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Developing dowel-laminated timber panels from short salvaged timber elements

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Abstract

Reusing salvaged timber in structural applications could offer a sustainable solution towards a circular economy in the construction sector. However, this is associated with some challenges such as length limitation, which would require further processing and end-to-end joining. The aim of this research was to develop a new approach using short, salvaged timber elements which can be used in the fabrication of dowel-laminated timber (DLT) panels without requiring significant processing or end-to-end jointing or gluing. In the developed approach, the salvaged timber elements were used in combination with new timber boards, which were all connected together using salvaged plywood tenons. The salvaged timber layers were prestressed in the system. This way, they could contribute to the bending performance of the DLT panels by resisting compression stress. The effectiveness of the new approach was evaluated on several small-scale and large-scale DLT panels. For the small-scale DLT panels, the bending stiffness before and after prestressing was evaluated. For the large-scale DLT panels, the first eigenfrequency, damping ratio, bending properties, and failure modes were evaluated. Analysing the results, it was concluded that the proposed approach can lead to a substantial improvement in the bending stiffness of the DLT panels without requiring end-to-end joining or gluing. On average, 40 % increase in the bending stiffness was achieved in the DLT panels after the prestressing. Therefore, the presented approach can be a suitable solution for reusing short, salvaged timber elements in DLT panels. This can further reduce the need for raw material and improve the sustainability aspects of DLT panels.

Keywords Bending stiffness; eigenfrequency; damping ratio; prestressing; salvaged wood; wooden connectors; reuse; circular economy.

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Contents

Preface

I would like to thank my supervisors Prof. Fink Gerhard and Derikvand Mohammad for the incredible opportunity that they offered me to work on this project and for their guidance. It was a great learning journey for me. I would like to thank them, and the whole department, for helping me during the process, from the developing of the starting idea to the conclusion of the project. Special thanks to Derikvand Mohammad for his assistance through all the process and to Joonas Jaaranen for his assistance during the test.

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I also would like to thank my friends and my family for their support, a special thanks to my parents that allowed me to have this amazing experience and for their always present support. I would like to add a special thanks also to all the people that I met during my time in Finland for their presence and contribution.

Otaniemi, 31 July 2022
Lorenzo Giordano

Symbols and abbreviations

Symbols

f_c	Characteristic value of the bending strength
F_c	Fracture load force at the fracture point
L	Length
b	Width
d	Thickness
EI_{eff}	Effective stiffness
EI_{local}	Local stiffness
ω	Displacement
ΔF	Force difference
$\Delta\omega$	Displacement difference
P_b	Design uniformly distributed load
E	Modulus of elasticity
I	Second moment of area
f	Fundamental frequency
ζ	Damping ratio

Abbreviations

CLT	Cross laminated timber
CNC	Computer numerical control
COV	Coefficient of variation
DLT	Dowel-laminated timber
DOL	Duration of load
EWPs	Engineered wood products
GLT	Glue-laminated timber
LVDTs	Linear variable differential transformers
LVL	Laminated veneer lumber
MC	Moisture content
NLT	Nail-laminated timber
UTM	Universal testing machine

1 Introduction

Over the past years, more considerations have been taken into account regarding the selection of the building materials as a result of the increasing environmental concerns. The application of the wood cascade concept gives to the engineers the possibility of targeting the environmental requirements. This is based on the concept of reuse for several times, in different applications, the same source. During its utilisation, the quality of the material decreases towards thermodynamic equilibrium (Sathre and Gustavsson 2006). The simplest possible cascade for wood, formed by just two links is to burn the materials after its service life and use it as energy recovery. However, as can be seen in Fig. 1, the potentiality of wood is way bigger after its first service life. Burning the wood at this stage is a waste that burdens on the natural habitat and the forest that is necessary to be preserved. In addition to that, moving from linear to circular economy has received specific research attention in recent years based on the use of salvaged timber materials in new applications (e.g., Satu Huuhka 2018, Klinge et al. 2019, Derikvand et al. 2021, Niu et al. 2021, Gengmu Ruan et al. 2021).

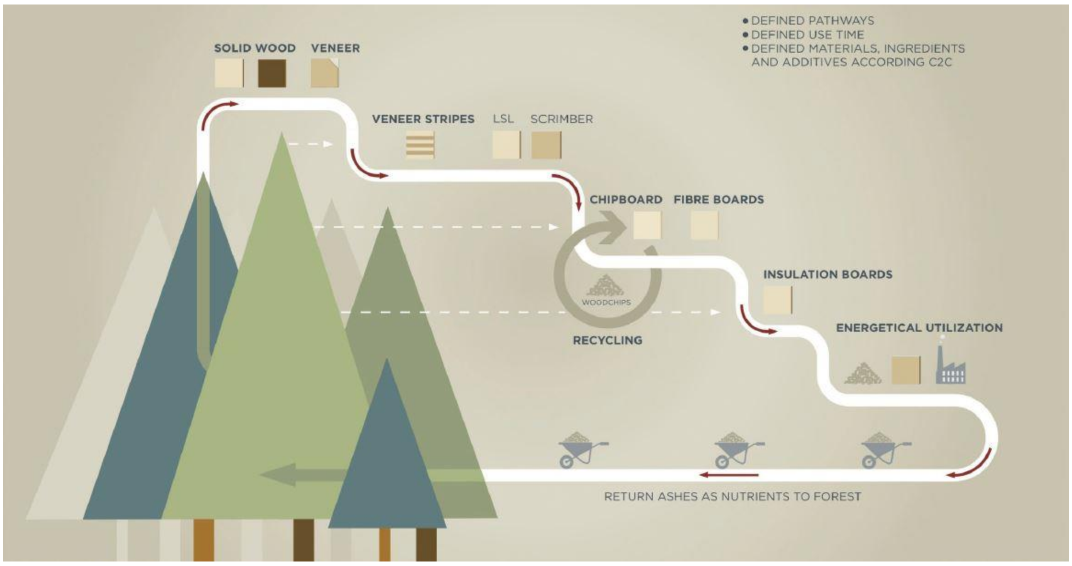


Fig. 1: Wood cascade (Ellen MacArthur Foundation, 2012. Wood cascade according to cradle to cradle [Graph]. Cascading Materials. https://thecirculareconomy.fandom.com/wiki/Cascading_Materials).

In the presented research, a practical application of the wood cascade is proposed by using salvaged timber boards in combination with new timber boards to fabricate dowel-laminated timber (DLT) panels. Salvaged timber is produced in large quantity, coming from different sectors and sources. Some examples can be demolished buildings as structural or non-structural material, construction sites where it was used to create formwork or falsework, timber production facilities as cut off or error in the production, or even dead standing trees. In the recent years, it has received attention from different research. The fact of using salvaged timber in the production of DLT panels, as an active part of the system, increase the value of this material and the sustainability of the final products. It allows the market to move towards the circular economy. Since the target is to reduce the environmental impact of the construction sector, using salvaged materials means that less new material is used. As a consequence, less fresh wood is requested so it increase the carbon storage capacity of the DLT panels. In addition to the salvaged timber used in the production of the panels, in this research also the connectors are made of salvaged plywood. The trend of the recent years is to substitute adhesive and metallic fasteners in engineered wood products (EWPs) with new and environmentally friendly solutions such as salvaged wooden connectors.

Although salvaged timber can be used in several different applications, it is necessary to point out that there are some limitations and precautions that must be considered. First of all, salvaged timber materials have different properties with respect to the fresh timber, therefore the comparison of the results from one test group to another could be affected by this. Another important aspect is the length limitation of the boards. Consequently, end-to-end joining such as finger joint or gluing is necessary to connect the boards together. These solutions involve a long processing procedure, which was decided to be avoided in this research. As an alternative, an interlocking pattern, without using any of the previously mentioned solutions, can be used to connect the small boards of salvaged timber together. This approach has a low environmental impact and presents also a lower cost since it does not involve any synthetic or metal fasteners. Another limitation of this material is that, usually, it is represented by a mix of species since it can come from different sources. An important challenge faced in this project was that the salvaged timber boards presented growth irregularities and distortions. This led to a pre-processing and accurate selection of the materials. Since the salvaged boards were previously used in another project (Gengmu Ruan et al. 2021), some wooden nails were present inside the boards. This led to a more accurate selection of the boards. Moreover, the mechanical properties of the salvaged timber are unknown. These can be affected by several factors like the duration of the load effect (DOL, static fatigue, e.g. Svensson 2009), natural aging phenomena, the storing condition, or mechanical and biological damages. Cavalli et al. 2016 discussed the effect of the aging phenomena. Different studies may present different results. This is due to the fact that the mechanical properties of wood have a large natural variability (e.g. Tord Isaksson 1999, Fink and Kohler 2011). Overall, the previous research works agree that aging can be considered just a side effect. On the other hand, transport and storage condition, environmental exposure and load history may be unknown. To solve this problem, a non-destructive inspection method can be applied to the salvaged timber boards (Dietsch P. and Kohler 2010, Fink and Kohler 2015 for assessment methods and approaches).

The aim of this project is to study the bending properties and the vibration characteristic of DLT panels made with short salvaged timber elements. The target is to reuse the salvaged material in an efficient way, not only as a space filler, but as an active part of the system. In this research is presented a new way of reusing short, salvaged timber elements for the production of DLT panels that do not require end-to-end joining or gluing, neither excessive processing. In the standard and commercial production, DLT products are fabricated using new and continues timber boards, joined together by wooden dowels (see AFTB 2016, StructureCraft Builders 2022) . On the other hand, with the present research, the new and continues timber boards were alternated to short salvaged timber elements, while salvaged plywood tenons were used as the connectors. After setting some hypothesis, and trying different possible approach, it was chosen to connect the salvaged timber boards using an interlocking pattern that guarantee prestressing in the system. In this way the bending performance of the DLT panels were increased thanks to the resistance, mostly in the compression stress of the salvaged boards, with respect to the same system considering just the fresh timber layers. At the beginning, several prototypes were produced, with different types of connections and interlocking patterns. Some of them were discarded because they were not effective, while some others were discarded because they required a long processing procedure. One of the key points of this research was to reuse the salvaged materials in an efficient way. This means also to reduce the processing of the timber as much as possible. The chosen pattern was formed by an alternation of fresh timber layers and salvaged timber layers, where the short boards were alternately nailed to the fresh layer (called mortise in this research). The boards that were not nailed, were then hammered inside the system (called tenons in this research) in order to introduce the prestressing force. At the beginning, two different mortise-tenon solutions were explored. Once where both presented a profiled surface (with end-to-end interlocking), while the other system is with a straight surface connection (without end-to-end interlocking). In order to see if this approach was effective, and also to understand which one of the previously presented solution was more efficient, it was chosen to perform a small-scale test. Eight small-scale DLT panels were produced, five of them with end-to-end interlocking, while the other three without end-to-end interlocking. The panels were formed by three layers, two of continuous fresh timber boards, and the middle one of salvaged timber elements. A three-point bending test, done both before and after the prestressing, confirmed that the presented approach is effective and that the system without end-to-end interlocking is more efficient. Subsequently, it was chosen to produce five large-scale DLT panels, formed by five layers each. Three layers of continuous timber boards, alternated with two layers of short salvaged timber boards. The bending stiffness of the large-scale DLT panels was evaluated through a four-point bending test both before and after the prestressing of the salvaged timber elements. As well as eigenfrequency and damping ratio were evaluated through a vibration test, also in this case before and after the prestressing. In addition to that, both the load carrying capacity and the failure modes of the prestressed large-scale DLT panels were studied. The target of this research is to study how much can the stiffness of the system increase with the selected layout of the panels and use of the materials.

2 Literature review

Over the past decades, a raising awareness could be noticed regarding the exhaustion of natural resources and the heavy effect of climate change partially due to the construction sector. During 2019, CO_2 emission from the construction sector reached the highest ever recorded. The global share of building construction final energy use and share of the total global energy related CO_2 emission are 35% and 38% respectively (2020 Global Status Report for Buildings and Construction | Globalabc 2022). In recent years, the focus moved towards new issues in the sector: material use and circular economy. The need of a closed-loop system is clear. This means using fewer raw or synthetic materials while exploiting the potential of biobased solutions for green and sustainable cities.

Since the ancient times, wood has always been one of the main construction materials due to its availability and its ease of application. Despite that, its mechanical properties have a wide range of variation caused by the fact that timber is a natural material. This means that it can have some growth irregularities such as knots and different slopes of grain etc. These natural characteristics depend on the type of the wood and different growth conditions. For this reason, and in order to increase the performance of timber, engineered wood products are constantly developed and improved. Nevertheless, most of these products are constructed using synthetic adhesive bonding or metallic fasteners. Some examples are glue laminated timber (GLT), laminated veneer lumber (LVL), nail laminated timber (NLT), plywood and cross laminated timber (CLT). The presence of the connectors or of the glue obviously increases the performance and the characteristics of the timber. It allows to reduce the cross section with respect to a fresh wood structure, the geometry can be more complex, and the material is more resistant because the mechanical properties are more homogeneous. For these reasons, the EWPs are largely used in the construction sector, as main structural systems as well as support systems.

Mass laminated timber is a term that refers to engineered wood products with a large section size used in the construction sector. These products represent a good alternative with respect to concrete and steel since the mechanical properties are comparable. Wood is actually a sustainable material, and the cost is competitive. One example can be the Brock commons student residence, Vancouver, Canada. It is an 18-storey residence building for more than 400 students. The structural materials are concrete and timber: the ground floor is reinforced concrete and also two reinforced concrete cores are present, while the rest of the structure is formed by CLT panels and glulam columns. The cost of construction for this new technology building resulted 8% higher than a comparable reinforced concrete building. This cost difference will most likely reduced over the years, since more and more CLT suppliers and designers will take part in the shift from the traditional materials towards timber and mass timber construction methods (Harte 2017).

As a drawback, using adhesive or metal parts in the production of EWPs badly influences the sustainability ratio, the recyclability and especially the end of life of the product. The production of these adhesives causes high emission of toxic gases in the atmosphere, which is harmful for the environment. Normally, the materials used in the EWPs are not harmful for humans, but during the life span, especially if the wood is exposed to severe condition such as rapid change of humidity or used in environments with a high temperature, it can cause the emission of formaldehyde (Sotayo et al. 2020). A long and constant exposure to this kind of gas can lead to an allergic reaction. For the above-mentioned reasons, the World Health Organization and the European Committee (World Health Organization. Regional Office for Europe 2010) released some standards with the target to reduce and limit the use of harmful additives. Therefore, the aim is to reduce the emission of toxic gases in the atmosphere during the production of the engineered wood products.

DLT products represent a greener alternative since they are more sustainable and do not include any adhesive or metal connections. DLT can be used, both as a beam-type element, as well as a slab-type element and it is produced by assembling together solid timber lamellae using wooden dowels or tenons. Until now, most of the studies have used hardwood dowels to produce DLT, the species used are Oak, Maple, Birch, Ash and Aspen. Derikvand et al. 2021 analysed the effectiveness of using connectors made from salvaged engineered wood products instead of hard wood ones. The connectors used were made from salvaged plywood and salvaged laminated veneer lumber, while connectors made from solid Oak were used as reference. The research shows how the salvaged plywood tenons can be used to improve the bending stiffness and the environmental impact of the DLT beams.

Nowadays, considering the positive environmental impact, the low cost and the better recyclability of wooden dowels, the research and use of this kind of connection drastically increased. During the production process, the density of the wooden dowels can reach up to three times the original density. Several researchers studied the mechanical properties of wooden dowels, such as bending properties and usage of wooden connection as fasteners (Ogunrinde 2019). The insertion of the dowel can take place through different techniques, and all of them do not require synthetic adhesives. The insertion method applied in this research is through a hammering procedure (Milch et al. 2017) (El-Houjeyri et al. 2019). Other possible methods include the use of an hydraulic press to compress the dowels with a bigger diameter into the holes (TKPS). In addition to that, the dowels can be inserted in the oven in order to reduce the moisture content, in this way they shrink and result smaller than the hole, but once the dowels will be inserted into the boards, the wood will reach an equilibrium of the moisture content at service. It means that the dowels will swell up, as a result a tight fit is reached (Dietrich Buck et al. 2015). Finally, the dowels can also be inserted through an high speed rotational wood welding (O'Loinsigh et al. 2012).

DLT is normally produced using fresh, new timber boards. However, the use of salvaged timber in DLT production can have a significant effect on its sustainability aspects. Salvaged timber, which is the focus of this research, is available in huge quantity in the construction sector. It is represented by cut-off or rejection from the production process of the engineered wood products or the strength grading of the wood. Other examples can be the cut-offs of timber boards due to e.g. overlength, as well as the cut-out of openings like windows and doors from the CNC (computer numerical control) milling of plate elements. Salvaged wood can furthermore be considered the wood used for concrete formwork and falsework (Gerhard Fink et al. 2019) or demolished buildings, construction sites and even dead standing trees. Over the last few years, several studies were carried out on how to reuse the salvaged timber. Llana et al. 2022, for instance, produced cross laminated timber (CLT) using European Oak timber (*Quercus robur L.*) coming from the demolition of 200-years-old building. The research shows how the bending properties of the samples formed by salvaged hardwood timber is comparable to the CLT made by new hardwood timber of the same species, however it has lower bending strength. A study on how to reuse salvaged timber boards from dead standing White Spruce trees (*Picea glauca*) for the production of CLT was done by Ma et al. 2021. They found out, after numerical and experimental evaluation, that the CLT solution proposed in their research can be applied for structural applications since it satisfies the standard requirements. Another research on CLT panel was done by R. Arbelaez et al. 2020, the 3-layers CLT panel was produced varying the layup and the amount of salvaged timber boards. Structural uses potentials were demonstrated in this research. Rose et al. 2018 fabricated cross-laminated secondary structure (CLST) using salvaged timber boards coming from demolitions and construction sites. In this research is shown how, high quality salvaged timber boards, can replace regular CLT in certain applications.

Dimensions, availability and quantity of the salvaged wood vary between the different categories, but often they can represent acceptable structural qualities. However, to call this solution sustainable, the processing of the timber, if needed, must be the less possible. Even if some research connect through end-to-end joining or finger joining the short fresh timber boards to use them in mass laminated timber (Dziurka et al. 2022). In order to do so with salvaged timber, processing and use of synthetic glues is required, and this badly influence the sustainability aspect of this material and it increases also the production cost. Moreover, the salvaged material is supposed to come from regional companies. Consequently, the source of the reused materials are the local industries itself. Since the availability and the dimensions of the salvaged timber may vary depending on the geographical area or the period of the year, it may also affect the configuration and the resulting pattern of the structure. Full length boards or long cut-offs rejected due to some irregularities or errors can be found, although the majority of the salvaged timber boards have a reduced length. Therefore, most of the research focused on short span boards with a length smaller than one meter. Salvaging locally these materials for a structural or non-structural application in new projects allows to take full advantage of the environmental and economic potential of the wood.

Usually, connections between wooden boards are represented by metallic fasteners, since it represents a fast and efficient way, used also during the construction process. On the other hand, metal connectors are not environmentally friendly, and do not represent an optimal solution thinking about the end of the life of the product. However, wooden nails are an optimal solution for this problem. Since no pre- or post-processing is needed (e.g. predrilling), the construction procedure can proceed smoothly and the final product is made uniquely by wood (Gengmu Ruan et al. 2021). Some researches were carried out on the properties and the behaviour of the wooden nails (Ruan et al. 2021; Riggio et al. 2016). In the last cited research, wooden nails were suggested in refurbishment on historic timber building.

3 Research material and methods

At Aalto University some projects about salvaged timber, wooden dowels and wooden nails were carried out (Ruan et al. 2021; Gengmu Ruan et al. 2021; Gerhard Fink et al. 2019; Derikvand et al. 2021; Derikvand and Fink 2023). This work has as a starting point some of the conclusions from the previously cited projects. Since the target is to have a slab system all made from timber, without using synthetic fasteners or metal pieces, and a high relative percentage of salvaged timber, the first unknown to solve is how to arrange the boards in the system. In most of the dowel laminated timber projects, the boards are arranged vertically and connected by wooden dowels along the horizontal direction. Different options can be studied on how to insert the salvaged timber boards depending on the target resistance that is required. In this research there is not a target resistance to achieve, therefore the different patterns that are studied are focused more on the modularity of the solution proposed and on having a good amount of salvaged timber boards, around 50% of the total timber. The chosen one, is represented by a simple alternation of the two materials. The external layer is a fresh timber board, on which the short salvaged timber boards are fixed using wooden nails. After that, the second fresh board is placed and fixed again with wooden nails. This procedure can be repeated in order to obtain as many layers as needed, subsequently the system is connected together using plywood dowels. For the purpose of this research, the slabs were produced with five layers each, so it results with 60% of fresh timber and 40 % of salvaged material. However, the proposed solution can be considered as the basic system that can be repeated for the required dimension depending on the application.

3.1 Materials

The timber used for this project, both the fresh and the salvaged one, was already present and stored in the Lab of the department of Civil Engineering, Aalto University.

The fresh timber used to fabricate the slab is Spruce timber (*Picea abies*) with the Strength class C24. Since these boards were already stored in the laboratory environment with varying relative humidity for nearly two years before this research, they had some growth irregularities, like knots and pith, as well as regular drying distortions. The original dimensions of the boards are 45x120x4000 mm^3.

As regards the salvaged timber, the boards that were used were previously tested in the research “Sustainable design concepts for short span, timber-only structures” (Gerhard Fink et al. 2019; Ruan et al. 2022). Also in this case, the species of wood is Spruce (*Picea abies*), with original strength class

C24. The original dimensions of the salvaged timber boards were 45x120 mm^2 with a variable length between 800 and 900 mm. Since these boards came from previous research, they contained wooden nails and also some cracks were present. Some of them contained growth irregularities or were noticeably twisted. After minimal processing, the cross-sectional dimensions were altered to b x h = 117 x 44 mm^2, and the boards were cut to a length of 400 mm to 583.2 mm. Also, the fresh timber boards went through a small processing procedure in order to have the same width and thickness as the salvaged ones.

The salvaged plywood was acquired from the laboratory of Civil Engineering Department at Aalto University. This material was already used in another project (e.g. Derikvand and Fink 2021) as concrete formworks before being utilized in the present study.

3.2 Disposition of the boards and layup

Five main solutions were studied (Fig. 2) and the pros and cons for each of them were analysed. The first solution is just the repetition of two layers: fresh wood and salvaged timber (Fig. 2a). In this case the salvaged timber boards are in contact. During the building procedure wooden nails should be used to connect the salvaged timber to the fresh boards so there is no need of using clamps. Then the tenons should be used to connect the whole structure. In the second solution the layup is the same as the first one but in this case the salvaged timber boards are not in contact (Fig.2b). Furthermore, the wooden nails are useful just during the construction phase to connect the salvaged timber to the fresh timber, so avoiding the use of clamps. On the other hand, in this solution the number of nails can be reduced as much as possible because the salvaged timber will be present just where the tenons are, so these keep together all the structure, and the wooden nails are no longer useful. The problems of this solution are the aesthetic part and also the fire safety because the structure have some gaps between the laminated layers. For these reasons this solution is not developed. In the third solution the layup changes and it is an alternation of three layer of fresh timber and three layers of salvaged materials (Fig. 2c). In this case the boards of salvaged timber are in contact. The building procedure is different from before: the wooden nails are used to build first the three layers of fresh timber connecting them together. Then the three layers of salvaged timber boards are also build using wooden nails, but in this case the connections are very important, and the chosen arrangement is the shear-tension arrangement, denoted with T, with one nail per shear plane and an inclination of 15° (Ruan et al. 2021). Finally, all the system is joined using wooden tenons. The nailing part of the salvaged timber is very important because the tenons cannot go through all the salvaged timber so some boards will be connected just by nails. This solution is not developed because in case of a point load in the salvaged timber part, the structure will have a lower capacity, not comparable with the one of the fresh timber. The fourth solution is a repetition of three layers of fresh wood and 3 layers of salvaged timber, but the boards of salvaged timber are not in contact, they are present just where the tenons are (Fig. 2d). During the construction phase the nailing procedure is useful to keep the boards in the correct position until the tenons join the system together. This solution is not developed for the same reason of solution two and solution three. The fifth solution is a repetition of one layer of fresh timber and two layers of salvaged timber and again one layer of fresh timber (Fig. 2e). Each salvaged layer is connected to the respective layer of fresh wood. The salvaged boards can be in contact or not, but since previously the problem of having them not in contact were already explained, it was chosen to have them in contact. In the building phase, first is assembled the subsystem formed by one layer of fresh timber, which the salvaged timber boards are nailed on, and then all these double layers are joined using wooden tenons following the layup explained previously. All in all, the solution one was developed because it was the most promising one since one of the targets was to use as much as possible the salvaged material but also to have a strong structure.

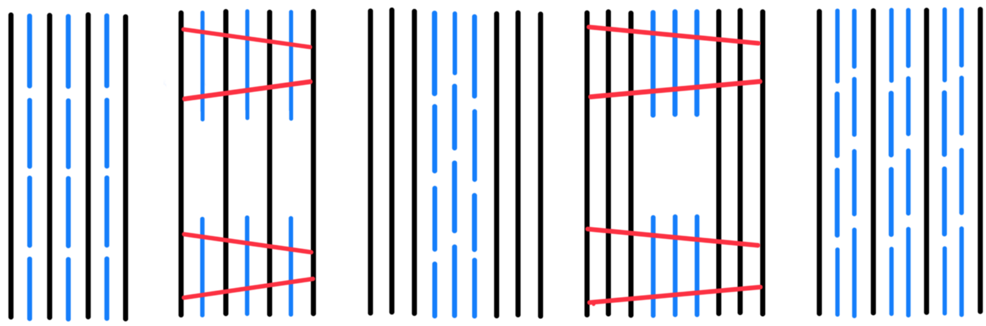


Fig.2: (a) First solution, (b) second solution, (c) third solution, (d) fourth solution, (e) fifth solution.

3.3 Connectors

Once the pattern is chosen, the focus moves on how to connect the salvaged timber boards to the fresh timber and then how to connect all the layers together. Densified hardwood nails made from European Bleach (*F. sylvatica L.*) are selected to connect fresh and salvaged timber. The nails are produced by Lignoloc®, and the chosen dimensions are length of 75 mm with a diameter of 4.7 mm. On the VHT – The German Test Institute for Timber and Drywall Construction is it possible to find the mechanical properties of the wooden nails. In order to insert them, a six-bar air pressure coin nailer (Frasco) was used. When shot, the wooden nails undergo a high-speed rotation that create a large amount of heat due to the friction with the board. This entails the welding of the lignin of the wood that create a bond with the wood that surrounds the nail. This procedure is fast and does not require any predrilling, as a consequence wooden nails are selected to speed up the construction process (Gengmu Ruan et al. 2021). According to the homogeneity of the structure, it was chosen to have fresh timber on both the external side. As a consequence, the first layer is the fresh timber, on top of this one are fixed the salvaged boards using wooden nails. Since the wooden nails are used during the construction procedure to fix the salvaged board on the fresh timber, is not important to shoot the nails with a certain angle. On the other hand, some precautions have to be considered. Since the nails do not require any predrilling, they require a minimum distance of 10 cm between nails and between the nail and the end of the board otherwise some cracks can occur. This pattern of two layers is then repeated another time, and then the last layer is just fresh timber. In this way the final result is a system made of five layers, three of them are fresh wood while the other two are salvaged timber. The best solution for this project it appears to be using tenons made by salvaged birch plywood (19-mm-thick). Connectors made of plywood were already object of different studies about composite structures (e.g. Chang et al. 2011; Daňková et al. 2019; Derikvand et al. 2021). It is preferable to use tenons because, with respect to the dowel, they have a certain resistance against rotation, they are easier to produce in the lab and guarantee and higher resistance of the system. The tenons are supposed to cover the whole dept of the slab that, at this stage, is 225 mm. This value is obtained because the thickness of one board is 45 mm, and the slab is made by 5 boards. Different orientation options are studied for what concerns the tenons. The first option, commonly used in the industry, is to have the connectors inserted with a 90° angle with respect the orientation of the boards. This option, in the early stage of the research, was then discarded since it can create some problem to the edge boards after some time. At the beginning no problem would occur if the construction procedure were done in a workmanlike manner, but after some years the external boards would get detached from the main system because the connection would became lose and some gaps between the tenons and the timber boards will appear. On the other hand, the second option is to have the tenons with a certain inclination, as it can be seen from fig.3. This guarantees that also after some years the edge boards will not separate from the main structure. Even without a tight fit and despite the small angle, this solution does not allow to the system to fall apart.

Fig.3: Prototype with inclined dowels.

In the prototype the chosen inclination for the dowels is 60°, but the target is just to show that, giving a certain inclination to the connection, the system will remain together even if it is tried to be teared apart. In reality a 60° angle cannot be applied because a certain distance between consecutive tenons has to be present, and with such a big angle there is not enough space to insert all the needed connection. In this solution even a small angle is enough to guarantee the compactness of the system. The drawback of this solution is that, since the tenons have to cover the whole span, it is most probable to encounter some problems during the insertion of them. For instance, it is not possible to hammer them inside the hole because the end of the tenons will break. The insertion procedure will be difficult because the span is too much. To avoid these problems, it was chosen to have the tenons oriented perpendicular to the main direction of the boards since, once that the middle pieces are inserted, a pre compression will be introduced in the system. As a consequence, the tenons will be compressed as well against the surface of the holes and this led to a strong connection of the whole system. According to this solution, the tenons are also easier to insert.

Fig.4: Final pattern of the wooden dowels.

3.4 Small scale DLT specimens

The salvaged timber layers were prestressed in the system in a way that they contribute to the bending performance by resisting compression. Two solutions were studied: a mortise-tenon connection, in which an end-to-end interlocking is provided, and, to have a base of comparison, also panels without end-to-end interlocking system were produced. The mortise boards were fixed to the fresh ones, while the tenon boards were then hammered inside the system. The main aspect of this solution is the prestressing obtained after the insertion of the middle board. The full procedure that ends with the choice of the previously explained connection can be found in the attachment, section 6.1 Study of the interlocking system (6.1).

Once the interlocking pattern was chosen, the next step was to produce the specimens for the test. However, before starting the mass production and the full-scale test, it was decided to perform a small-scale test focusing on the interlocking part. The target was to study and understand if the chosen interlocking pattern was actually able to increase the capacity of the system. Three possible scenarios were expected before conducting the test. The first one was that it will be discovered that the option with end-to-end interlocking does not add any capacity to the system. In this case the interlocking pattern would be discarded, and a simple straight connection would be used instead (without end-to-end-interlocking). The second scenario was that the option with end-to-end interlocking increase the capacity of the system. If the test confirms this, the next step is to execute the same test but with panels without end-to-end interlocking (with the vertical surface of the board, still with the angle but not with the profile). If the results of this last test are similar to the results of the previous one with the end-to-end interlocking pattern, the choice for the mass production would be the option without end-to-end interlocking because the construction procedure would be faster since there is no need of using the table router. Once that the tenon and mortise salvaged boards would have been processed with the table saw and the angled surface was cut, the piece would be ready to be used. Moreover, the test can demonstrate that the added capacity is the same. The third option is that the first test, the one with end-to-end interlocking show that this solution increase the capacity of the structure, while the second test without end-to-end is not able to add as much capacity as the other solution. In this last case, the pattern used during the mass production is represented by the end-to-end interlocking system where the tenon boards are hammered along the vertical direction.

3.4.1 Small scale DLT specimens' production

The production process for this preliminary test proceeded quite straight forward. In total eight panels were produced, each one with a length of 120 cm and formed by three layers. For each panel were needed two fresh timber boards that formed the external layers. The middle layer of the system was made of three short salvaged timber elements. The configuration of the small-scaled DLT panels, before and after prestressing, as well as the dimensions of the end-to-end interlocking system can be seen in fig. 6.

Fig. 5: salvaged board profiled with mortises and tenons shape.

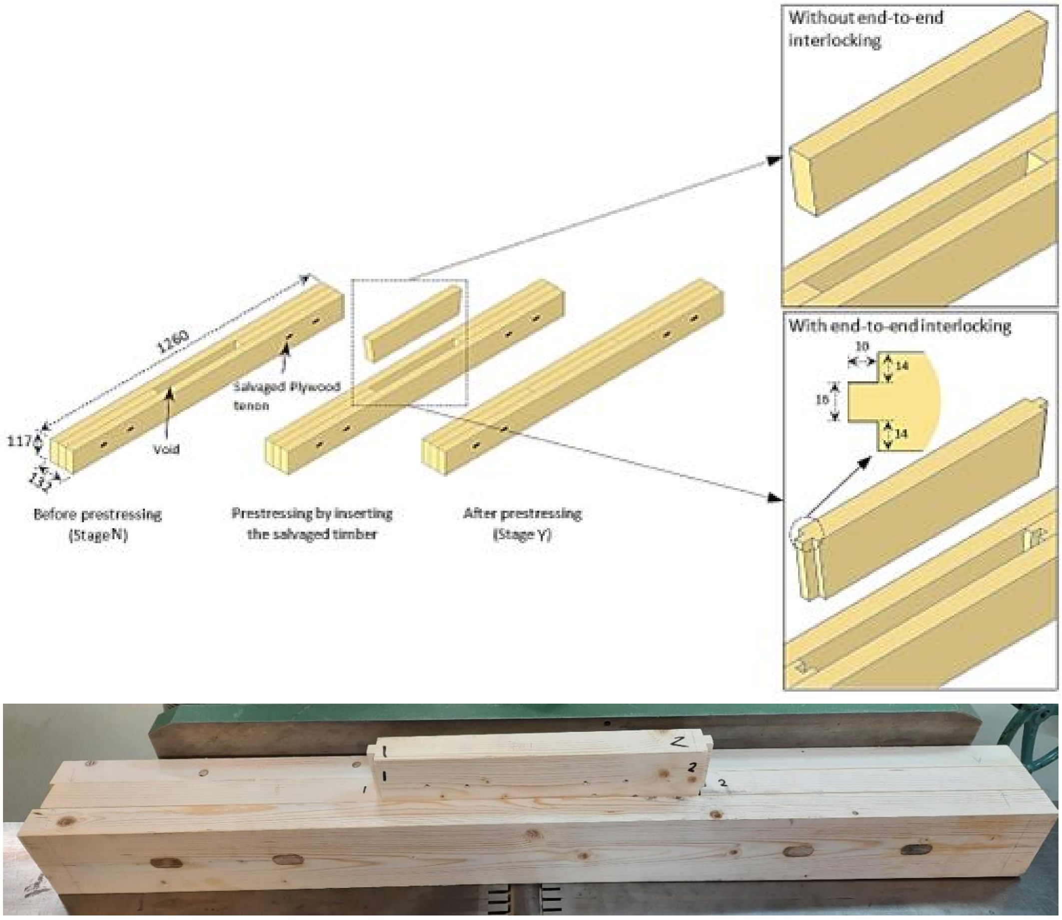


Fig.6: Configuration of the small-scale DLT panels before and after prestressing. Dimensions in mm.

To produce the samples, firstly both the salvaged and the fresh boards, went through a short processing procedure in order to have the same width and thickness. Secondly, the salvaged boards were cut using the table saw with an inclination of 88°. Thirdly, the same boards were processed using the table router to create the tenons and the mortise shape (fig. 7). Once both the fresh and the salvaged timber boards were ready, the assembling procedure could begin. In order to have a precise assembling and since the sample in this case was small, it was decided to fix the first mortise board to both the fresh timber boards at the same time using temporary screws. After that the tenon part was inserted until 3 cm to the edge, and then the other mortise boards were positioned and pushed against the tenon. Once the gaps were closed due to enough pressure, the mortise board was fixed using two temporary screws, one per side. Then other screws were added in the exact point where the tenons of plywood will be inserted. For each panel there were 4 plywood tenons, and both of them went through the fresh and the salvaged timber, in the mortise boards, as it is possible to see from fig. 6. The fabrication process of the tenons followed the suggestion by Derikvand et al. 2021. Since the tenons of plywood have an elliptical shape, as it can be seen from fig. 8(a), it was necessary to perform two holes for each tenon and then to enlarge the hole in order to obtain the desired shape. Plywood tenons were chosen because the composite efficiency of the plywood tenons result more than two times higher than the conventional Oak dowels and also higher than the Oak tenons. Moreover, it was shown a good potential of the salvaged plywood dowels in the DLT projects (Derikvand et al. 2021). The chosen radius of the tenons was 9.5 mm (Derikvand et al. 2021), as a consequence the final dimensions of the tenons were b x h = 38 x 19 mm^2 with the length that can differ depending on how many layers the laminated system is formed of. It was necessary also to increase the length of the tenons since the initial part of them will be then cut after the insertion using a hand saw. The tenons were produced from a salvaged plywood panel. At the beginning it had a rectangular shape, and the length was bigger than the final one (fig. 8b). To create the rounded shape a router machine was used, it consists of a conical concave blade with a high-speed rotation. Thanks to the jig in fig.9a, the plywood was pushed against the blade that gave it the rounded shape at the edges (fig. 9b). This procedure is fast but must be done four times for each tenon. After that, by using a wood sander, it was possible to create a smooth end to the tenons (fig. 9c), this will make the insertion of it in the laminated panel easier.

Once the tenons were ready and the panel were laminated using temporary screws, it was necessary to mark on the boards the exact position of the centre of the holes for the tenons. This procedure was done using the calibre, the two centres of the respective hole must be marked on the board with a high precision because even a small error can lead to drilling a hole that is too big or too small. If the hole is too big, the tenons would be lose and this could bring several stability problems after some time. On the other hand, if the hole is too small, during the hammering procedure several cracks in the boards would be formed and so the capacity of the structure would be reduced. Once that the correct position of the holes was marked, it was possible to start with the drilling procedure using the floor standing drill press (fig. 10). The first hole was made at one end of the panel, but before removing the temporary screws previously inserted, it was necessary to clamp the end of the specimen. This way the three layers will be pressed together, the clamp will be removed just after the insertion of the tenon. After removing the screw on one side of the panel, it was clamped to the machine and the two holes were drilled, then to create the tenon's shape the drill bit was moved between these two holes and along all the thickness of the laminated panel. This way the final hole had the same shape as the tenon. Before proceeding to drill the other three holes, it was necessary to insert the tenons and remove the clamp. The insertion of the tenons caused significant friction inside the mortises, however, it was possible to lubricate the tenons with e.g., a small amount of oil to ease the insertion process. There are different alternatives on how to insert the tenons, the chosen one in this case was to hammer them inside the laminated panel (Milch et al. 2017; El-Houjeyri et al. 2019). Other alternatives can be to press them inside using a hydraulic press into holes with smaller diameters (TKPS) or high speed rotational wood welding (O'Loinsigh et al. 2012). Another solution can be to dry the tenons to a lower moisture content (MC) than the lamellae previously assembled. This way, the tenons can swell up and reach the equilibrium moisture content at service, which result in a secure fit with the hole walls (Dietrich Buck et al. 2015). During the hammering procedure, as already said before, the dimension of the holes must be accurate. Otherwise, it happens that, if the hole is too small, the tenon can break because hammered too hard or the boards around the tenon will crack due to too much pressure. When the first tenon was inserted, it was then possible to remove the clamp and repeat the same procedure for the other three holes. It is possible to see the final result in fig.6, five samples were produced to be tested.

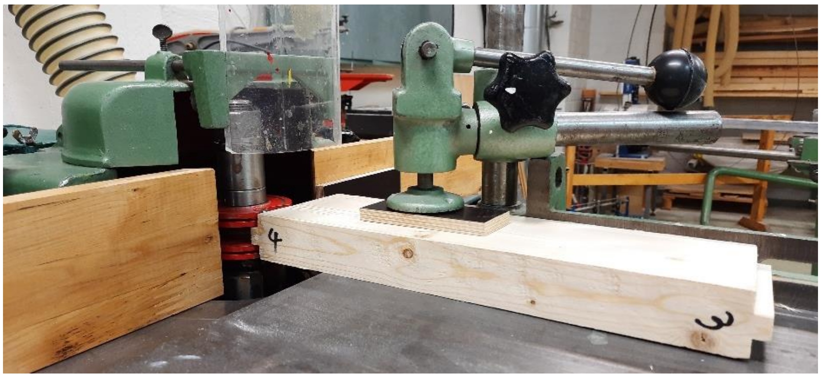


Fig. 7: table router processing to create mortise and tenon shape (in the picture salvaged board with tenon shape).

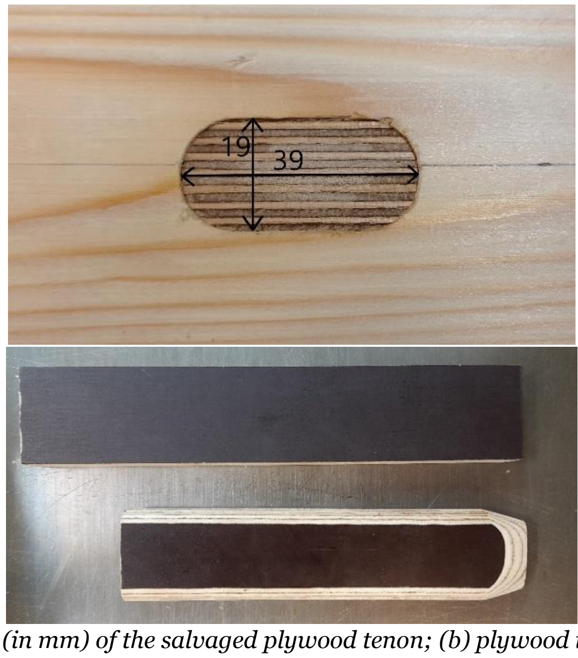


Fig. 8: (a) dimension (in mm) of the salvaged plywood tenon; (b) plywood tenon before and after the processing.

Fig. 9: (a) jig used to create the rounded shape of the tenons, (b) procedure to create the rounded shape of the tenons, (c) procedure to create the smooth end to the tenons.

Fig. 10: Drilling procedure to produce the hole for the tenon.

3.4.2 Test overview

The experimental investigation on the small-scale specimens included non-destructive three-point bending tests using the UTM machine. The effective bending stiffness EI_{eff} was investigated non-destructively. The test was a load-control test. The final dimensions of the small-scale DLT specimens were b x h x l = 132 x 117 x 1260 mm^3. Three centimetres per side along the longest side of the samples are required to guarantee a good support during the bending tests. The setup of the test can be seen in fig. 11, the distance between the two supports is 1200 mm, one support was fixed while the other one was free to move in order to have a static system. The distance between the point of application of the load and the support was 600 mm on both sides. To distribute the load equally in each layer of the laminated beam, a metal plate was placed at the point of application of the point load. LVDTs were placed on both sides of the beam (fig.11, fig. 12) in order to get the data of the global mid-span deflection since the screws, where these sensors rest, are on the same vertical line of the support. Each specimen was investigated two times: before prestressing (the samples are marked as 'Stage N' in fig. 6) and after prestressing (the samples are marked as 'Stage Y' in fig. 6). The test set up and the loading procedure were the same both in the solution with end-to-end interlocking, as well as in the solution without end-to-end interlocking.

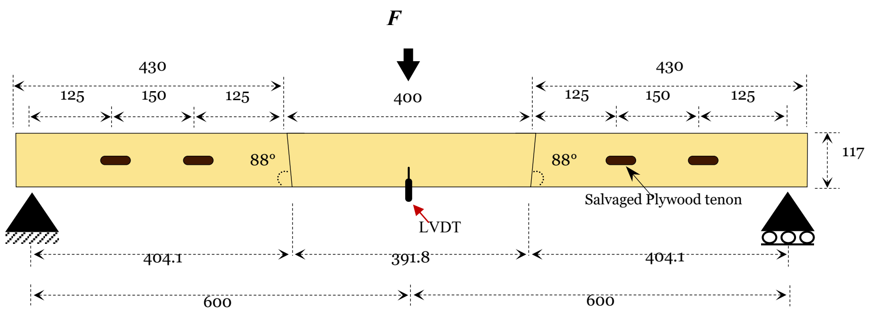


Fig.11: Dimensions of the salvaged timber elements in the small-scale DLT panels and the three-point bending test set-up. Dimensions in mm.

Fig. 12: Specimen S_12 with end-to-end interlocking ready to be tested.

3.4.3 Small scale test with end-to-end interlocking

As loading procedure, it was chosen to perform a cyclic test. First of all, the maximum strength was calculated. Since the properties of the middle layer were unknown, to perform the calculation of the maximum strength, just the two layers of fresh timber were considered. Based on the result of this calculation, it was chosen the value of the 40% F_c and 10% F_c for the cyclic test according to the standard testing procedure. A small load level at 40% F_c was selected for the test to ensure that no unexpected damages would occur. Based on the EN 408 (EN 408), for a rectangular shape sample under 3-point bending load, the following formula was used:

$$f_c = \frac{3F_c * L}{2b * d^2} \quad (1)$$

Where:

f_c is the characteristic value of the bending strength (24 N/mm²).

F_c is the fracture load force at the fracture point (N).

L is the length of the support span (1200mm).

b is the width of the laminated panel (44*2 = 88 mm).

d is the thickness of the laminated panel (115 mm).

Reversing the formula:

$$F_c = \frac{f_c * 2b * d^2}{3L} \quad (2)$$

In the end, F_c = 14.7 kN, therefore 40% F is 5.87 kN and 10% F is 1.47 kN. The loading cycle is shown in fig. 13. The specimen was loaded at a constant speed from zero till the 40 % of the maximum force, the speed load was 2.94 kN/min (this value was obtained from: 40%F/2min), once that the 40% was reached, the load remained constant for 30 seconds. Then it went down to the 10% F with the same constant spend, once that the applied force was 10% F, the load remained constant for 30 seconds. Subsequently it went up again to 40%F, and from this loading cycle were taken the value to calculate the stiffness of the panel. At 40%F the load remained constant again for 30 second, after that the system was unloaded and the same procedure was done for every specimen. The cyclic procedure was done because, since the panels were laminated with different materials, there can be some imperfection and internal movement can occur after the application of the load. For this reason, the purpose of the first cycle was to settle the system and prevent any movement during the second cycle since, as mentioned before, it was the one where the value to calculate the stiffness were taken from.

Initially, the panels were tested without the piece in the middle in order to obtain the stiffness of the system considering just the two fresh layers. Once that all the specimens were tested, the middle piece was inserted through a hammering procedure. Since during the construction phase the middle piece was inserted till 3 cm from the bottom and since the inclination of the surface was 2°, considering the height of the panel being 117 mm it was possible to calculate how much new material was inserted in the system.

As is possible to see in fig. 14, using the following formula:

$$x = a * tg(\alpha) \ (3)$$

Where:

x is the unknown dimension of the added material.

a is the height of the piece above the panel (30mm).

α is the angle of the inclined surface (2°).

From the previous equation it was obtained that the insertion of the middle piece added approximately 1 mm of wood on each side. Therefore, the length of the middle pieces was in total approximately 2 mm larger than that of the hole in which it was inserted. Moreover, compressive force between the salvaged boards was introduced. Therefore, these boards were not used any more as space filler but as a member that increased the capacity of the whole system. Once that the middle pieces were inserted, the panels were tested again following the same procedure of the cyclical test. In the end, the data were analysed and the stiffness for each specimen was calculated.

To calculate the stiffness for each specimen in both configurations, the straight-line portion of the load-deflection curves of the 'reloading' cycles was used. In accordance with EN 408 (EN 408),the following formula was used:

$$EI_{eff} = \frac{L^3 * \Delta F}{48 * \Delta\omega} \ (4)$$

Where:

EI_{eff} is the stiffness of the DLT panel (kN*m²).

L is the length of the DLT panel (1200 mm)

ΔF is the difference between 40% F and 10% F.

Δω is the difference in the displacement between 40% F and 10% F.

It is important to point out that the actual load carrying capacity was not measured and therefore the load range might have been smaller than required in EN 408 (EN 408).

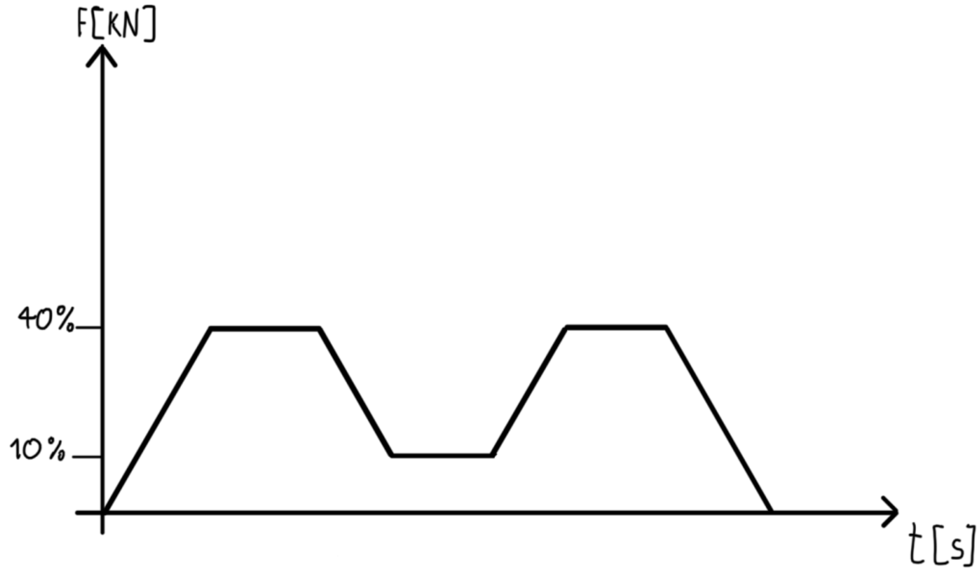


Fig. 13: Loading procedure for the three-point bending test.

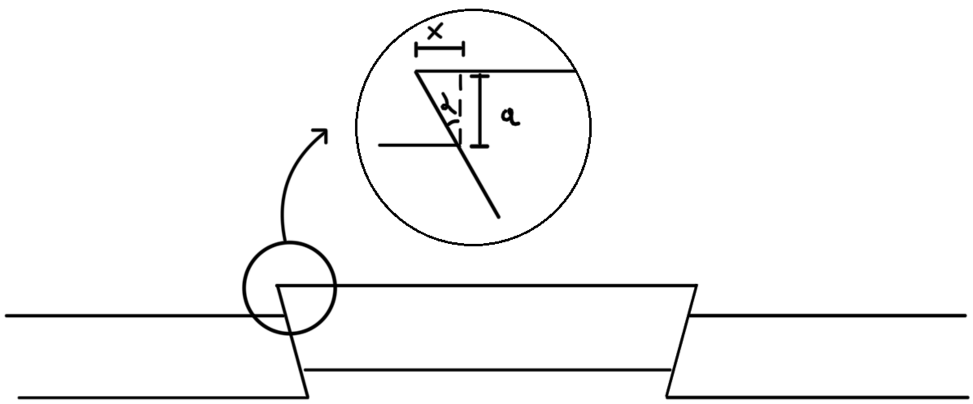


Fig. 14: middle piece calculation of the added material.

3.4.4 Small scale test without end-to-end interlocking

The expectation, that was then confirmed by the tests, was that there was no difference between having a profiled angled surface (solution with end-to-end interlocking) or just the angled surface (solution without end-to-end interlocking). First of all, the systems were tested without the piece in the middle, following the loading procedure of fig. 13, for all the three specimens. Subsequently the middle pieces were inserted and hammered inside, and then the three samples were tested again with the cyclic loading procedure (fig. 13). On the S_1314 it was also decided to do an additional test. Up to this point the application of the load was on all the three layers thanks to a metal plate used to distribute uniformly the load. Since the middle board was hammered inside and not fixed in any other way, it can be argued that, under a certain value of the load, the inserted piece pop up changing the layout of the system. As a consequence, an additional test was done in which the load was only applied on the two fresh timber layers, leaving the middle layer of salvaged timber free to move. The specimen S_1314 was loaded in this way firstly with the cycle already used (fig. 13) then unloaded to see if there were some movements, and secondly loaded till the breaking point. In both cases no movement of the middle part occurs, not even after the fracture of the panel. This mean that the friction forces between the boards were bigger than the pop-up force, this was also due to the fact that the angle chosen for the inclined surface was small (2°). Since the results of this last test were positive as expected, it was chosen to continue the others test loading the system on every layers as previously done. On the specimen S_1112 and S_1516 it was decided to perform also a ten cycles test before breaking them in order to see if there were any variation of stiffness during the repetitive loading and unloading procedure. This additional cyclic test was done out of curiosity and only on two specimens in order to get an idea on what would be the best way to test the large scale DLT specimens. Therefore, on these two samples it is decided to do two different cyclic tests, in both the tests the value of 10% F and 40% F, as well as the loading speed and the time in which the load is applied, were the same, what was different was the loading procedure. On specimen S_1112 it was performed the cyclic test shown in fig. 16a. The system was loaded from zero to 40% F, then after 30 seconds it was unloaded to 10% with the same constant speed and, once that the 10% it was reached, the load remained stable for 30 seconds. This one cycle was then repeated ten times. While for specimen S_1516 it was performed the cyclic test in fig. 16b. The initial part was the same as the previous one since the system was loaded from zero to 40% F, then after 30 seconds it was unloaded to 10% with the same constant speed and, once that the 10% was reached, the load remain stable for 30 seconds. After that it returned up to 40% F where it stayed constant for 30 seconds and then with the same constant speed it went down to zero (since the system cannot be unloaded completely, the machine reaches a point near zero but not exactly zero). This one cycle was then repeated ten times. Looking at the results it is then decided to use the first option (fig. 16a) also for the following test since it was more consistent.

Fig. 15: Laminated system without end-to-end interlocking ready to be tested.

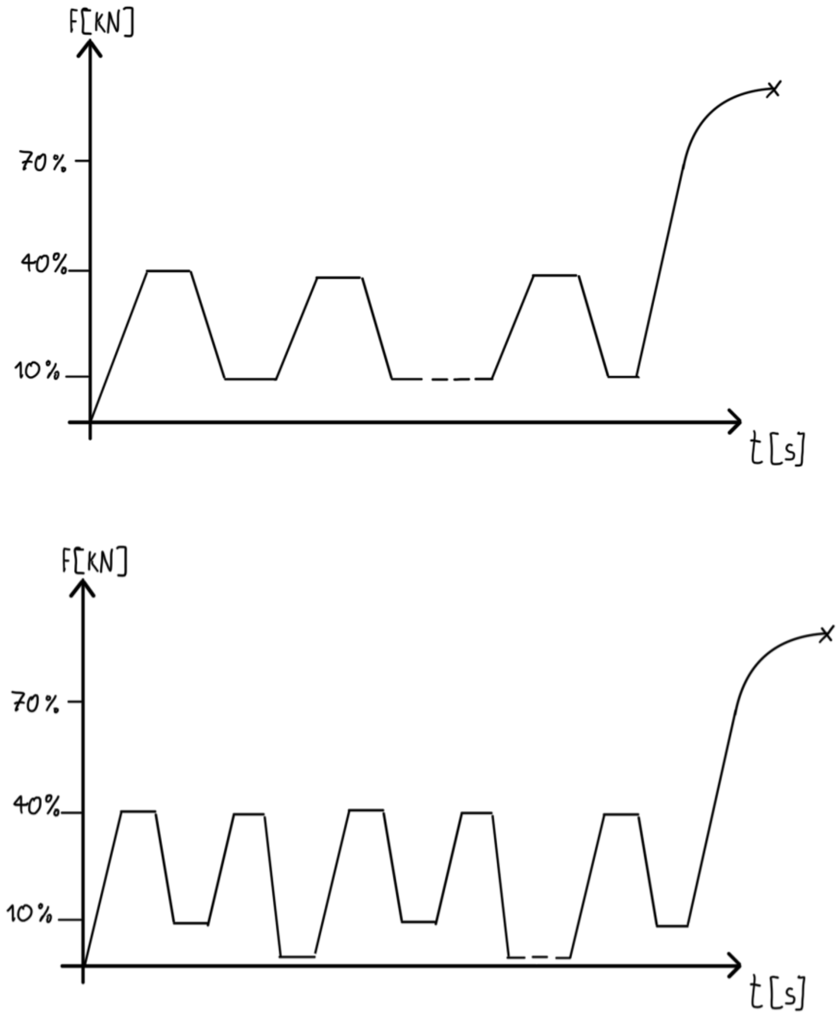


Fig. 16: (a) first type of cyclic test (used also for the future test), (b) second type of cyclic test.

3.5 Large scale DLT specimens

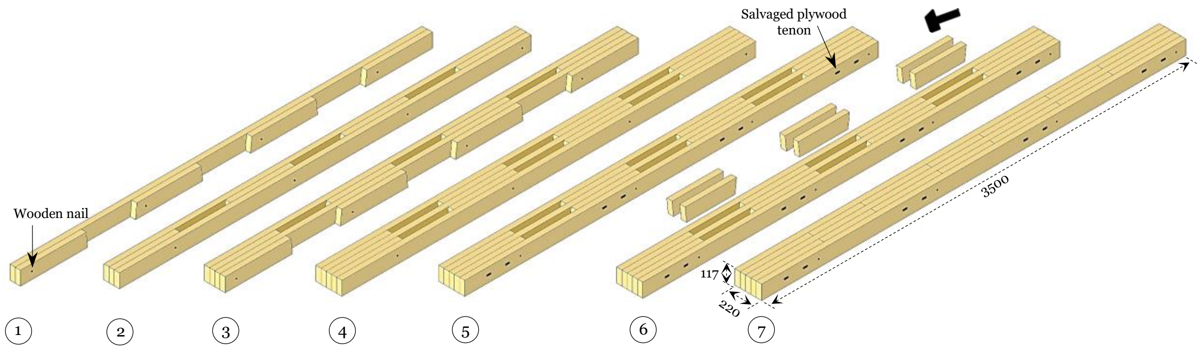
In the end, the obtained results confirmed the expected one since the increment of stiffness was the same in both the panels with end-to-end interlocking and in the one without end-to-end interlocking. As a consequence, it was chosen to use the solution without end-to-end interlocking for the mass production of the slab. Five sample were produced, and each sample was formed by five layers, three layers of fresh wood and two layers of salvaged materials (fig. 17). The final dimensions of the large-scale DLT panels were b x h x l = 220 x 117 x 3500 mm^3. The inner and the outer cross section of the salvaged timber elements had been cut with 88° and 90° angles respectively. The floor span calculation can be found in the Attachment, section 6.2 Floor span calculation (6.2).

It was chosen to perform the test considering the length for the office building since is the most widespread application for this kind of research. Therefore, for the mass production the final length of the panels was 3.50 m but during the test the distance between the support was 3.20 m according to the result of the previous calculation.

Fig. 17: presentation of the five samples produced, placed next to each other, ready to be tested.

3.5.1 Mass production

The construction procedure was similar to the one of the small samples. The first layer was a fresh wood one, on that the salvaged mortise boards were placed and nailed (fig. 18_1). After nailing the first one, the tenon board was placed having 3 cm of that outside the system, then the second mortise board was placed and nailed to the fresh wood. This procedure was repeated for the whole length of the specimen. For each layer of salvaged wood, there were four mortises nailed to the fresh timber board and three tenons inserted subsequently through hammering procedure. After having these two layers, the middle board of fresh timber was then nailed to the system (fig. 18_2). Subsequently, the second raw of salvaged timber was placed and nailed to the fresh one (fig. 18_3). In the end, the last fresh timber layer was nailed to the salvaged one (fig. 18_4). During the assembly procedure, clamps were used to keep the system together and to keep the mortises in place before nailing. Before inserting the salvaged timber elements into the void, the system was ready to be drilled in order to insert the plywood tenons. They were inserted following a constant pattern as it is possible to see from fig. 19. It was chosen to have the tenons inserted with a constant pattern in the part where the salvaged wood boards were nailed to the fresh layers. This way, the insertion of the other boards could proceed smoothly. To drill the holes (fig. 18_5) the same procedure of the small samples was followed, before that it was necessary to mark the position of the holes with a high accuracy because, as mentioned before, the holes and the tenons must have the same dimensions. A small hole could have led to difficult insertion and cracking of the boards caused by too much pressure. On the other hand, a hole that was too big do not guarantee a strong connection since the system would be loose. To drill the hole, the floor standing drill press was used (fig. 20). Since the specimens had a length of 3.50 m, in order to make the hole in an accurate way some supports were used. The panel was clamped to maintain the laminated boards in the same position during the drilling procedure. One clamp per time was removed, and the specimen was also fixed to the machine in order to avoid any movement. The first hole was made at one end of the sample, some practical issues occurred during the first hole because it was noticed that the vibration of the machine affected the precision of the hole. The solution to avoid this problem was to drill the hole slowly, especially at the beginning when the drill bit first enters in the wood. Two holes were required for each position, then to create the tenon shape the drill bit was moved between these two holes and along all the thickness of the panel. In this way the final hole had the same shape and dimensions of the tenon. Contrary to what was done before, for this solution it was decided to first drill all the holes and then to insert all the tenons. Consequently, after drilling one hole a clamp was placed to avoid any movement of the boards. It was noticed that, due to the high rotational speed and the quite high thickness of the laminated system, the holes in the last two boards had a slightly smaller shape with respect to the entrance point. This problem can be solved by using a steadier machine. After making all the holes, the specimen was then ready for the insertion of the plywood tenons. The same procedure was used for hammering the plywood tenons as described for the small-scale DLT specimens. After the insertion of the tenons no cracks appeared. Once that they were inserted the last procedure was to cut the part that was in excess with a hand saw. This procedure was then repeated for all the five panels. After that, the specimens were ready to be tested without the middle piece. It is important to remember that the length of each void, in the salvaged timber layers, was approximately 2 mm smaller than the one of the salvaged timber boards that was supposed to be inserted into the void at the final stage of the fabrication. Due to this insertion process, prestress actions in the system were created. In this way, the bending performance of the panels were improved because each layer that contained salvaged timber elements resisted compression stresses.



1 Nailing the first row of salvaged timber elements to a new timber board

2 Nailing the second new timber board to the salvaged ones

3 Nailing the second row of salvaged timber elements to the new one

4 Nailing the third new timber board to the salvaged ones

5 Laminating the entire layers using salvaged plywood tenons (Stage N, before prestressing)

6 Placing and hammering the salvaged timber elements into the voids (i.e., prestressing procedure)

7 Final DLT panel (Stage Y, after prestressing)

Fig. 18: Fabrication steps of the large-scale DLT panels. Dimensions in mm.

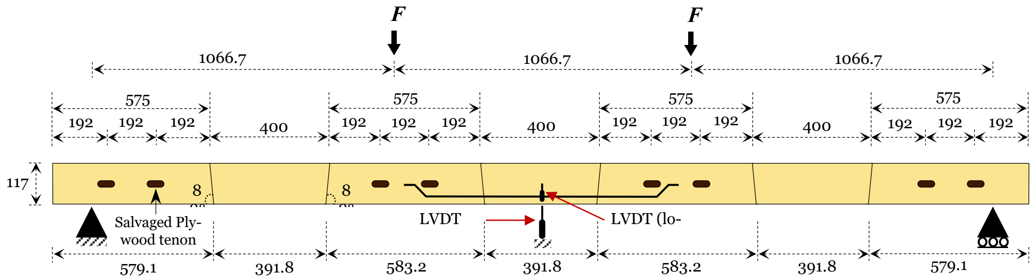


Fig. 19: Dimension of the salvaged timber elements in the large-scale DLT panels and the four-point bending test set-up. Dimensions in mm.

Fig.20: Drilling procedure to make the holes for the plywood tenons.

3.5.2 Test overview

The experimental investigation on the large-scale DLT specimens included vibration tests, non-destructive bending tests, and destructive bending tests. Each specimen was investigated two times: before prestressing (the samples are market as 'Stage N' in fig. 18) and after prestressing (the samples are market as 'Stage Y' in fig. 18). The following test were performed on the samples, described more accurately in the following sections:

- Non-destructive four-point bending test (Stage N).
- Destructive four-point bending test (Stage Y).
- Vibration test (Stage N and Stage Y).

The four-point set up for the test can be seen in fig. 19, the distance between the two support is 3200 mm, one support is fixed while the other is free to move in order to have a static system.

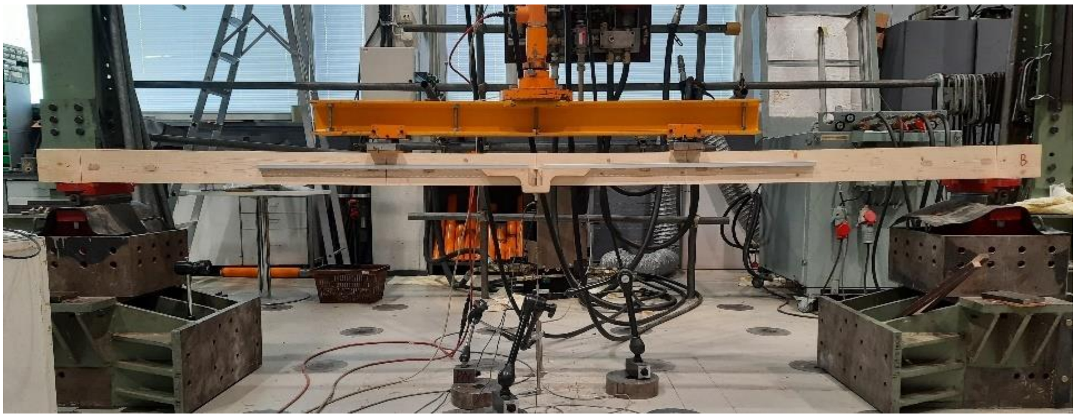


Fig.21: Board B during the test.

3.5.3 Vibration test

Before starting with the bending test, it was also performed a vibration test on a simply supported test set-up as shown in fig. 19,21. The specimens were divided in 10 intervals of 320 mm each, so in the end the application points were eleven. For the vibration test each point was hit three times in order to being able to obtain an average value. To perform the vibration test, a modal impact hammer, an accelerometer, a charge amplifier and a dynamic signal analyser were used (fig. 22). The hammer was used to hit the specimen in the middle board (fresh timber), and the sensor was placed under the 5th point. The vibration test was carried out in both the configuration, first without and then with the middle piece. To register the data the Data Physics SignalCalc Software was used, and the data were analysed and processed using MATLAB.

Fig. 22: Tools used for the vibration test.

3.5.4 Four-point bending test

For this test it is chosen to divide the samples in three equal parts with the points of application of the load, as a result the distance between the supports and the points of application of the load is 1067 mm, as well as the distance between the two points of application of the load. In these points, to distribute equally the load in the system, a metal plate with a soft cushion is used. Since the system is formed by laminated timber boards, it is possible that there is not a full contact between the support and the panel. To avoid this problem, thin metal plates are used to fill the gaps and to let all the boards be in contact with the supports. Five different sensors are used in this test, two LVDTs were placed on the lateral surfaces of the panel to measure the local mid-span deflection. Three LVDTs are installed on the bottom surface of the three fresh timber boards of the panel to measure the global mid-span deflection. The lateral LVDTs rested on two screws each, with a distance of 950 mm from each other. The screws are inserted with an angle slightly smaller than 90° with respect to the vertical, in this way the sensors were not able to slip. On the other hand, the LVDTs placed under the system measure the global displacement that is the sum of the local displacement plus the shear displacement. The data are analysed based on the global displacement.

As regards the four-point bending test, for the loading procedure, since the previously used cyclic test resulted efficient, it was decided to perform it again, as can be seen in fig. 24a. First of all, the maximum strength was calculated. Since the properties of the middle layer are unknown, to perform the calculation of the maximum strength only the three layers of fresh timber were considered. It was chosen to perform the test based on the standard testing procedure. First of all, F_{max} was calculated (5) and then the value of

40% F and 10% F were used. For a four-point bending test, in order to calculate F_{max} the following formula from the EN 408 (EN 408) was used:

$$F_c = \frac{f_c * 2b * d^2}{3*(L-L_i)} \quad (5)$$

Where:

f_c is the characteristic value of the bending strength (24 N/mm^2).

F_c is the fracture load force at the fracture point.

L is the length of the support span (3200mm).

L_i is the distance between the two points of application of the load.

b is the width of the panel (44*3 = 132 mm).

d is the thickness of the panel (117 mm).

In the end F = 13.55kN, as a consequence 40% F is 5.42kN and 10% F is 1.35kN. The loading cycle is shown in fig. 24a. The board was loaded to a constant speed of (40% F)/(2 min) = 2.71kN/min from zero to 40% of the maximum force, then the value remained constant for 30 seconds. Then it went down to the 10% F with the same constant speed, once that the applied force was 10% F, the load remained constant for 30 seconds. Subsequently it went up again to 40%F, and from this loading cycle were taken the value to calculate the stiffness of the board. Then it remained at 40% F for 30 seconds again and, with the same constant speed it went down again to zero (fig. 24a). This procedure was then repeated for all the five specimens. The cyclic procedure was done because, since the panels were laminated with different materials, there can be some imperfection and some internal movement of the system after the application of the load. For this reason, the purpose of the first cycle was to settle the system and prevent any movement during the second cycle since, as mentioned before, it was the one where the value to calculate the stiffness of the panel were taken from.

At the beginning the samples were tested without the piece in the middle (Stage N) (fig. 23a) in order to obtain the stiffness of the system considering just the three fresh wood layers. After testing all of them, the middle pieces were inserted (Stage Y) (fig. 23c) through a hammering procedure as previously showed in fig. 18_6. As explained before, since during the construction phase the middle pieces were inserted up to 3 cm from the bottom side of the specimens and since the inclination of the surface is 2°. Having the thickness of the boards of 117 cm, using the formula (3) it is possible to obtain that for each piece that was inserted, approximately 1 mm per side of wood was added to the system. Since the length of the panel as a whole did not change, it meant that compressive force between the salvaged boards was introduced.

Once that the middle pieces were inserted, the five samples were ready to be tested again (fig. 23c, fig. 18_7).

During the insertion of the middle pieces, some cracks appeared due to the pressure inside the system and the procedure that was adopted. In the section Future Development, some precautions are explained in order to avoid these problems. After the insertion of the middle pieces, it was noticed that the previously drawn lines, that were straight before, result fragmented. This was due to the fact that the insertion introduced an increase of the pressure of the system which brought to the movement of the salvaged layers (fig. 25).

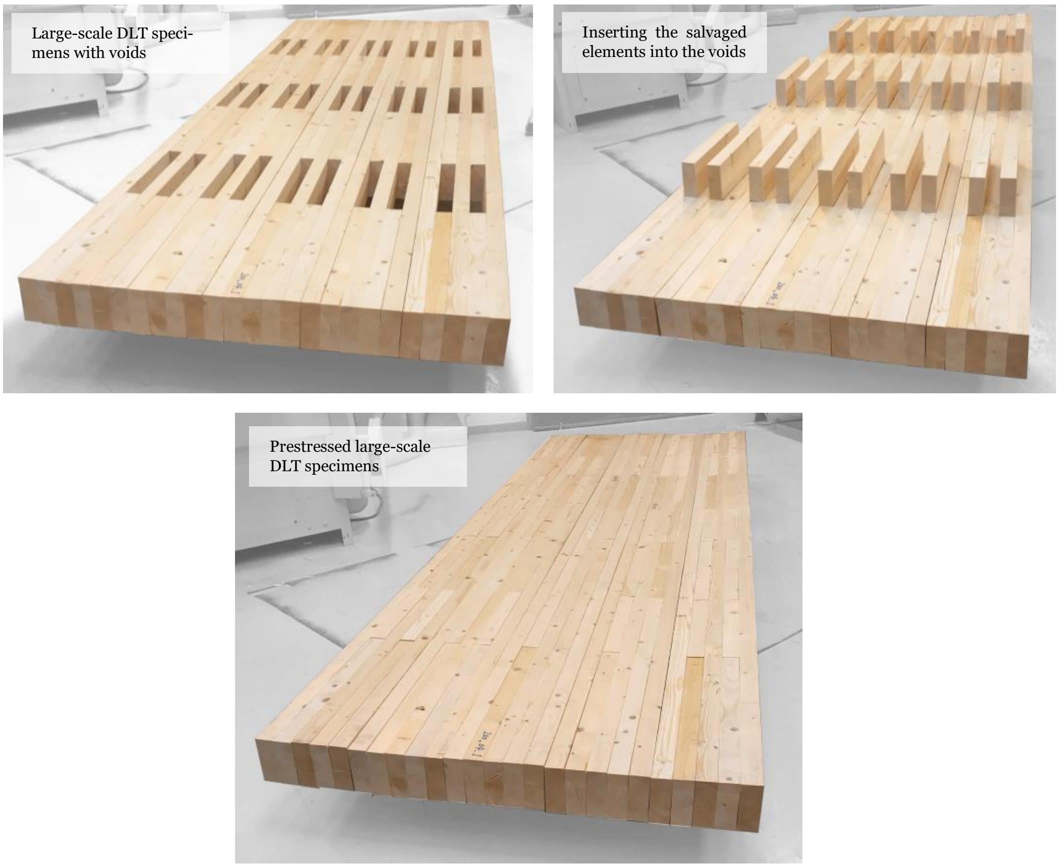


Fig. 23: (a) Slab system without the piece in the middle, (b) slab system during the insertion of the middle piece, (c) slab system at the end of the construction procedure.

The load range used to test the large-scale DLT specimens after prestressing was 10% F = 2.5 kN and 40% F = 10 kN. Note: the range was slightly lower for the first specimen tested, after which the load was adjusted. For each specimen, a total of ten loading cycles with the selected load range was applied. Afterwards, the load was increased up to 70% of F_{max} according to the load control method and then the load was increase up to the breaking point according to the displacement control method (fig. 24b). In the end, the data were analysed and the stiffness for each panel was calculated.

To calculate the stiffness (EI_{eff}) for each large-scale DLT panel, in both configuration, the global mid span deflection was used, in accordance with the EN (EN 408). While the local bending stiffness EI_{local} was calculated using the local mid-span deflection. The first portion of the load-deflection curves within the first 'reloading' cycle was used to calculate EI_{eff} and EI_{local}.

The following formula from the EN 408 (EN 408) is used:

$$EI = \frac{a * l_1^2 * \Delta F}{16 * \Delta\omega} \quad (6)$$

Where:

EI is the stiffness of the DLT panel (kN*m²).

a is the distance between the support to the nearest point of loading (1067 mm)

l_1 is the gauge length of the DLT panel (3200 mm)

ΔF is the difference between 40% F and 10% F.

Δω is the difference in the displacement between 40% F and 10% F.

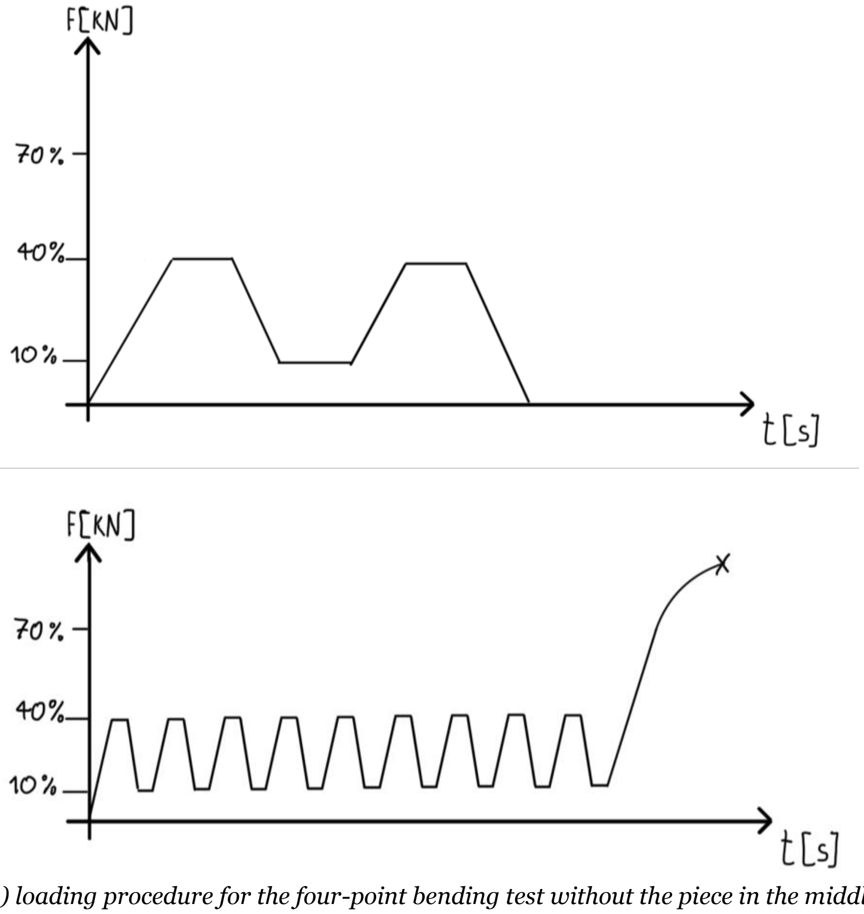


Fig. 24: (a) loading procedure for the four-point bending test without the piece in the middle (Stage N), (b) loading procedure for the four-point bending test with the piece in the middle (Stage Y).

Fig. 25: movement of the salvaged timber layers after the insertion of the middle boards

4 Results

4.1 Small-scale DLT specimens three-point bending test

4.1.1 Panels with end-to-end interlocking

The results for the sample with end-to-end interlocking are showed in the tab. 1. As it is possible to notice the average increment of the stiffness EI_{eff} is of the 31.8% after the insertion of the salvaged timber element into the void, with a COV (coefficient of variation) of 6.1%. The load-deflection curves of the small-scale DLT panels with end-to-end interlocking are shown in fig. 26.

Symbol	End-to-end interlocking	EI_{eff} (kN.m^2) Before prestress (Stage N)	EI_{eff} (kN.m^2) After prestress (Stage Y)	Increase (%)
TA	Yes	154.8	190.9	23.3
S_12		132.0	164.3	24.5
S_56		152.8	196.7	28.7
S_78		127.8	186.5	45.9
S_910		131.6	179.9	36.7
Average		139.8	183.7	31.8
COV (%)		8.3	6.1	

Tab. 1: Increment of stiffness of the panels with end-to-end interlocking.

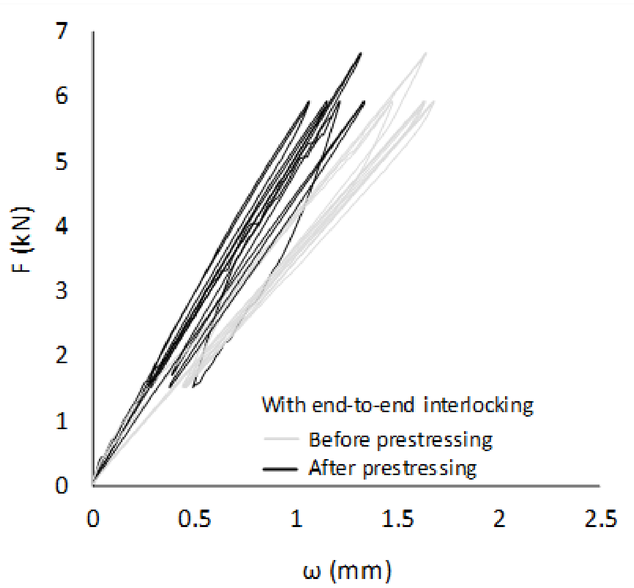


Fig. 26: Load-deflection curves of the small-scale DLT panels with end-to-end interlocking.

4.1.2 Panels without end-to-end interlocking

New tests were carried out on three specimens, constructed following the same procedure and using the same materials of the previous five. However, the salvaged board were without end-to-end interlocking, but it had the surfaces inclined of 2° as well as the other specimens previously tested. The obtained results with the subsequent increment of stiffness are shown in tab. 2. As it is possible to notice, the specimen S_1516 presented a lower increment of stiffness with respect to the other two, this is due to the fact that the stiffness of the sample, even before the insertion of the middle part was higher than the other two. Since the properties of wood are different from board to board and the given value are average value, it is possible to have some boards stiffer than others. As a consequence, since the stiffness was already high, after the insertion of the middle piece the increment was similar to the other in kN*m² but it resulted lower in percentage.

The load-deflection curves of the small-scale DLT panels without end-to-end interlocking are shown in fig. 27.

Symbol	End-to-end interlocking	EI_{eff} (kN.m^2) Before prestress (Stage N)	EI_{eff} (kN.m^2) After prestress (Stage Y)	Increase (%)
S_1112		102.3	144.1	40.9
S_1314	No	106.0	144.8	36.5
S_1516		171.4	200.0	16.7
Average		126.6	162.9	31.4
COV (%)		25.1	16.1	

* COV = Coefficient of variation

Tab. 2: Increment of stiffness of the panel without end-to-end interlocking.

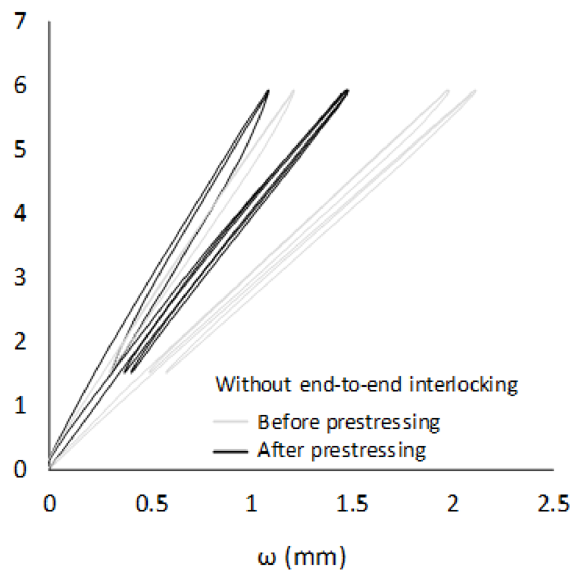


Fig. 27: Load-deflection curves of the small-scale DLT panels without end-to-end interlocking.

Furthermore, the ten static load cycles that were applied on the specimens showed no important effect on the stiffness.

After the cyclic tests, the samples were loaded till the breaking point. Up to 70% F_{max} using the load control, then following the displacement control method. As it is possible to see from the following figures (fig.28-34), the main failure was a shear failure due to the fact that the span of the specimens was limited. On the sample S_1516 is possible to notice also a bending failure due to the presence of a knot.

In the end, it was noticed that there was not substantial difference between the system with and without end-to-end interlocking. As a consequence, the end-to-end interlocking was no longer considered in the subsequent experiment on the large-scale DLT panels.

Fig.28: Failure of sample S_1112.

Fig. 29: (a) shear failure A, (b) shear failure B.

Fig. 30: Failure of sample S_1314.

Fig. 31:(a-b) Shear failure C.

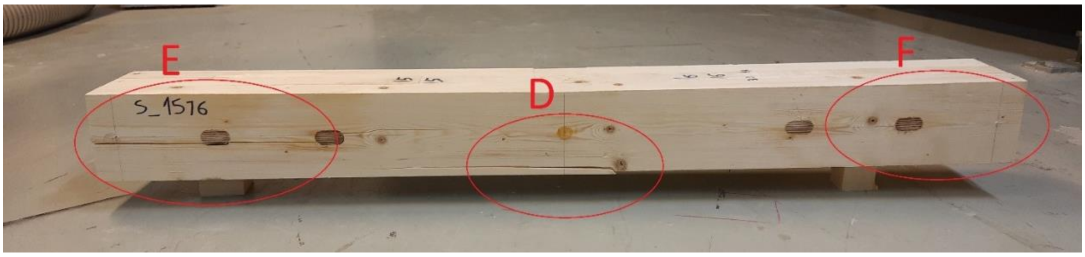


Fig. 32: Failure mode of sample S_1516.

Fig. 33: Bending failure D.

Fig. 34: (a) Shear failure E, (b) shear failure F.

4.2 Large-scale test

4.2.1 Vibration test

The fundamental frequency (*f*) and the damping ratio (ζ) of the dowel laminated panels are given in tab. 3. On average, the first eigenfrequency of the samples with the middle pieces was 6.5% higher than the one without. On the other hand, the damping ratio increased in some specimens and decreased in others. This can be due to the fact that the result of the vibration test may vary according to the experimental condition (Jaaranen and Fink 2022). In the present research, it was likely due to the fact that the panels were not fully in contact with the support since the system was laminated. This might have affected the support conditions, and as a consequence, the vibration characteristic.

The first vibration mode for each sample, before and after the prestressing, can be seen in the Attachment, section 6.3 The vibration mode of the large-scale DLT panels (6.3).

Symbol	*f* (Hz)		Increase (%)	ζ (%)		Increase or decrease (%)
	Before prestressing (Stage N)	After prestressing (Stage Y)		Before prestressing (Stage N)	After prestressing (Stage Y)	
Panel A	23.8	26.8	12.6	3.7	3.0	-18.9
Panel B	24.7	25.9	4.9	3.8	3.9	2.6
Panel C	25.5	25.6	0.4	3.7	5.2	40.5
Panel D	23.8	26.4	10.9	5.7	1.8	-68.4
Panel E	26.1	27.1	3.8	5.1	3.4	-33.3
Average	24.8	26.4	6.5	4.4	3.5	-20.5
COV (%)	3.7	2.1		19.1	32.2	

Tab. 3: results of the vibration test on the large-scale DLT panels.

4.2.2 Four-point bending test

The results from the four-point bending tests can be seen in tab. 4 (the data are analysed based on the global displacements). As regards EI_{eff} it is possible to notice the average increment of stiffness is 38.8%, with a COV (coefficient of variation) of 6.4%. For EI_{local}, instead, an average increase of 36.2 % was observed, although the COV in this case was slightly higher. The results are consistent, and the increment of stiffness is in line with what was expected. However, the failure mode of the new timber boards generally governed F_{max}. Generally, is needed a comparison to the bending strength of conventional three- and five-layer DLT panels to quantify the effect of prestressing, that in this research was not conducted. However, due to the low number of test samples, a qualitative comparison would contain anyway large uncertainties. Despite that, a certain prestressing effect could be assumed considering the average bending stiffness f_m = 33.9 MPa (assuming five continues layers) or f_m = 56.4 MPa (assuming three continuous layers).

Symbol	EI_{local} (kN.m²)		Increase (%)	EI_{eff} (kN.m²)		Increase (%)	F_{max} (kN)
	Before pre-stressing (Stage N)	After pre-stressing (Stage Y)		Before pre-stressing (Stage N)	After prestress-ing (Stage Y)		After pre-stressing (Stage Y)
Panel A	301.5	399.7	32.6	216.1	306.1	41.6	31.4
Panel B	338.1	427.2	26.4	243.8	337.6	38.5	33.7
Panel C	369.8	479.4	29.6	268.7	358.9	33.6	32.8
Panel D	309.0	490.4	58.7	242.8	345.3	42.2	33.4
Panel E	374.4	508.8	35.9	267.4	371.3	38.9	28.0
Aver-age	338.6	461.1	36.2	247.8	343.9	38.8	31.9
COV (%)	8.8	8.9		7.8	6.4		6.6

Tab. 4: Bending properties of the large scale DLT panels.

Different load ranges were used to calculate EI_{eff} and EI_{local} from the two stages. Since in the Stage N the load carrying capacity was unknown, a smaller range was used for the calculation: 1.35 – 5.42 kN. On the other hand, for Stage Y, it was used 2.5 – 10 kN. However, looking at the load-deflection curves of fig. 35, it can be noticed that the selection of the load ranges did not affect the following conclusions.

After the cyclic tests, the panels were loaded till the breaking point. Up to 70% F_{max} using the load control, then following the displacement control method. The main failure was a bending failure in all the specimens. The failure occurred in one of the fresh timber layers, mainly due to a knot in the tension zone, with the subsequent propagation of the failure to the weakest part (plywood tenons or other knots) following the direction of the grains. For the specimen S_A, at the failure point, there was the complete cracking of one salvaged board, the one that had tenons inside. In the sample S_C at the maximum failure, in addition to the typical bending failure around knot, also a shear failure occurred at one end of the board leading to the breaking and subsequent separation of one salvaged board that had tenons inside. In both cases, this was probably due to the shear stresses that were transferred through the connectors to the salvaged timber boards. No bending failure was observed in any of the salvaged timber elements. Since the 'bending type' failures only occurred in the fresh boards, instead of the salvaged one, may indicate that the solution proposed in this research was not substantially dependent on the bending strength of the salvaged timber boards. This represent an important finding since the uncertainty in the strength properties is an important challenge for reusing salvaged timber.

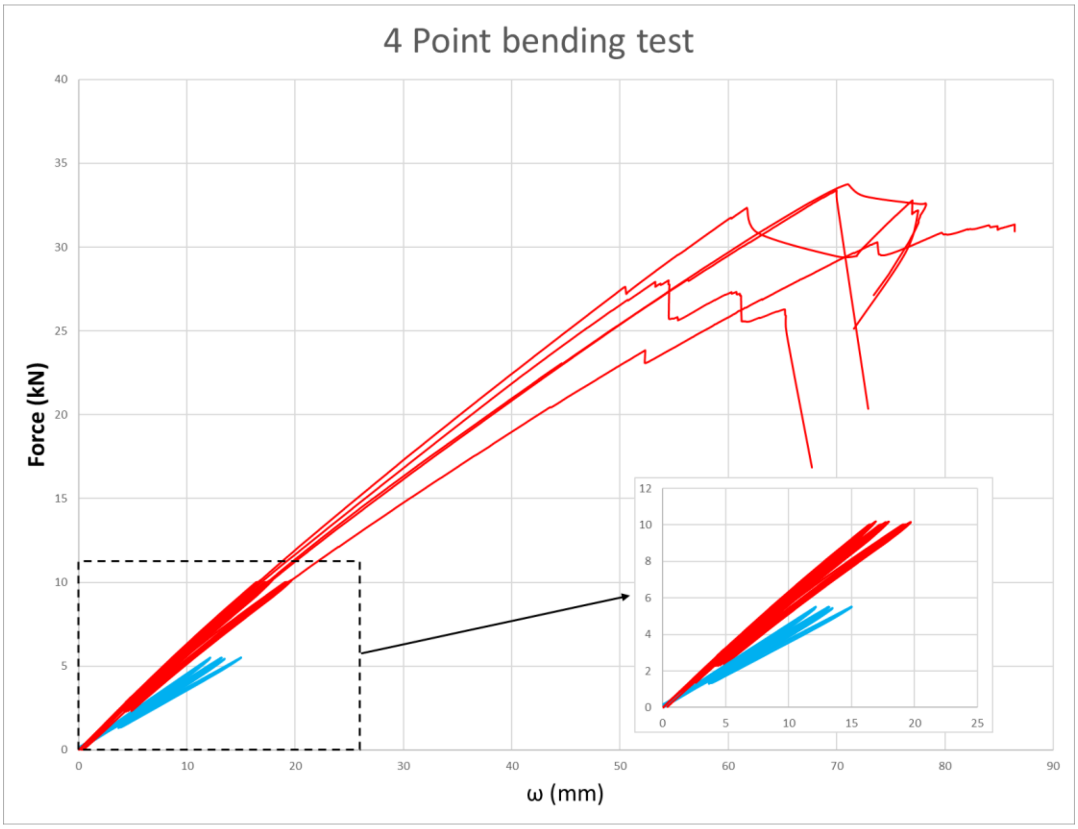


Fig. 35: Load-deflection curves of the large-scale DLT panels.

The sample A failed in bending at 31.4 kN. As it is possible to see from fig. 36, the failure occurred in the fresh timber layer, in a knot. The subsequent propagation follows the slope of the grain towards the weak section of the boards: the holes where the tenons were inserted. At the maximum failure load, one of the pieces of salvaged timber, the one in the middle, broke and exposed the tenons (fig. 37). The fact that it broke completely is probably due to the presence of a previous crack formed during the hammering of the middle pieces.

Fig. 36: Failure mode specimen A.

Fig. 37: breaking of the salvaged timber board

The sample B failed in bending at 33.7 kN. As can be noticed from fig. 38, the failure happened in the mid fresh layer, and it propagated following the direction of the grain to the weakest section of the board.

Fig. 38: Failure mode specimen B

The specimen C failed in bending at 32.2 kN. Looking at the fig. 39 is possible to notice that the failure is similar to the one of specimen B since it happened in the mid fresh layer, and it propagated to the weaker section following the grains direction. At the maximum load, a shear failure occurred in one of the supports (fig. 40a), one of the salvaged timber boards failed and broke exposing the tenons (fig. 40b).

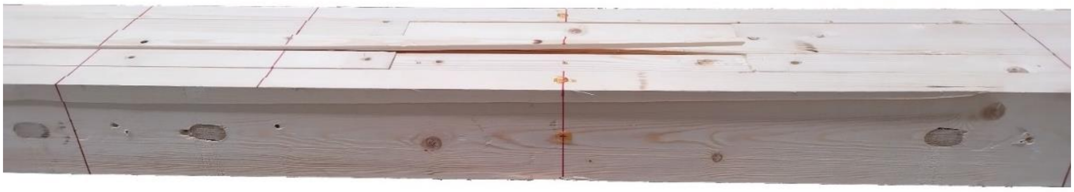


Fig. 39: Failure mode specimen C.

Fig. 40: (a-b) Shear failure of specimen C.

The sample D failed in bending at 33.4 kN. It is possible to see from fig. 41 that the failure occurred first in the external layer of fresh timber due to a knot and them in the middle layer of fresh timber, also in this case due to a knot. Then the cracks propagated in the weakest section of the board.

Fig. 41: Failure mode of specimen D.

The specimen E failed in bending at 27.3 kN. The failure occurred in the external fresh timber layer, in a knot, and then it propagated following the grains direction to the weakest section, where the tenons were inserted (fig. 42).

Fig. 42: Failure mode of specimen E

Looking at the graph in fig. 43, a solid plate all made by fresh timber boards is considered 100% for the value of the stiffness. It is possible to see that the samples made by 3 layers, since they are made by two layers of fresh timber and one layer of salvaged material, the stiffness (calculated considering just the fresh layers) is 66.7% of the stiffness that the same plate would have if it would be made by three fresh layers. While the samples made by five layers, three of fresh timber and two of salvaged materials, have a stiffness of 60% with respect to the same plate all made by fresh timber. Looking at the graph it is possible to see that, thanks to the introduction of the interlocking system to the layers of salvaged wood, the stiffness of the system was increased in both cases approximately by the same amount in percentage. Looking at the three layers specimen, the amount of increase in the stiffness with respect to the starting point (66.7%) in order to reach the 100% is: 100/66.7 = 49.9%. Thanks to this solution the increase of stiffness that was obtained is in average 31%. As a consequence, the system reaches a stiffness of 1.31*66.7 = 87.4% with respect to the 100% (configuration with three fresh layers that is the maximum stiffness that can be reached). While, for the specimen with five layers, the amount of increase of the stiffness with respect to the starting point (60%) in order to reach the 100% is: 100/60 = 66.7%. Thanks to the interlocking solution, the increment of stiffness obtained was in average 39%. As a consequence, the system reached a stiffness of 1.39*60 = 83.4% with respect to the 100%.

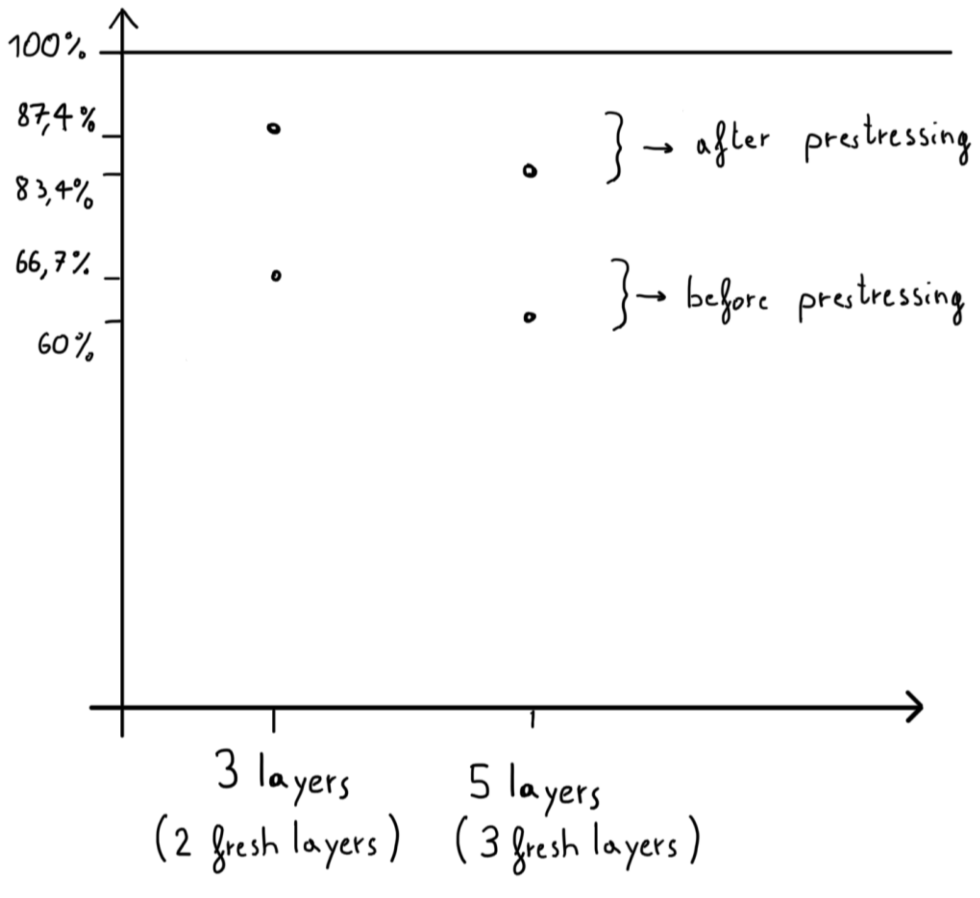


Fig. 43: Increment of stiffness due to the interlocking system for the three layers and five layers sample.

4.2.3 Deconstruction

After testing all the panels, it was chosen to deconstruct some of them in order to understand how the plywood tenons behave. The specimens B and C were completely deconstructed, while for specimen D just the two ends of the boards were deconstructed. Not all samples were disassembled because two of them are used as show case. In total 20 plywood tenons were analysed, 8 for sample B, 8 for sample C and 4 for sample D (fig. 44). The disassembly procedure was done by cutting the panels in smaller pieces and then, using the table saw to get rid of the wood around the tenons. For each sample, it was noticed that just one tenon presents shear deformation (fig. 45) and the deformed one, in all cases, is the most external one. The failure occurred on the most external one because it was the one that was subjected to the most pressure. Part of this deformation could be also a consequence of the insertion of the middle pieces through the hammering procedure since lots of pressure was introduced to the slab system. However, the failure of the tenons most probably occurred during the failure of the panels. After the failure, since that tenon became the weak part, the deformation increased.

Fig. 44: (a) Tenons from specimen B, (b) tenons from specimen C, (c) tenons from specimen D.

Fig. 45: Failure mode of the tenons in the disassembled specimens, C D B respectively.

5 Conclusions

The aim of this research is to develop and investigate a method for reusing short, salvaged timber elements in fabricating structural mass laminated floor system without the need for end-to-end joining or gluing. This led to the development of a DLT system made with a mixture of fresh timber and salvaged timber elements. The salvaged timber layers were prestressed in the system in a way that they contribute to the bending performance by resisting compression. The salvaged timber boards were used in every other layer of the DLT slab, so the effectiveness of using salvaged material was analysed not only as a space filler, but as an active and structural part of the system. With respect to a full slab made by only fresh timber, using salvaged timber allows to save raw, new material and, instead of just using the already utilised timber as energy recovery, it gives new value to a material that was already used. Therefore, the burden on the forests and the natural environment is reduced and the preservation and development of the latter is facilitated. Initially, the DLT slab was fabricated using a mechanical interlocking system for the salvaged boards, different patterns were studied, especially regarding the compression zone of the panels, and some prototypes were built. In the end, the chosen pattern was represented by a mortise-tenon solution where the mortise boards were connected to the slab using wooden nails and salvaged plywood dowels. While the tenon ones were inserted inside the system through a hammering procedure. In this way, since the dimension of the tenon boards was slightly bigger than the distance between subsequent mortise boards, new materials was introduced inside the system. This entailed the generation of compressive forces inside the system, in the salvaged timber layers, which increased the stiffness of the slab.

5.1 Small scale DLT specimens

First of all, it was decided to build eight small-scale DLT samples to analyse the effectiveness of the chosen interlocking pattern. Two different solutions were studied and tested, five samples where the tenon boards had a profiled surface (with end-to-end interlocking), while the other three samples where the tenons boards had a planar surface (without end-to-end interlocking). A three-point bending test was performed on these eight specimens to evaluate the bending stiffness non-destructively and the following conclusion were drawn:

1) For both the configurations, the chosen interlocking pattern increase the stiffness of the system. As regards the configuration with end-to-end interlocking, the average increment of stiffness was of 31.8%, while for the one without end-to-end interlocking, the average increment of stiffness was of 31.4%. Therefore, as expected, having an end-to-end interlocking between salvaged boards do not improve the

capacity of the system. On the other hand, due to the presence of some gaps in the solution with end-to-end interlocking, occurred during the fabrication process, the contact area was reduced. For this reason, for the fabrication of the large-scale specimens, it was chosen to use the planar surface solution.

2) In either the configuration, during the loading cycle, and for the second configuration even at the breaking point, there was no pop up of the middle piece even if it was not connected to the system, but it was just hammered inside. This fact showed that the friction forces were bigger than the pop-up forces. Therefore, it was proven that the chosen connection was effective.
3) On the three specimens without end-to-end interlocking, also the cyclic test was done in order to see if the repetitive loading and unloading procedure would have affected the performance of the system. The results showed that there was no difference in the stiffness between the first and the last cycle. However, this was a short-term test, in order to have a complete view on this effect, a long-term test needs to be done.

5.2 Large scale DLT specimens

Five samples were produced, based on the results of the previous tests, the solution without end-to-end interlocking was chosen to be tested under four points bending load. Also, a vibration test was performed. From the tests, the following conclusions could be withdrawn:

1) The average increment of stiffness, in agreement with the results of the small-scale test, was 39%, in line with the required values from the normative.
2) Even at the breaking point, both the middle boards, inserted just by pressure, and the plywood tenons, did not move or pop up from the system. For each disassembled specimen, was observed that one plywood tenon failed, and in all three cases it happened to be the most external one.
3) Due to the prestressing, the first eigenfrequency of the large-scale DLT panels usually increased, while on the damping ration there was an inconsistent influence. This might be caused by the variable support conditions and the uneven bottom surface of the specimens.
4) With the method proposed in this research, the bending failures were mainly present in the new timber boards instead of the salvaged ones.
5) A long-term test is suggested to analyse how the mechanical properties of the panels are after some years of utilization.

5.3 Future development, environmental potentials and recommendations

During the construction procedure, it was noticed that some technical and practical aspects of the slabs could be improved. Some problems occurred during the drilling procedure, but that was due to the equipment available in the wood lab. On the other hand, for what concerned the middle piece that was inserted by hammering, the dimensions could be optimized in order to have an easier procedure. By now the middle piece had a length of 40 cm, so to insert it, it was necessary to hammer it on both sides. This procedure can produce some cracks on the other boards because rotational forces were introduced inside the system. To solve this problem, a solution could be to have a smaller middle piece, that allows to be inserted by hammering it in only one point or using a hydraulic press. In this study, fixed dimensions of the salvaged timber boards were used, but with the previously presented suggestion, the middle pieces do not require to have fixed dimensions. As a consequence, the fixed part of the salvaged timber (mortise boards) has also different dimensions and require less processing. The final goal is to have a system that allows to insert the plywood tenons following a constant patter, in order to guarantee the consistency of the system, but that does not depend on the position of the salvaged timber boards.

The environmental potentials of this solution are based on the concept of wood cascading. This concept is based on reutilising the same wood, in several different way, having a decrease of the quality of the material during its utilisation towards thermodynamic equilibrium. The material that in this research is called salvaged timber, is normally just used as energy recovery, skipping several steps of the cascade. At this stage, the material presents good properties, comparable to the ones of the fresh timber. However, since the salvaged material is usually formed by cut off during the production or already used timber, the dimensions are reduced. With the solution presented in this research, it is possible to reutilise the salvaged timber as an active part of the system thanks to the compressive forces that are formed after the insertion of the middle piece into the slabs. As a drawback, not every board of salvaged wood can be used since several challenges need to be acknowledged. One of the most important challenges is that the initial grade and the previous load history of the salvaged boards are usually unknown. This leads to additional uncertainties related to the mechanical properties of the new products that are developed from such materials. In this case, the application of a non-destructive inspection method of the boards might be useful.

All in all, the results obtained from this research indicate a high potential of reusing salvaged timber in the DLT slabs. The analysed prestressing method represents an optimal solution to increase the capacity of the system. Reusing salvaged timber in structural application increases the values of the materials that otherwise would have been used only for energy recovery.

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6 Attachments

6.1 Study of the interlocking system

In the following section, the full procedure that ends with the selected interlocking patter is presented.

Up to this point, the salvaged timber boards were just considered and used as a space filler, but since the quality of the wood is high, they can actually be used to increase the capacity of the system. This can be done by using an interlocking pattern. Another option is to add precompression to the system in form of compression between the boards. The first idea is to have interlocking between the salvaged boards. Having some boards used as mortise and some of them used as tenons guarantees that not all of them need to be nailed to the fresh timber. In the fig. A1 is possible to notice that the tenons are nailed to the layer of fresh wood, while the mortise is just wedged in the middle. This guarantee to use less nail and having an interlocking pattern like the one on the picture speeds up the construction procedure. This procedure allows to create a subsystem formed by two layers: one of fresh wood and the other of salvaged material, and then to join all this subsystem together with wooden tenons. On the other hand, this shape does not increase the capacity of the system so is not the optimal solution. Is it possible to notice that, loading the salvaged material, it needs a certain amount of deformation before being able to actually carry the load. It means that, in the composite system, the fresh timber boards have to be deformed in order to let the salvaged material increase the capacity of the system. But with this kind of connection the compression is perpendicular to the grain, and this is something that is to avoid since is the weaker direction of timber. This solution represents a good interlocking pattern, but the target was also to increase the capacity of the system. For this reason, new solutions were investigated.

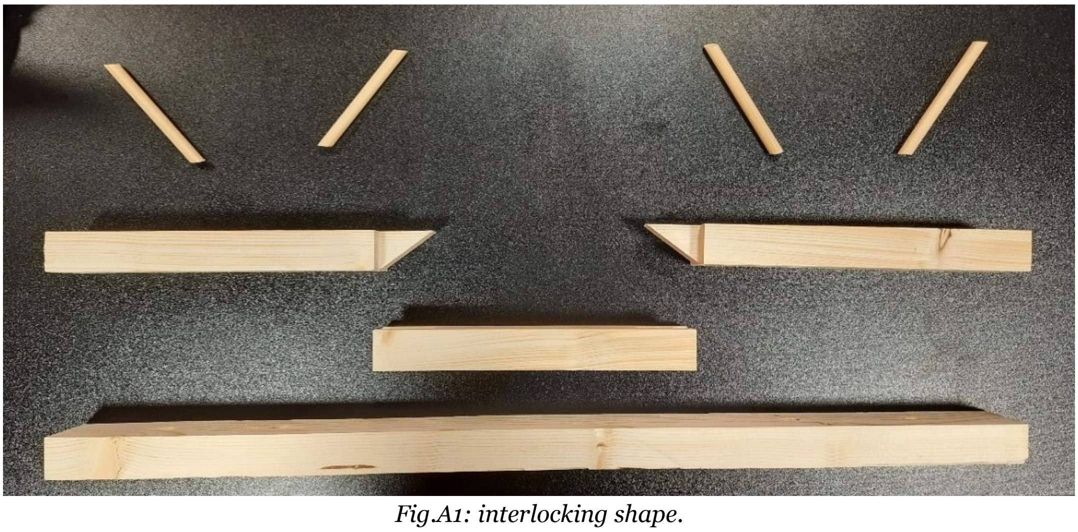

Fig.A1: interlocking shape.

Four hypotheses were set before continuing the research:

- The focus was the compression zone, so what happen in the tension side was not really important for the purpose of this research.
- The connection had to be easy to cut and assemble in order to maintain a low cost for the production.
- The interlocking between boards had to be guarantee, it allowed to have a simpler and faster construction phase.
- The limitation of the tools present in the lab had to be considered.

First of all, some ideas of connection were studied, rectangular shape connection, triangular one, rounded one, double triangular connection, finger joint connection and dovetail connection. In the end the selected one is a mortise and tenon interlocking pattern along the vertical direction of the small face of the boards.

- Rectangular shape connection (Fig. A2) with the tenon slightly bigger than the mortise. In this way there is full contact between the surface of the different boards so the problem of the previous example, where a deformation is needed to let the salvaged timber work, is solved. Despite that, the main problem of this kind of connection is that the compression is perpendicular to grain in the interlocking part, and since it is the weakest direction of the timber, having compression perpendicular to grain is to avoid. All in all, this connection guarantees a good level of interlocking, but it does not add any capacity to the system.

Fig. A2: Mortise-tenon rectangular shape interlocking pattern.

- Triangular shape connection (Fig. A3). This kind of connection can actually increase the capacity of the system because the bottom part of the triangle, once that the system is loaded, applies compressive force on the other board. Since it has a triangular shape, the compressive forces are not only perpendicular to the grains, but it has also a component that is parallel to the grain. As a drawback, it was hard to realize a really accurate connection since it needs to be really precise and without even a minimum gap to work as it should. As it is possible to see from the fig. A3 the small gap present between the mortise and the tenon reduce the contact area in the compression zone, as a consequence the capacity of the system is reduced. The challenge part of the production process is to obtain the mortise and the tenons of the exact same size. Since the production procedure is long and time consuming, this is not an optimal solution. One of the targets of this research is to explore the different options on how to use the salvaged timber in an efficient way. It means also that the production procedure cannot be too elaborate otherwise, industrial wise speaking, it is not convenient. Therefore, the industry will not develop this kind of structure and the salvaged timber will continue to be seen just as an energy recovery material and so it will be burn even if it has a way bigger potential.

Fig. A3: Mortise-tenon triangular shape interlocking pattern.

- Rounded shape connection (fig. A4). The solution turned out to be not efficient because the rounded shape does not help to add any capacity to the system and moreover it is difficult to realize. In addition to that, some problems occurred with the blade. According to the previous reasons, this kind of connection has been discarded.

Fig. A4: Mortise-tenon rounded shape interlocking pattern

- Double triangular shape connection (fig. A5). It represents a good solution from a theoretical point of view, both tenons are in the compression zone of the boards and even with a small angle, it can increase the capacity of the system. The drawbacks of this solution are the same of the single triangular shape connection: the realization is challenging and time consuming. In the end, even if the solution appears to be promising, it was discarded because it is too difficult to produce.

Fig. A5: Double mortise-tenon triangular shape interlocking pattern.

- Finger joint connection (fig. A6). As well as the previous solutions, the focus was only on the compression side of the boards, therefore the finger joint connection is present just in the part of the boards that is under compression. This solution guarantees a good level of interlocking, to join the two boards it is necessary to hammer them since the blades gives a really accurate cut, this procedure is fast, so the system is easy to assemble. Once that are connected no gap are present and there is full contact between the boards. The cutting procedure is also simple and can be done using the table router. On the other hand, the compression is perpendicular to grain, this led to a brittle failure of the wood. Consequently, it does not add any capacity to the system, so the finger joint does not represent the optimal solution for this kind of system.

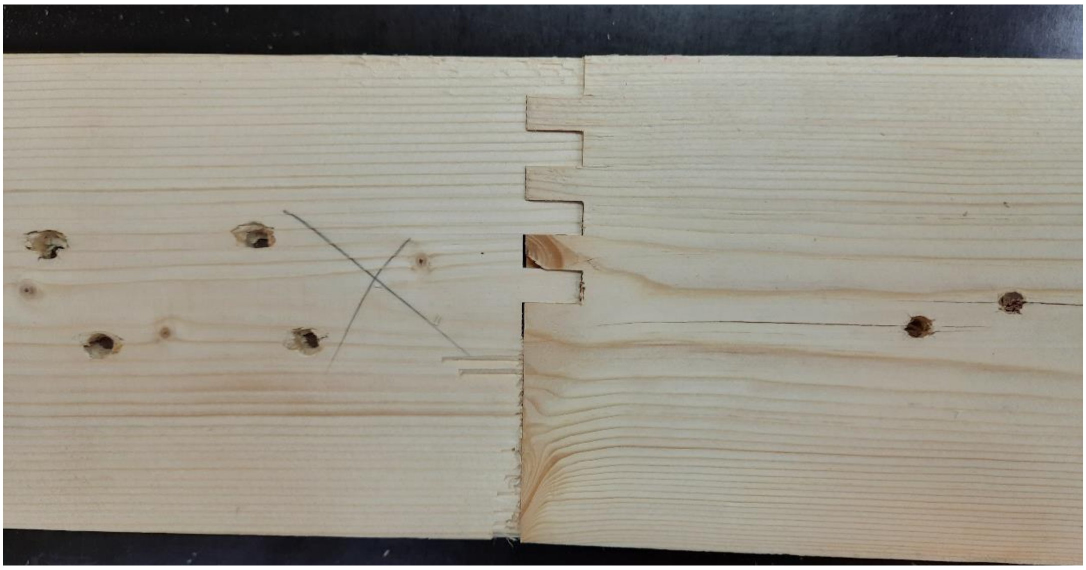

Fig. A6: Finger joint interlocking pattern

- Full board triangular shape connection (fig. A7). Even a small angle is sufficient to increase the capacity of the system. The boards are symmetrical with respect to the vertical axis, which speed up the construction procedure. In order to produce this kind of connection, a table saw is required and using the jig in fig. A8 is it possible to maintain the boards orientated in vertical direction. For each board, four cuts are required. Even if this interlocking pattern seems to be promising, it turns out to be quite long to produce. Some gaps can be present in the connection, as a consequence the connection is weak and not efficient. For the previously explained reason this pattern is discarded.

Fig. A7: Mortise-tenon full board triangular shape interlocking pattern.

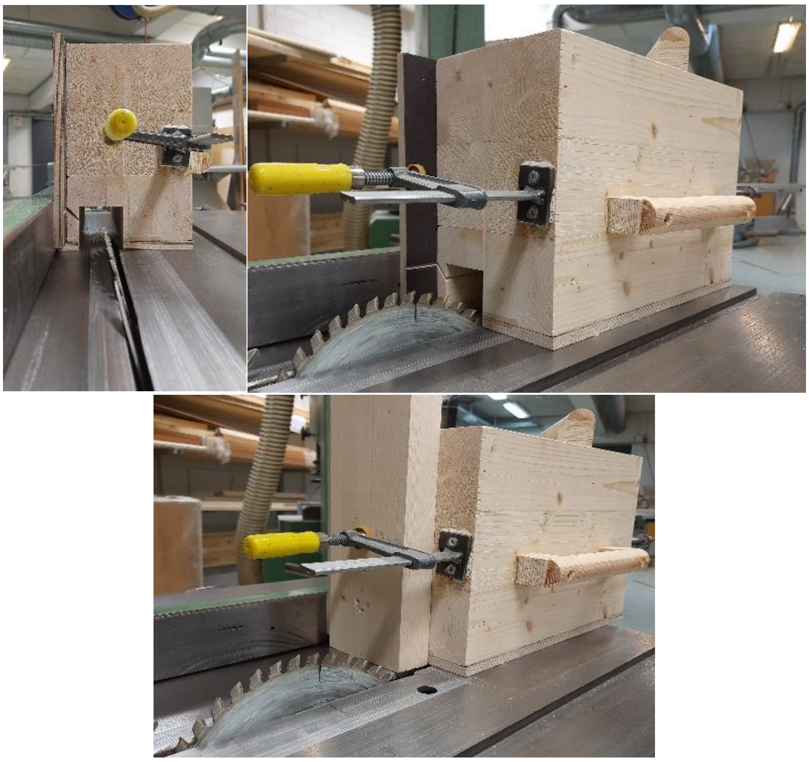

Fig. A8: Jig used to cut the full board triangular shape interlocking pattern.

- Dovetail connection. This is the only connection that is analyzed on the tension side of the boards. This idea comes from the connection used for the hardwood in the furniture. Each board is symmetrical, and the machine use to execute the cut in the shape of dovetail is the table router. Between two boards is inserted through hammering procedure a double dovetail connection made of plywood. The part of the boards that is in the compression side present a flat surface that have full contact with the next one, while on the tension side there is the dovetail connection. In this way, once that the system is loaded, the capacity should increase with respect to the normal connection represented by the flat surface only. Despite that, the dovetail connection is small and is not able to add enough capacity to the system because the wood, with such a small connection in the tension side, behave softly. Finally, this connection is discarded because not able to add any consistent capacity to the system.

- Mortise and tenon interlocking pattern along the vertical direction (fig. A9). This solution was the one implemented into the system. Increasing the compressive strength between boards during the construction procedure increase the capacity of the system. The contact surface between the boards is not flat nor vertical: in order to guarantee the fact that, once that the tenons is inserted, compressive forces are created, the contact surface have to be slightly angled. On the other hand, the angle has not to be too big. Otherwise, once that the system is loaded, since the tenon is not fixed with the wooden nails but just with compressive force, it will pop out during the loading procedure. In order to avoid this, an angle of two degree is chosen. In this way, hammering the tenons inside the system, it creates compressive forces but since the angle is small, when the structure is loaded the friction force between boards does not allow the tenons to pop out. As regards the production procedure, first of all the boards are processed so both the salvaged timber and the fresh timber have the same width and thickness. After that, the salvaged boards are cut with a 2° angle on both sides, then the table router is used to create the shape of mortise or tenon. At the beginning, an angle of 10° was chosen but then the 2° angle was preferred. In order to do that, some rotating blades are used. To create the tenons four blades are used, two for each side with a 16 mm of gap in the middle. As regards the mortise, just two blades are used, in the middle of the boards to create the desired shape. Before doing that, is important to set the table router with the correct angle so that the angle of the cut is the same as the angle done with the table saw. During the construction procedure first the mortise salvaged timber board will be fixed to the fresh timber, then the tenons part will be inserted till 3 cm of it are outside the panel (fig. A10a). Then the second mortise will be inserted and nailed to the fresh wood. Just after all the mortises are fixed following this procedure, the tenons can then be hammered inside (fig. A10b), this guarantee that compressive forces are formed between mortises and tenons boards even before loading the system. Really high accuracy is required during the construction procedure, both during the execution of the cut using the table saw and using the table router, the two machines must be set using the same angle. In this way no gaps should occur and there should be a full contact surface. Once that the tenons boards are inserted, is necessary to control that all the boards of the system are at the same level to perform the test otherwise during the loading process the load is not applied uniformly to the system.

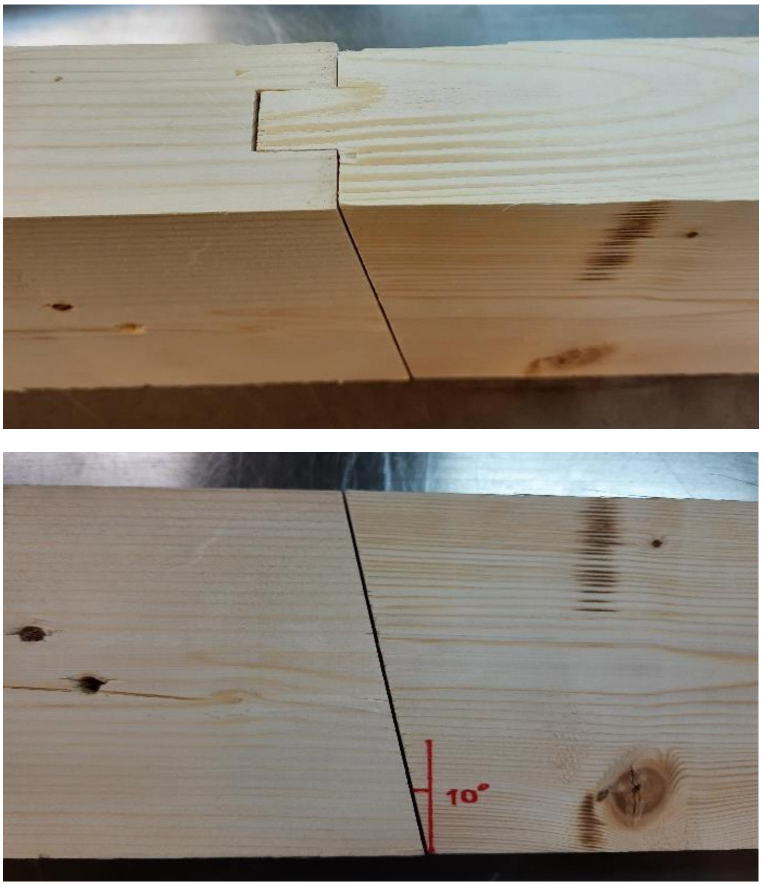

Fig. A9: Vertical profiled mortise tenon interlocking pattern.

Fig. A10a: tenon board before hammering.

Fig. A10b: tenon board after hammering.

- Mortise and tenon interlocking pattern along the horizontal direction (fig. A11). During the development of the previous idea, an alternative is also explored, based on the same concept of hammering the tenon boards, but in a different direction. The boards should be hammered from the lateral side, and on the vertical surface of the salvaged boards there is a mortise-tenons interlocking pattern. This solution turned out to be difficult to realize. Another problem is that, since the surface is angled along the horizontal direction, once that the system is loaded, horizontal forces are formed that try to split the system. This is due to the fact that, during the loading procedure, the compressive force between the salvaged timber boards, since the surface is not straight but angled, would have one component towards the external side. Since the tenon boards are not nailed to the fresh timber but just hammered inside the system and then covered by another layer of fresh timber, once the system is loaded the compressive force would have a component along the horizontal direction that tries to split the system. This direction of the force must be avoided in the DLT because no glue or fasteners are used to keep the system together but just plywood tenons. For the previously explained reasons this solution is discarded.

In the end, the interlocking solution that is chosen is represent by the mortises and tenons pattern where the tenons are hammered along the vertical direction (fig. A10 a-b).

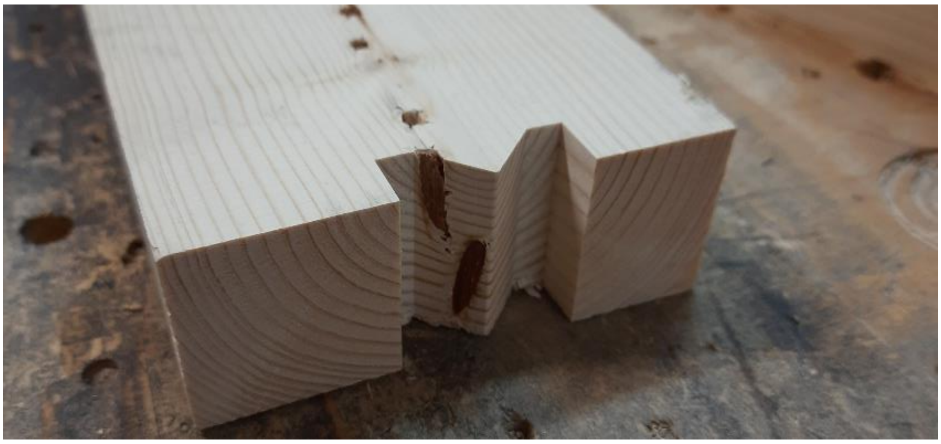

Fig. A11: Lateral hammering direction tenon board.

6.2 Floor span calculation

The span of the panels is calculated using the formula for a beam under uniform load:

$$\omega = \frac{5}{384} * \frac{P_b * L^4}{EI} \quad (7)$$

Where:

ω is the displacement.

P_b is the design uniformly distributed load for residential and office floors.

L is the length of the panel (the unknown value).

E is the modulus of elasticity (N/mm^2).

I is the second moment of area (mm^4).

Reversing the (7) having as unknow the final length L, two values are calculated. For residential building L = 3.54 m while for office building L = 3.20 m.

6.3 The vibration mode of large-scale DLT panels

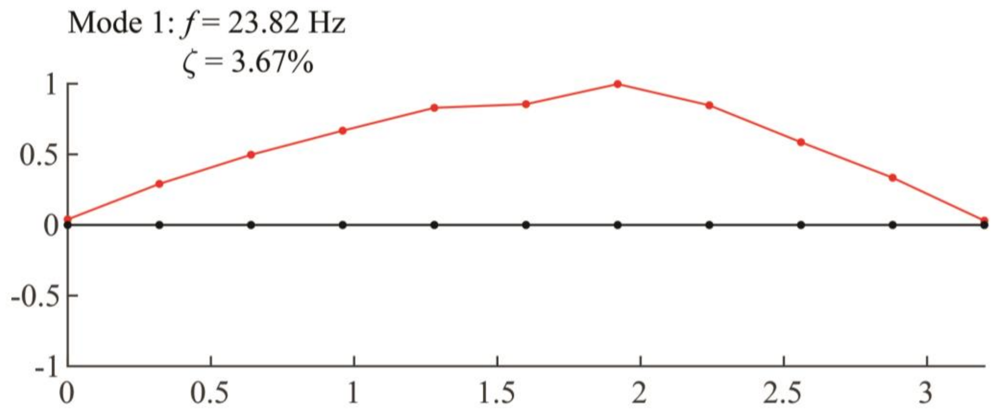

Fig. A12: The first vibration mode of specimen A before prestressing.

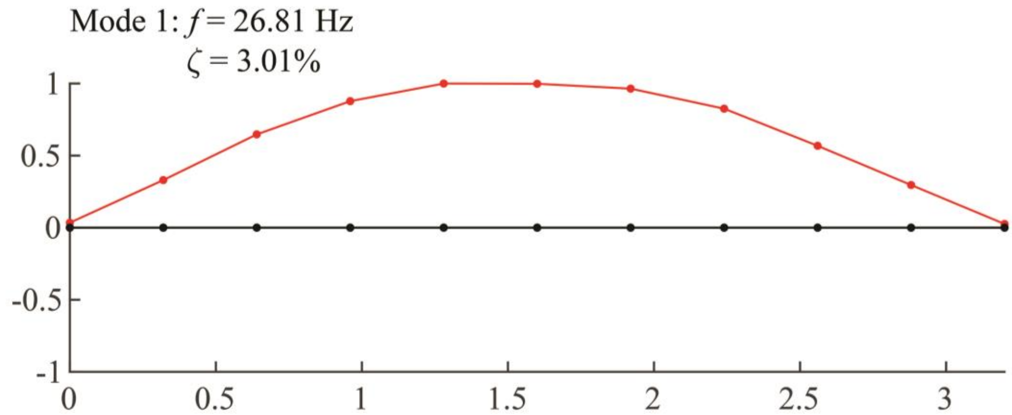

Fig. A13: The first vibration mode of specimen A after prestressing.

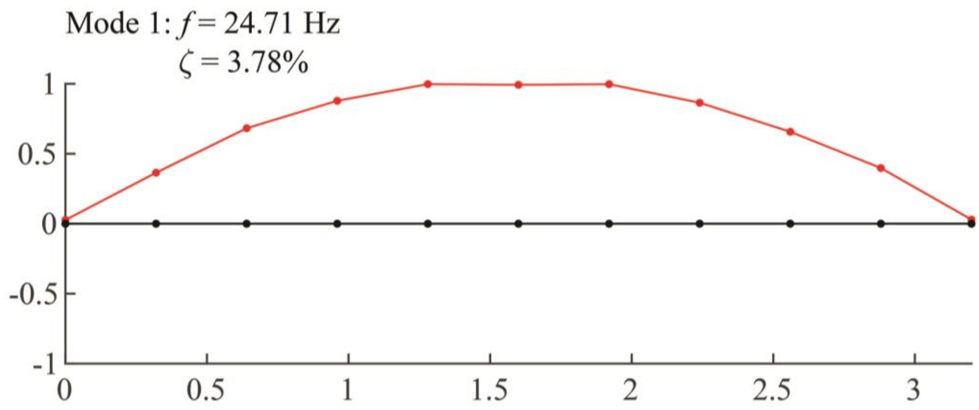

Fig. A14: The first vibration mode of specimen B before prestressing.

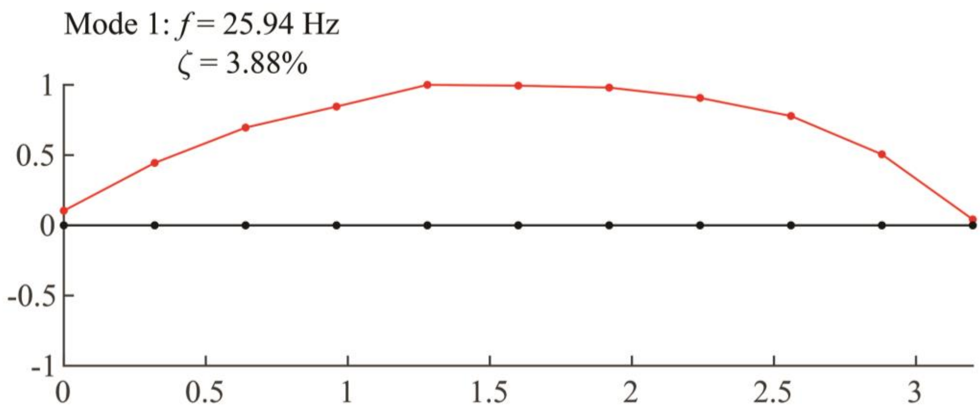

Fig. A15: The first vibration mode of specimen B after prestressing.

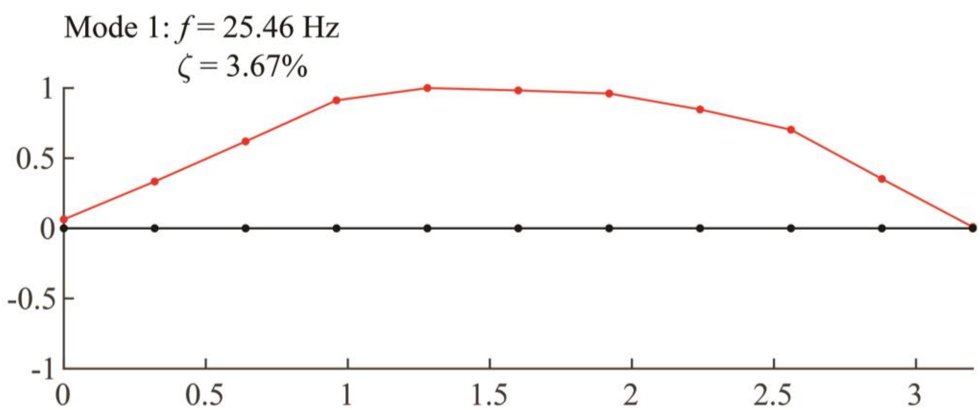

Fig. A16: The first vibration mode of specimen C before prestressing.

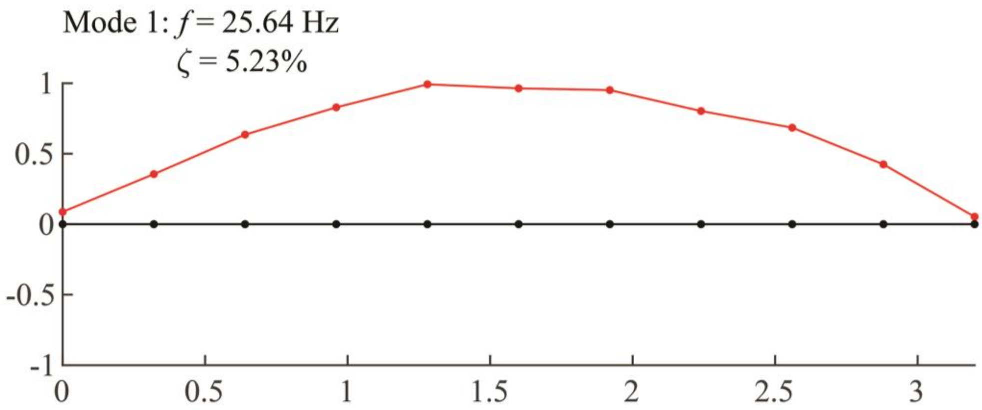

Fig. A17: The first vibration mode of specimen C after prestressing.

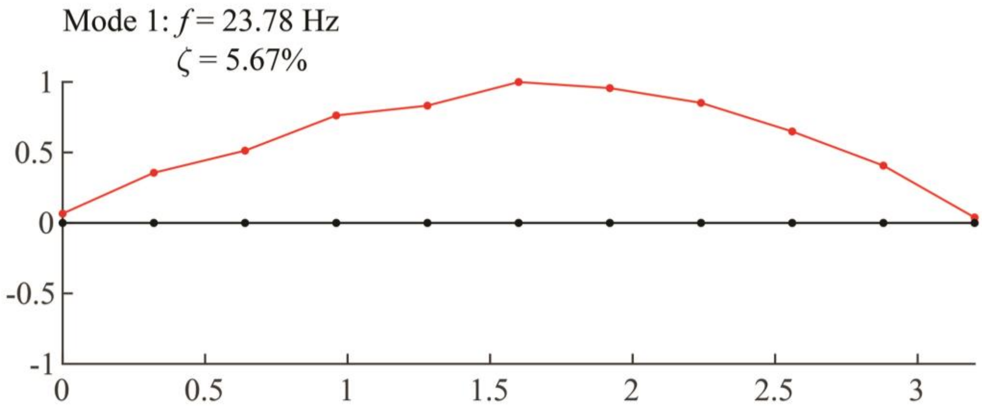

Fig. A18: The first vibration mode of specimen D before prestressing.

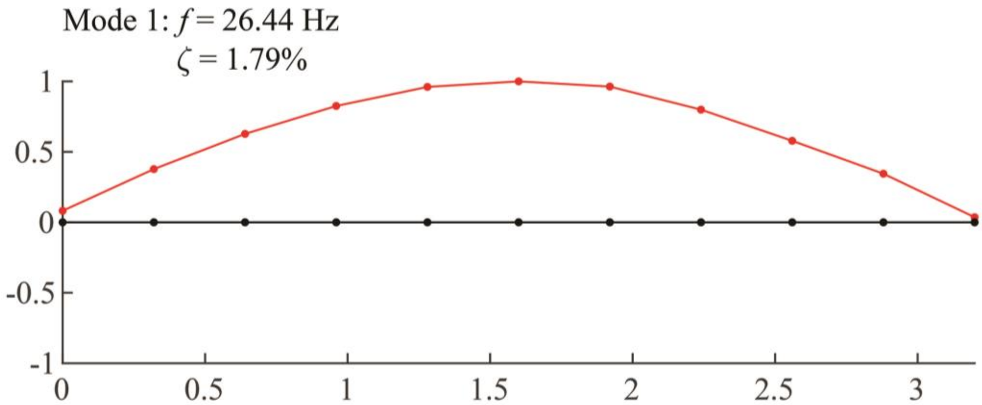

Fig. A19: The first vibration mode of specimen D after prestressing.

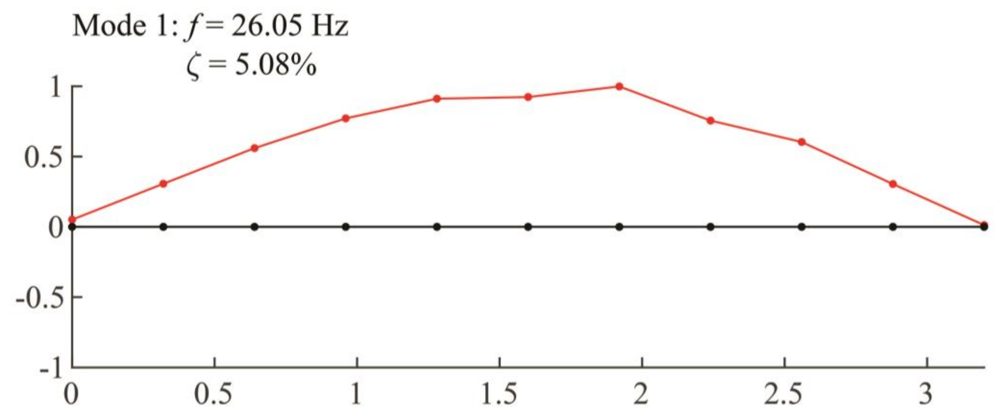

Fig. A20: The first vibration mode of specimen E before prestressing.

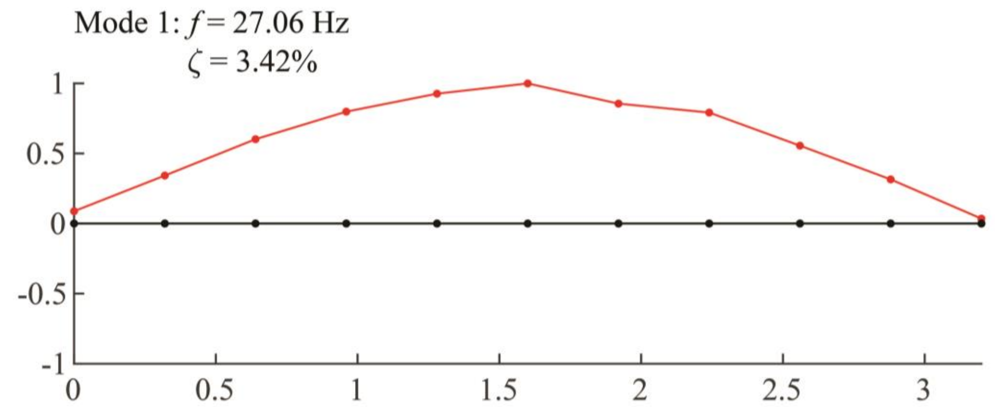

Fig. A21: The first vibration mode of specimen E after prestressing.