for preliminary sizing and ULS and SLS has been used, 7- The literature shows that higher the scarf joints the better the elastic behaviour of the joist, based on that we changed the slope of the splayed scarf joint from 1:4 in the first mechanical test to 1:8 for the second one

8- Scarf joint slope also can be determined based on the specie mechanical characteristics; soft timber needs higher slope ration than hard timber.

*9- More exploration about defining the scarf joint slop ration when timber species with the different density are being used in the same joist*

*10- More exploration needed to figure out the corelation between waste and structural performance of IGST with different slope ration*

11- Matching algorithm:
three different Matching algorithm were explored in the research, MILP, best fit algorithm, and Hungarian combinatorial algorithm.

12- Since the design task is to produce multiple beams from reclaimed stock based on length and capacity, The Hungarian algorithm is used because it efficiently provides an optimal one-to-one matching between reclaimed timber pieces and interlocking glued solid timber design requirements, minimizing total costs or maximizing benefits, ensuring each piece of timber is uniquely paired with a design element.

*13- For future research, the slope of the scarf joint can be integrated with LCA in the process of matching, which need more complex matching algorithm so its better explore more in the other two methods*

*14- the main parameter that affect the Enviromental impacts with ReCipe method has been defined in the literature, however the focus of following work focused more on finding a methods to realise the process of matching in addition to the aspects related to timber mechanical properties, so integrating the LCA in the process was out of the research scope in the workflow part.*

## 6.2 The workflow conclusion

The design workflow:

15- the design workflows was simplified to generate configuration that alternate between the following proportions (1:1 , 1:2, 1:3), with extension in the demand length to accommodate the waste of the scarf joint, choosing between the previous division is the structural design choice.

16- The aforementioned choice could be optimized based on the matching cost, the primary script for the optimization process is codded in grasshopper but hasn't been tested and explored further

17- The scarf joint is considered numerically as an extension to the length, by approximately adding the hight of the lamella multiplied by the slop ratio added to all the pieces, which is valid to count the required length but it is false assumption when it comes the distribution of the extension between the pieces, which can be solved computationally solved for accurate result.

For the structure workflow:

18- To know what is the required strength for each member from the aggregation, we assume that the whole IGST work as big solid joist, By checking the deflection the beam hight is edited to not pass the serviceability limit, this process need to be done manually, but it would be more efficient to be considered in the code.

19- Regarding the ULS, the load is fractured based on the glulam rule of thumbs, the process is simple if the design passes the SLS checked the demand is correct

20- The process of mapping the values from the result of the analysis toward the design was done on grasshopper approximately by weaving the strength cluster, need validating if it this process is accurate

From stock to grade workflow:

21- There are two methods developed to check the strength demand by calculating the strength and buckling capacity of both the design and the load and to use it directly match between the supply and demand, this method is efficient when the stock has element with the same condition, which was the assumption made to make the process faster, ideally it is better to use the MOE and MOR values of the grading methods which is calculated to represent the elasticity of each piece

*22- Future work is recommended to test the grading workflow and check the feasibility, since in this research dump data is used to check workability of the code and the parametric design*

## 6.3 The first phase mechanical test:

23- Examining the graphs reveals key differences in stiffness and flexibility among the specimens. Most specimens, except Specimen 3, experience a sudden force drop when the lower lamella breaks due to lamination issues. After this drop, strain shifts from the lower to the upper lamella, causing non-linear elastic behavior, especially in Specimens 5 and 6. Specimen 7, made from a single piece of timber, shows minor force drops and gradual collapse without significant non-linear behavior.

24- Specimen 5 exhibits the highest stiffness, withstanding over two tons before failure. Specimen 6 also performs well, staying elastic longer despite higher deformation before breaking. Specimen 7 has the longest period of plastic deformation before failure.

25- Optimizing Strength in Interlocking Glued Solid TimberTo enhance the strength of interlocking glued solid timber (IGST) from reclaimed sources, consider these factors:

i. Glue Selection and Application: Choose the right type and amount of adhesive, and ensure proper clamping and surface treatment during lamination to optimize strength and durability.
ii. Grain Orientation: Align grain perpendicular to the applied force and avoid diagonal grain orientation in the lower lamella to prevent tearing. Ensure uniform grain direction across all lamellas for better structural integrity.
iii. Scarf Joint Enhancement: Use nipped scarf joints instead of plane ones to reduce delamination and improve joint strength.

## 6.4 The second phase mechanical test:

*26-* The mechanical tests showed that all three specimens exceeded the serviceability limits under the applied load. Despite this, actual deflections were less than theoretical predictions. It is important to specify whether the load application was static or instantaneous, as each method follows different guidelines. Specimen D exhibited slightly less deflection than Specimen C by 2-3 mm, while the parallel joist deflected the most, exceeding Specimen C by 0.5 cm and Specimen D by 7 mm. Specimen A, partially made with casein bio-based glue, has not yet been tested due to time constraints but will be tested soon.

*27-* Several factors contributed to the differences in performance and the effectiveness of the IGST. Re-grading is necessary to accurately determine the strength of the lower lamellas. Specimen D's increased stiffness is due to more scarf joints, which reinforce timber fiber with epoxy resin along the xz axis.

*28-* For future research, more robust validation is needed. This includes using an LDTV device to record load and deflection simultaneously under controlled conditions. Improving these conditions will enhance the reliability of future results. The 3.6-meter span was chosen to observe full-scale application, suitable for IGST, but requires skilled carpenters and increases manufacturing time and costs. Reducing specimen size could streamline production, making them easier to manufacture, maneuver, and test for ultimate and serviceability limit states (ULS and SLS).

# 7 Reflection

## 7.1 Graduation process:

### How has the design approach evolved from P2 to P4?

From P2 to P4, the project hasn't changed much in concept, but the main approach to the design assignment has shifted from focusing solely on the computational workflow to maximize

IGST production from reclaimed stocks. Instead, it now concentrates on how different types of wood perform within this concept. After the first bending test, several aspects have proven to be important, including the grain direction of the interlocking lamellas, the corner of the slope, partial delamination, and even the path of cracks and fractures. The layout of the proposed anatomy has become intertwined with the layout of the timber, adding complexity to the concept. Mixing hardwood and softwood reveals more problems to tackle but can significantly increase the strength threshold of the joist, potentially expanding IGST usage for various functions and structural elements in the future.

### What challenges were encountered as the project evolved?

The project is steadily becoming more concrete. Initially, I rushed to finish the part focusing on the grasshopper script using combinatorial algorithms to match a designed beam with available stocks, allowing me to shift focus to another step. However, this diverted attention from another crucial aspect—evaluating reclaimed timber. Though the computational workflow and necessary tools for timber evaluation are defined, I struggled to find a Laser Doppler vibrometer or a microsecond timer due to time constraints. Despite this, I proceeded with specimen preparation for the bending test using available resources, recognizing the opportunity to address these gaps between P4 and P5 in the second phase experiments.

### How did collaboration and mentorship influence your project approach?

After P2, Gilbert pointed out a crucial aspect: timber is unlike other materials, so treating it generically wouldn't contribute to the proposed IGST concept. Collaborating with him and Stijn helped alleviate my stress regarding my limited knowledge of timber. Stijn's discussions helped me strike a balance between what I know can be done and what I lack experience in approaching. Each meeting provided insight into the project's progress and rationalized next steps. Gilbert's extensive timber experience highlighted project gaps, providing clear guidance for the next steps. His support extended beyond literature, facilitating connections with Lorin Brasser, a carpenter with expertise in reclaimed timber. Lorin's insights into the practicality of the project were invaluable for the real-size beam experiments.

## 7.2 Societal impact

### To what extent are the results applicable in practice?

The main intention of the project is to focus clearly on developing a method of reusing timber that allow carpenter to participate in the building industry my picking simple straight forward structurally efficient engineered timber products , part of this goal was achieved by developing series of clear workflow to make the process of using reclaimed timber more touchable which it is still a gap in the practise, however, to achieve this goal it is not only about developing workflows, the study should be extended to see how much carpenters envision them self in the future timber structure industry, specially when big consultant companies have the upper hands in the building industry, which might be an obstacle in the way of pushing the concept of using reclaimed element further, or simply it delays it.

Due to the time constrains such an impact was beyond my reach, but it would be nice to do a study that focus on small carpenters across the Netherlands, to see what they need to make this more viable, and link that with the a business model that take all the constraints in considerations.

### To what extent has the projected innovation been achieved?

Honestly, such topic doesn't relate only to timber structure, it has various aspect, from evaluating the timber, classifying it, develop a tool to help matching the design with stock, at each one of the aforementioned concept, an innovation has taken place, some of them are only a concept that needs extra validation by more experiments like the process of regrading reclaimed timber, other innovations need to be researched further to check whether the assumption that has been taken is valid when it comes to the practise, like workflow that figure out form the FEA what is structural demands needed in the matching process, even though the process was checked and seems logical, better evaluating tools and methods can be used to get more accurate results, so in this case the innovation is in the process but not completely achieved

### Does the project contribute to sustainable development?

Since the one of the main objective of the project is to use reclaimed timber, in order reduce the environmental impact of making mass timber structure which considered to have high demand in the near future, I can say yes the project deal directly with developing a sustainable methods to do create engineered timber product

### what is the impact of your project on sustainability (people, planet, profit/prosperity)?

I mentioned earlier my personal intention on creating tools that help small carpenter to take part in the circular building industry, as well as the objective of the research is to find a way to use reclaimed timber in the industry should have an effect on reducing logging wood from forest, which is a vital part in lowering the global carbon emissions

### *what is the socio-cultural and ethical impact?*

In the introduction, I mentioned that part of the timber we are wasting in Europe specially in the Netherlands and Belgium is imported from different corner of the globe specially tropical hard wood from Indonesia, and some timber species from Africa, which unfortunately a considerable percentage of these timber is uncertified ,which means than it includes illegal practices to import it from the source till Europe, such a case should be highlighted, and the valuable timber that was illegally sourced, should be treated not as a waste that should be burned but also as human natural resources that should be wisely evaluated and used.

### how does the project affect architecture / the built environment?

It aims at developing a structural element, easily manufactured, cost efficient, and it has the potential to compete with other timber products, like glulam and LVL, in term of structural performance

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# 9. Table of Figures:

# 10. Appendix

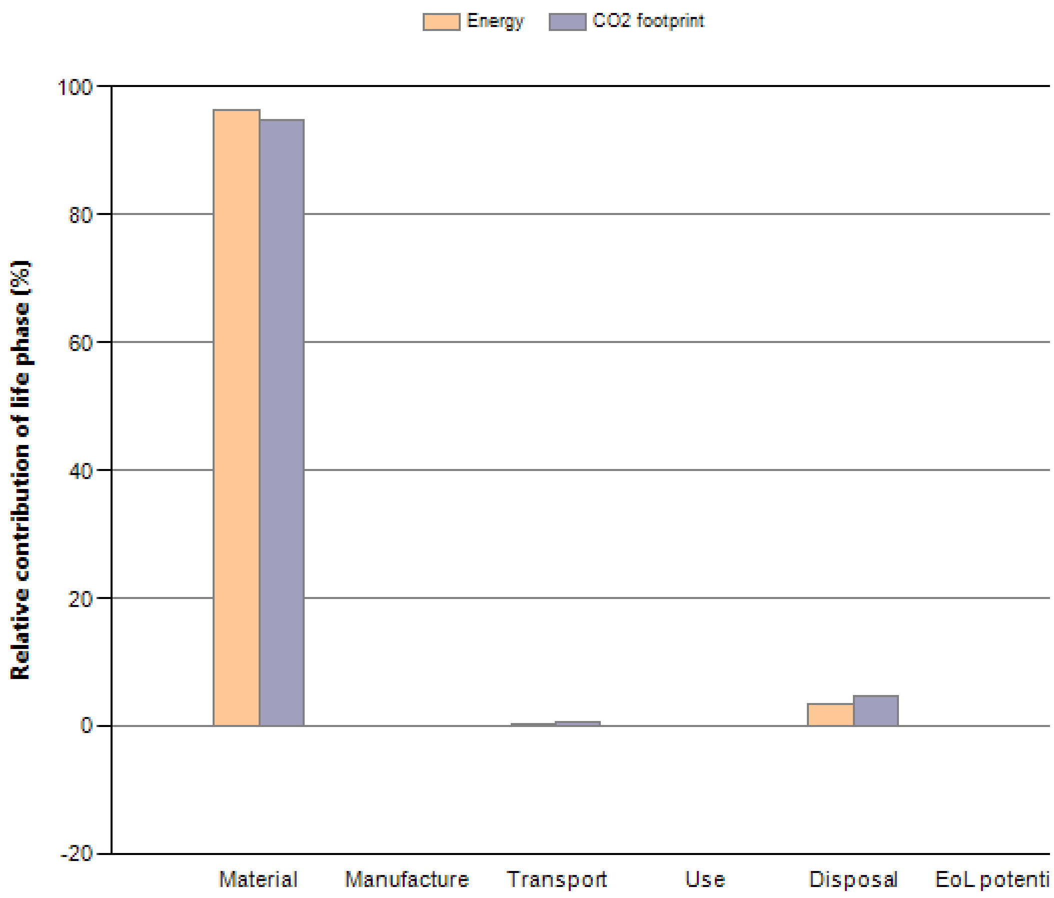
## Environmental impact:

Ansys GRANTA EDUPACK

**Eco Audit Report**

| | |
|---|---|
| Product name | Reclaimed beam |
| Country of use | World |
| Product life (years) | 15 |

**Summary:**




Energy details

CO2 footprint details

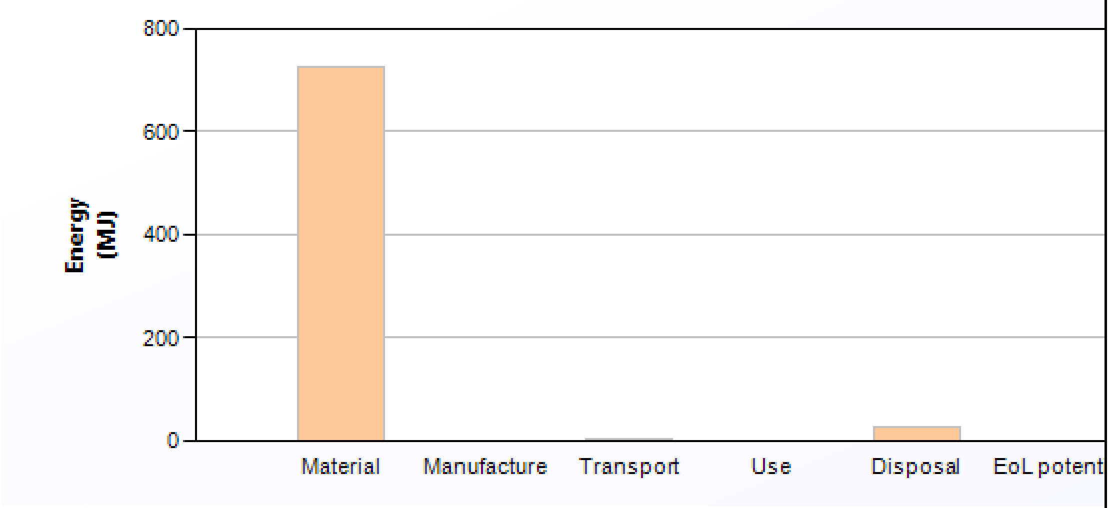
| Phase | Energy (MJ) | Energy (%) | CO2 footprint (kg) | CO2 footprint (%) |
|---|---|---|---|---|
| **Material** | 725 | 96.3 | 35.6 | 94.8 |
| **Manufacture** | 0 | 0.0 | 0 | 0.0 |
| **Transport** | 2.77 | 0.4 | 0.2 | 0.5 |
| **Use** | 0 | 0.0 | 0 | 0.0 |
| **Disposal** | 25.2 | 3.3 | 1.76 | 4.7 |
| Total (for first life) | **753** | **100** | **37.6** | **100** |
| **End of life potential** | 0 | | 0 | |

**Eco Audit Report**

Ansys GRANTA EDUPACK

Summary

## Energy Analysis




| | Energy (MJ/year) |
|---|---|
| **Equivalent annual environmental burden (averaged over 15 year product life):** | 50.2 |

## Detailed breakdown of individual life phases

## Material:

Summary

| Component | Material | Recycled | Part mass | Qty. | Total mass (kg) | Energy (MJ) | % |
|---|---|---|---|---|---|---|---|

| | | content* (%) | (kg) | | | | |
|---|---|---|---|---|---|---|---|
| **IGST** | Spruce (along grain) | Reused part | 30 | 4 | 1.2e+02 | 0 | 0.0 |
| **GLUE** | Epoxies | Virgin (0%) | 6 | 1 | 6 | 7.3e+02 | 100.0 |
| Total | | | | **5** | **1.3e+02** | **7.3e+02** | **100** |

*Typical: Includes 'recycle fraction in current supply'

**Manufacture:** Summary

| Component | **Process** | **Amount processed** | **Energy (MJ)** | **%** |
|---|---|---|---|---|
| Total | | | | **100** |

**Transport:** Summary

**Breakdown by transport stage**

| Stage name | Transport type | Distance (km) | Energy (MJ) | % |
|---|---|---|---|---|
| **van** | Light goods vehicle | 10 | 2.8 | 100.0 |
| Total | | **10** | **2.8** | **100** |

**Breakdown by components**

| Component | Mass (kg) | Energy (MJ) | % |
|---|---|---|---|
| **IGST** | 1.2e+02 | 2.6 | 95.2 |
| **GLUE** | 6 | 0.13 | 4.8 |
| Total | **1.3e+02** | **2.8** | **100** |

**Use:** Summary

**Relative contribution of static and mobile modes**

| Mode | Energy (MJ) | % |
|---|---|---|
| **Static** | 0 | |

| | | |
|---|---|---|
| **Mobile** | 0 | |
| Total | **0** | **100** |

**Disposal:** Summary

| Component | **End of life option** | **Energy (MJ)** | **%** |
|---|---|---|---|
| **IGST** | Remanufacture | 24 | 95.2 |
| **GLUE** | Landfill | 1.2 | 4.8 |
| Total | | **25** | **100** |

**EoL potential:**

| Component | **End of life option** | **Energy (MJ)** | **%** |
|---|---|---|---|
| **IGST** | Remanufacture | 0 | |
| **GLUE** | Landfill | 0 | |

| | | | |
|---|---|---|---|
| Total | | **0** | **100** |

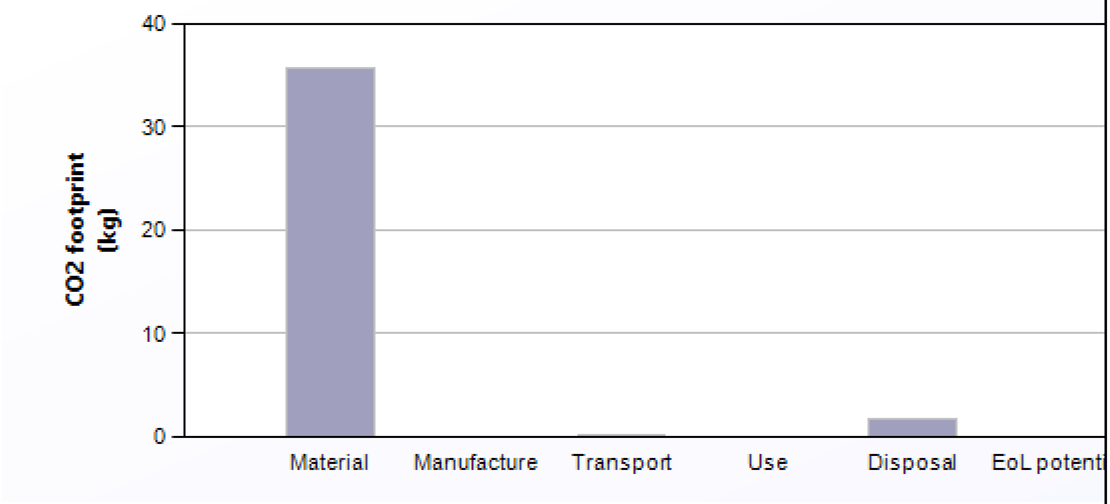
**Notes:**

Summary

**Eco Audit Report**

Summary

## CO2 Footprint Analysis




| | CO2 (kg/year) |
|---|---|
| Equivalent annual environmental burden (averaged over 15 year product life): | 2.5 |

## Detailed breakdown of individual life phases

## Material:

Summary

| Co mp one nt | Ma- te- rial | Re cy cl ed co | Pa rt ma ss | Q ty . | Total mas s (kg) | C O 2 fo | % |
|---|---|---|---|---|---|---|---|

| | | **ntent* (%)** | **(kg)** | | | **ot-print (kg)** | |
|---|---|---|---|---|---|---|---|
| **IGST** | Spruce (along grain) | Reused part | 30 | 4 | 1.2e+02 | 0 | 0.0 |
| **GLUE** | Epoxies | Virgin (0%) | 6 | 1 | 6 | 36 | 100.0 |
| To-tal | | | | **5** | **1.3e+02** | **36** | **100** |

*Typical: Includes 'recycle fraction in current supply'

**Manufacture:** Summary

| Component | **Process** | **Amount pro-cessed** | **CO2 foot-print (kg)** | **%** |
|---|---|---|---|---|
| Total | | | | **100** |

**Transport:** Summary

**Breakdown by transport stage**

| Stage name | **Transport type** | **Distance (km)** | **CO2 footprint (kg)** | **%** |
|---|---|---|---|---|
| **van** | Light goods vehicle | 10 | 0.2 | 100.0 |
| Total | | **10** | **0.2** | **100** |

**Breakdown by components**

| Component | **Mass (kg)** | **CO2 footprint (kg)** | **%** |
|---|---|---|---|
| **IGST** | 1.2e+02 | 0.19 | 95.2 |
| **GLUE** | 6 | 0.0095 | 4.8 |
| Total | **1.3e+02** | **0.2** | **100** |

**Use:** Summary

**Relative contribution of static and mobile modes**

| Mode | **CO2 footprint (kg)** | **%** |
|---|---|---|
| **Static** | 0 | |
| **Mobile** | 0 | |

| | | |
|---|---|---|
| Total | **0** | **100** |

**Disposal:**

Summary

| Component | **End of life option** | **CO2 footprint (kg)** | **%** |
|---|---|---|---|
| **IGST** | Remanufacture | 1.7 | 95.2 |
| **GLUE** | Landfill | 0.084 | 4.8 |
| Total | | **1.8** | **100** |

**EoL potential:**

| Component | **End of life option** | **CO2 footprint (kg)** | **%** |
|---|---|---|---|
| **IGST** | Remanufacture | 0 | |
| **GLUE** | Landfill | 0 | |
| Total | | **0** | **100** |

**Notes:** [Summary](#)

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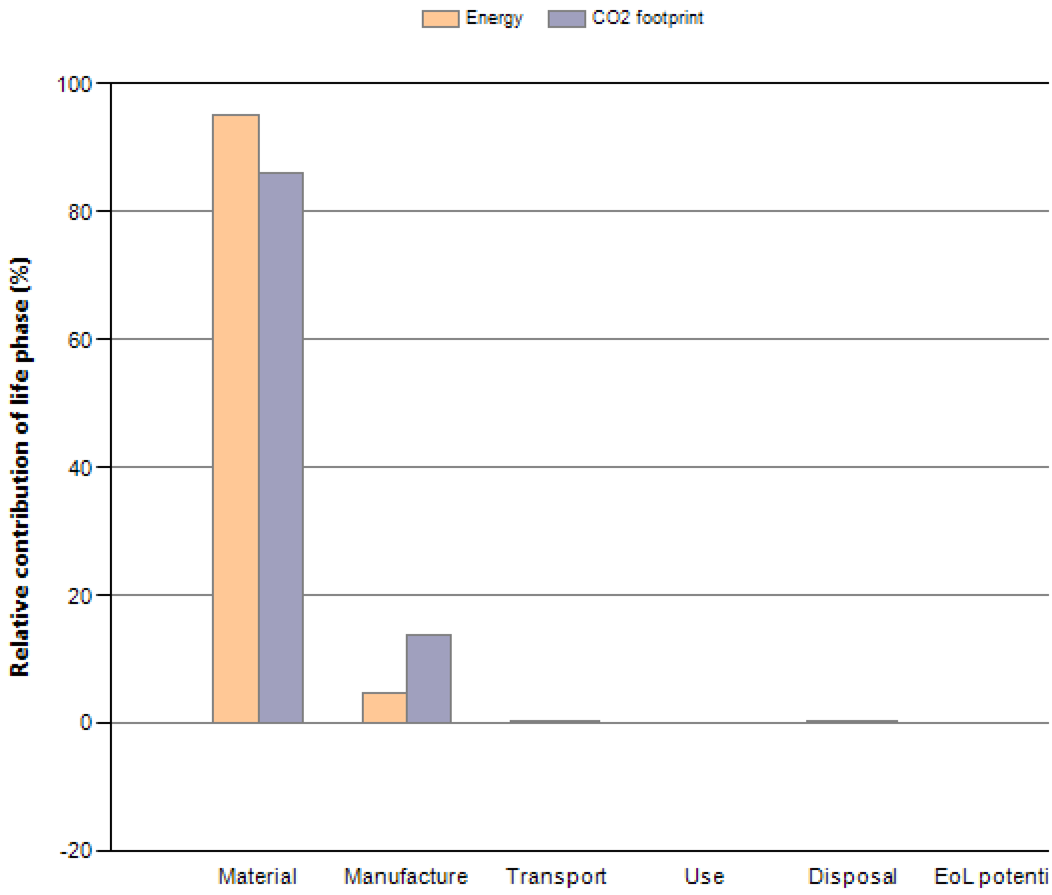
**Eco Audit Report**

| | |
|---|---|
| Product name | new beams |
| Country of use | World |
| Product life (years) | 15 |

**Summary:**



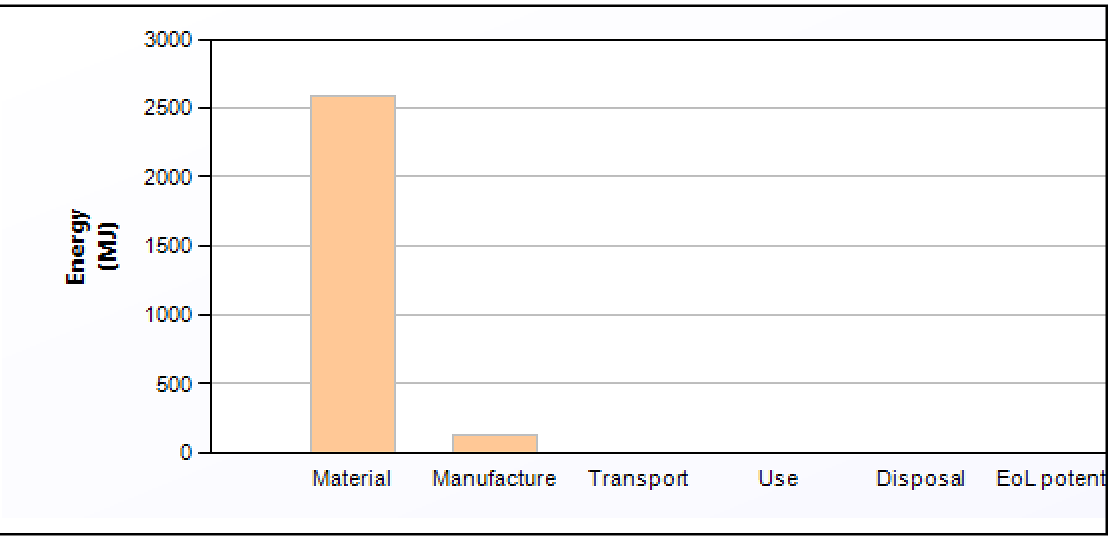

Energy details CO2 footprint details

| Phase | Energy (MJ) | Energy (%) | CO2 footprint (kg) | CO2 footprint (%) |
|---|---|---|---|---|
| **Material** | 2.59e+03 | 95.0 | 66.8 | 86.0 |
| **Manufacture** | 132 | 4.8 | 10.6 | 13.6 |
| **Transport** | 2.77 | 0.1 | 0.2 | 0.3 |
| **Use** | 0 | 0.0 | 0 | 0.0 |
| **Disposal** | 1.2 | 0.0 | 0.084 | 0.1 |
| Total (for first life) | **2.73e+03** | **100** | **77.6** | **100** |
| **End of life potential** | 0 | | 0 | |

**Eco Audit Report**

Summary

## Energy Analysis




| | Energy (MJ/year) |
|---|---|
| Equivalent annual environmental burden (averaged over 15 year product life): | 182 |

## Detailed breakdown of individual life phases

## Material:

Summary

| Component | Material | Recycled | Part mass | Qty. | Total mass (kg) | Energy (MJ) | % |
|---|---|---|---|---|---|---|---|

| | | content* (%) | (kg) | | | | |
|---|---|---|---|---|---|---|---|
| **IGST** | Spruce (along grain) | Virgin (0%) | 30 | 4 | 1.2e+02 | 1.9e+03 | 72.0 |
| **GLUE** | Epoxies | Virgin (0%) | 6 | 1 | 6 | 7.3e+02 | 28.0 |
| Total | | | | **5** | **1.3e+02** | **2.6e+03** | **100** |

*Typical: Includes 'recycle fraction in current supply'

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**Manufacture:** Summary

| Component | **Process** | **Amount processed** | **Energy (MJ)** | **%** |
|---|---|---|---|---|
| **GLUE** | Polymer molding | 6 kg | 1.3e+02 | 100.0 |
| Total | | | **1.3e+02** | **100** |

**Transport:** Summary

**Breakdown by transport stage**

| Stage name | Transport type | Distance (km) | Energy (MJ) | % |
|---|---|---|---|---|
| **van** | Light goods vehicle | 10 | 2.8 | 100.0 |
| Total | | **10** | **2.8** | **100** |

**Breakdown by components**

| Component | Mass (kg) | Energy (MJ) | % |
|---|---|---|---|
| **IGST** | 1.2e+02 | 2.6 | 95.2 |
| **GLUE** | 6 | 0.13 | 4.8 |
| Total | **1.3e+02** | **2.8** | **100** |

**Use:** Summary

**Relative contribution of static and mobile modes**

| Mode | Energy (MJ) | % |
|---|---|---|

| | | |
|---|---|---|
| **Static** | 0 | |
| **Mobile** | 0 | |
| Total | **0** | **100** |

**Disposal:**

Summary

| Component | **End of life option** | **Energy (MJ)** | **%** |
|---|---|---|---|
| **IGST** | None | 0 | 0.0 |
| **GLUE** | Landfill | 1.2 | 100.0 |
| Total | | **1.2** | **100** |

**EoL potential:**

| Component | **End of life option** | **Energy (MJ)** | **%** |
|---|---|---|---|
| **IGST** | None | 0 | |
| **GLUE** | Landfill | 0 | |
| Total | | **0** | **100** |

Summary

**Eco Audit Report**

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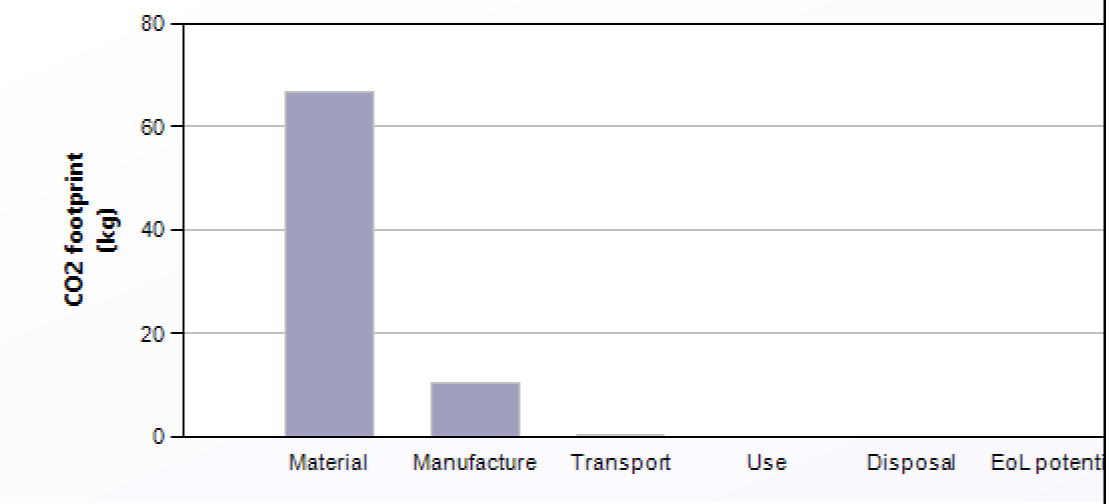
Summary

## CO2 Footprint Analysis




| | CO2 (kg/year) |
|---|---|
| Equivalent annual environmental burden (averaged over 15 year product life): | 5.17 |

## Detailed breakdown of individual life phases

## Material:

Summary

| Component | Material | Recycled co | Part mass | Qty. | Total mass (kg) | CO2 foot-pri | % |
|---|---|---|---|---|---|---|---|

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | **ntent* (%)** | **(kg)** | | | **nt (kg)** | |
| **IGST** | Spruce (along grain) | Virgin (0%) | 30 | 4 | 1.2e+02 | 31 | 46.7 |
| **GLUE** | Epoxies | Virgin (0%) | 6 | 1 | 6 | 36 | 53.3 |
| To-tal | | | | **5** | **1.3e+02** | **67** | **100** |

*Typical: Includes 'recycle fraction in current supply'

**Manufacture:** Summary

| Compo-nent | **Process** | **Amount processed** | | **CO2 foot-print (kg)** | **%** |
|---|---|---|---|---|---|
| **GLUE** | Polymer molding | 6 | kg | 11 | 100.0 |
| Total | | | | **11** | **100** |

**Transport:** Summary

**Breakdown by transport stage**

| Stage name | Transport type | Distance (km) | CO2 footprint (kg) | % |
|---|---|---|---|---|
| **van** | Light goods vehicle | 10 | 0.2 | 100.0 |
| Total | | **10** | **0.2** | **100** |

**Breakdown by components**

| Component | Mass (kg) | CO2 footprint (kg) | % |
|---|---|---|---|
| **IGST** | 1.2e+02 | 0.19 | 95.2 |
| **GLUE** | 6 | 0.0095 | 4.8 |
| Total | **1.3e+02** | **0.2** | **100** |

**Use:** Summary

**Relative contribution of static and mobile modes**

| Mode | CO2 footprint (kg) | % |
|---|---|---|

| | | |
|---|---|---|
| **Static** | 0 | |
| **Mobile** | 0 | |
| Total | **0** | **100** |

**Disposal:**

Summary

| Component | **End of life op-tion** | **CO2 foot-print (kg)** | **%** |
|---|---|---|---|
| **IGST** | None | 0 | 0.0 |
| **GLUE** | Land-fill | 0.084 | 100.0 |
| Total | | **0.084** | **100** |

**EoL potential:**

| Component | **End of life op-tion** | **CO2 foot-print (kg)** | **%** |
|---|---|---|---|
| **IGST** | None | 0 | |
| **GLUE** | Land-fill | 0 | |
| Total | | **0** | **100** |

**Notes:** Summary

## Calculating for the bending moment for the 4 points bending test:

Bending Moment Calculation for a 4-Point Bending Test

Objective

To calculate the bending moment at the loading points in a 4-point bending test setup.

Test Setup

**Total span of the beam (L)**: 3.6 meters

**Distance from each support to the nearest loading point (a)**: 1.1 meters

**Load applied at each point (P)**: 15 kN

Calculation Steps

**Determine the Distance Between the Load Points**:

$b = L - 2a = 3.6 - 2 \times 1.1 == 1.4$ m

**Calculate the Reaction Forces at the Supports**:

$$R = \frac{p}{2} = \frac{15}{2} = 7.5\ m$$

**Calculate the Bending Moment at the Loading Points**:

$M = R * a$= 8.25 kn

Result

The bending moment at each loading point is 8.25 kN·

ULS validation:

1. **Calculate the Stress** ($\sigma_{m,d}$):

$$\sigma_{m,d} = \frac{6 \times M_{Ed}}{b \times h^2}$$

Convert $M_{Ed}$ to N-m:

$$M_{Ed} = 8.25\,\text{kN-m} \times 1000\,\text{N/kN} = 8250\,\text{N-m}$$

Substitute the values:

$$\sigma_{m,d} = \frac{6 \times 8250}{0.08 \times (0.18)^2}$$

Calculate $h^2$:

$$h^2 = 0.18^2 = 0.0324\,\text{m}^2$$

Now, calculate $\sigma_{m,d}$:

$$\sigma_{m,d} = \frac{6 \times 8250}{0.08 \times 0.0324}$$
$$\sigma_{m,d} = \frac{49500}{0.002592}$$
$$\sigma_{m,d} \approx 19062500\,\text{Pa}$$
$$\sigma_{m,d} \approx 19.0625\,\text{MPa}$$

2. **Check the Ratio**:

$$\frac{\sigma_{m,d}}{f_{m,d} \times k_h}$$

Substitute $f_{m,d} = 19.2$ MPa and $k_h = 1.03$:

$$\frac{19.0625}{19.2 \times 1.03}$$
$$\frac{19.0625}{19.776}$$
$$\approx 0.964 < 1$$

## Conclusion:

The calculated stress ($\sigma_{m,d} \approx 19.0625\,\text{MPa}$) is less than the allowable stress ($f_{m,d} \times k_h \approx 19.776\,\text{MPa}$). Therefore, the condition $\frac{\sigma_{m,d}}{f_{m,d} \times k_h} < 1$ holds true.