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PLASTIC DESIGN OF BESPOKE INTERLOCKING TIMBER-TO-TIMBER CONNECTIONS FOR ROBOTIC ASSEMBLY

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ABSTRACT: *CantiBox* is a robotically assembled pavilion composed of linear timber elements. The interweaving logic of the structure makes it possible to use exclusively interlocking timber-to-timber connections during the automatic assembly. The design of the connections is based on the static method of limit analysis, which allows adjusting the geometry of each joint according to the internal force distribution.

KEYWORDS: Spatial timber structure, Interlocking timber-to-timber joints, Robotic assembly, Limit analysis

1 INTRODUCTION

In recent years, the timber industry has increasingly promoted the introduction of digital technologies in the manufacturing and construction processes. Thanks to the major developments in Computer Numerical Control (CNC) machines, the production of complex and customized timber geometries is no longer a major challenge. Moreover, much scientific research has been carried out in the field of robotic assembly of timber structures made of plates and linear elements [1] [2] [3].

In this context, the *CantiBox* project demonstrates two novel contributions for jointed timber structures: (a) the application of the static method of limit analysis for designing interlocking timber-to-timber connections, which allows the adjustment of individual joint geometries based on real-time performance assessment; (b) the use of distributed mechanical tools operated by a robotic arm to achieve a fully automatic assembly process. Both contributions complete a critical knowledge gap that enables bespoke design and construction of spatial timber structures. Their flexibility to accommodate custom designs is enabled by the interweaving logic used to create a reciprocal network.

2 LIMIT ANALYSIS

2.1 INTERLOCKING TIMBER-TO-TIMBER CONNECTIONS

An approach based on the static method of limit analysis (e.g. lower bound theorem of the theory of plasticity) is well suited to the analysis and design of any structural timber element. Indeed, it is not restricted to a specific structural typology, scale or material [4] [5]. In the context of this project, the static method is adopted to address the analysis and design of interlocking timber-to-timber connections.

Figure 1: *The Cantibox project leverages innovative approaches to structural design and robotic assembly to enable the development of a customized spatial timber structure (©Ali Zigeli 2022).*

Timber-to-timber connections are particularly favourable for robotic assembly. Compared to other connections that require metal fasteners, an interlocking timber-to-timber connection is advantageous because it is composed of a smaller number of elements (i.e. a minimum of two) and thus requires fewer actions by the robotic arm (i.e. a minimum of one insertion). Therefore, this type of connection is highly suitable to be integrated into a digital automated process.

Digital fabrication makes it possible to achieve great freedom in terms of geometry. Since manufacturing complex interlocking timber-to-timber connections is no longer an obstacle due to recent developments in digital fabrication, their adoption is mainly limited by the difficulties in structural analysis. However, applying the

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static method of limit analysis to timber provides a new possible approach to the analysis and design of interlocking timber-to-timber connections. The illustrative representation of the state of internal forces in the form of strut-and-ties, or stress fields, makes the interactions between force and geometry explicit. It represents, therefore, the basis for the development of efficient connections.

2.2 PLASTIC DESIGN OF CONNECTIONS

The objective of plastic design is to analyze the connection, determine its load-carrying capacity by assessing the collapse load with reasonable accuracy and inform the design by optimizing its geometry. In an interlocking connection, the capacity is expressed as a function of two parameters: the contact surface A_i and its strength $f_{y,i}$. The former controls the flow of forces between timber elements, while the latter controls the flow of forces within an element. Given these two parameters, it is then possible to evaluate and adjust the capacity of the connection. The contact surface indicates the area available for force transfer. The contact surface strength indicates the maximum stress that a surface can withstand. In general, the larger the contact surface and/or the more efficient the internal force flow, the greater the connection capacity.

$$\text{Connection capacity} = f\left(A_i, f_{y,i}\right)$$

$\rightarrow F_{Rd,i} = A_{F,i} \cdot f_{y,i}$

$\rightarrow M_{Rd,i} = A_{M,i} \cdot f_{y,i} \cdot h_i$

A_i : Contact surface
$f_{y,i}$: Contact surface strength
h_i : Lever's arm

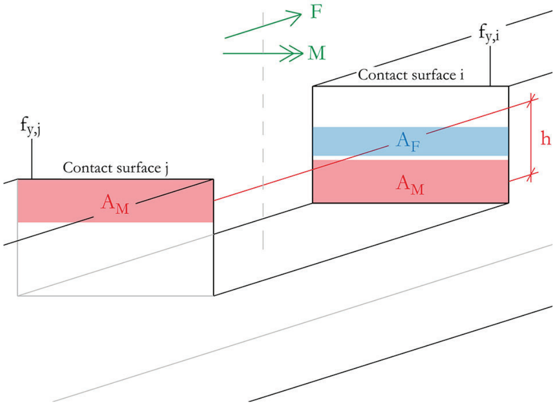


Figure 2: Schematic representation of the redistribution of forces in an interlocking connection.

2.2.1 Transfer of forces between timber elements

In the case of interlocking timber-to-timber connections, the forces between elements are transmitted through contact surfaces. Unlike other types of connection, here, only compressive forces are transferred. Being timber anisotropic, the positioning of the connection with respect to the grain's orientation is decisive.

Different strategies can be adopted to meet the material requirements [5]. In this project, three strategies are employed: (a) the tension forces are transmitted by designing connection geometries that transform tension into compression; (b) large contact surfaces enable the transmission of higher forces; (c) the transmission of different kinds of stresses required contact surfaces oriented in multiple directions.

2.2.2 Flow of internal forces in timber elements

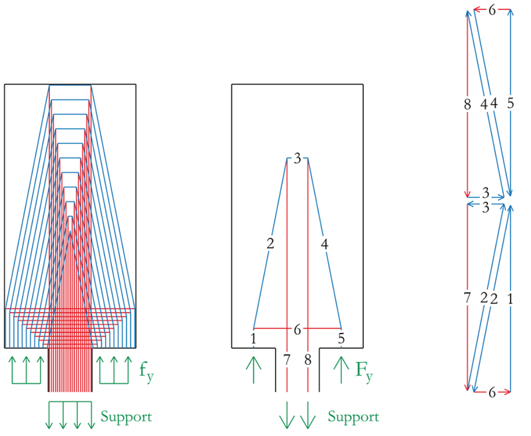
The compressive forces transmitted via contact surfaces are considered a starting point for analyzing internal forces. The limit analysis allows the visualization of the internal state of equilibrium, represented in the form of stress fields (continuous case) or strut-and-ties (discrete case). This representation is helpful for the analysis and especially for the design of interlocking timber-to-timber connections. Stress discontinuities may be present in the equilibrium state of the internal forces, in line with the plastic theory.

By comparing connections with different geometries, it can be observed that their structural capacity differs, although the joints have the same dimension of the contact surface over which the force is introduced [5]. In fact, some connections may favour a more efficient internal force flow than others (e.g. less force redirection or more effective exploitation of anisotropy). Therefore, it is necessary to conduct a quantitative analysis of the internal force flow to determine the capacity.

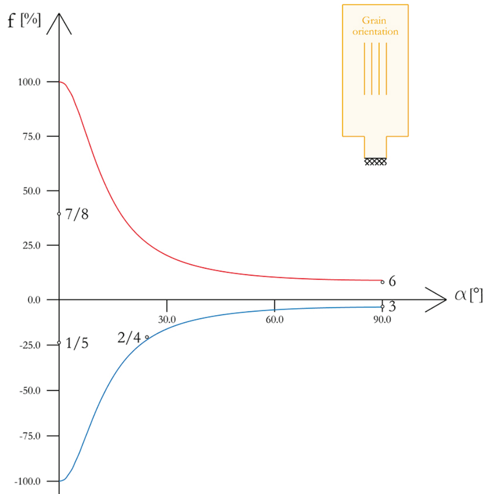
This analysis can be performed by means of stress fields, strut-and-tie models, force diagrams and yield conditions, as shown in Figure 3.

Stress fields and related strut-and-tie models, which show the resultants of the underlying stress field, represent the equilibrium condition of the internal force flow. They also provide visual information on internal forces, which is very useful in qualitative analysis. Given the geometry, the applied external forces and the boundary conditions, the compression force must be redirected towards the support. The force diagram represents the equilibrium of the forces acting in the strut-und-tie models using a closed cycle of vectors (i.e. force polygon) at each node, allowing for computing the magnitude of the forces. The compatibility of the internal stress states with the material properties is verified through yield conditions. In the yield conditions diagram, the individual stress states, one for each element of the strut-and-ties, are displayed. If the stress states lie within the curve of the yield conditions, the latter are respected. The yield conditions are represented by the uniaxial strength formula (i.e. Hankinson [6]) of the Swiss code 265 [7].

The possibility to model the internal forces, combined with the understanding of the material behaviour, allows for identifying possible critical situations and, consequently, improving the efficiency of the connection by manipulating the geometry or the internal forces model.



Stress field Strut-and-tie Force diagram



Uniaxial yield condition

Figure 3: *A parallelepiped timber element is tested. The element presents two notches through which the external load is transferred. Tension forces are shown in red, compression forces in blue and external forces in green. The analysis allows the understanding of the flow of internal forces and the assessment of the collapse load.*

2.2.3 Algorithm for the definition of contact surfaces

An algorithm is responsible for the plastic allocation of contact surfaces. Having defined as input the available contact surfaces A_i and the respective strength $f_{y,i}$, it determines which surface to activate for a given load. This process can also be performed manually, but in the case of combined loads, it becomes quickly tedious. The algorithm follows the principles below:

No overlapping between contact surfaces:

$$A_{Force} \bigcap A_{Bending} = \emptyset$$

Axial forces equilibrium:

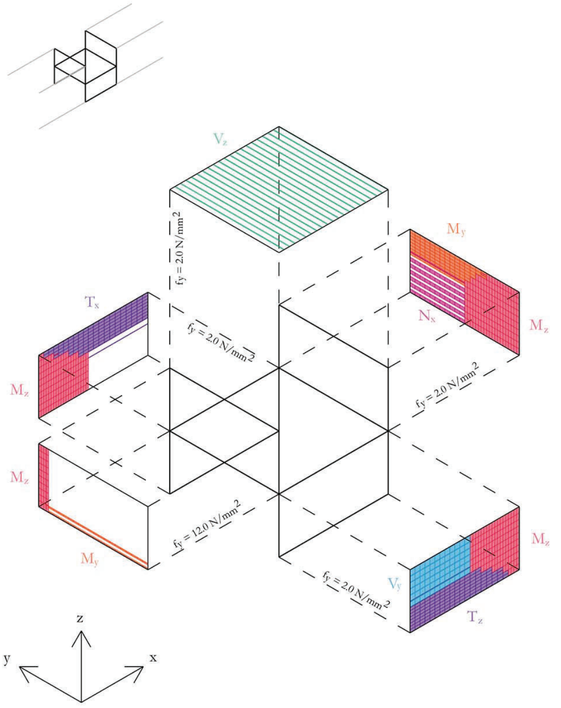
$$F + \int_{(+)} f_y \; dA_{Force} - \int_{(-)} f_y \; dA_{Force} = 0$$

Bending forces equilibrium:

$$M + \int_{(+)} f_y \cdot h \; dA_{Bending} - \int_{(-)} f_y \cdot h \; dA_{Bending} = 0$$

(+) positive side (-) negative side

The graphical representation of the result of the algorithm is shown in Figure 4.



N_x = 2.0 kN V_y = -3.0 kN V_z = -1.0 kN T_x = 0.1 kNm M_y = 0.1 kNm M_z = 0.6 kNm

Figure 4: *The algorithm is responsible for distributing the contact surfaces required for efficient force transfer between timber elements.*

3 PAVILION DESIGN

The *CantiBox* pavilion features a complex three-dimensional reciprocal structural system based on geometrically optimized and customized interlocking timber-to-timber connections.

3.1 STRUCTURAL CONCEPT

A reciprocal structure is composed of a minimum of three elements that support each other so that each element is supported either by another element or by the ground [8].

In this structural system, each element is essential, and the failure of a single element leads to a chain reaction that results in the collapse of the entire structure. This structural principle has been known for a long time, and its use is widespread [9].

Besides three-dimensional structures such as vaults or bridges, reciprocal systems are also used to obtain planar geometries. The adoption of reciprocal structures for the formation of ceilings is well known. Villard de Honnecourt, Sebastiano Serlio, and John Wallis provide relevant examples of this technique. In this case, the reciprocal system is called planar grillage [9]. Indeed, the planar structure composed of short timber elements forms the ceiling connecting the vertical structural elements of a building.

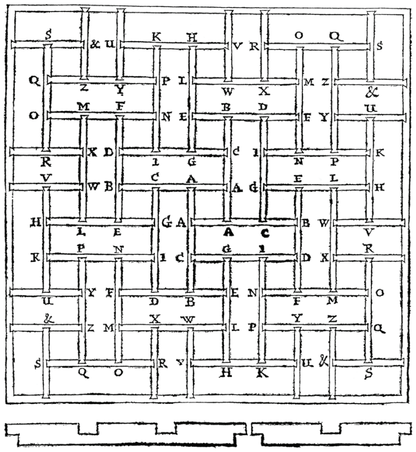


Figure 5: *Sketches of the planar grillage developed by Wallis [10]. The reciprocal structure allows long distances to be covered using multiple short elements that support each other.*

In the *CantiBox*, a planar grillage is used as a basic structural module. From a structural point of view, it acts like a Vierendeel truss. The reciprocal planar grillage module presents three horizontal and three vertical elements, as shown in Figure 6. The elements are interwoven, with connections oriented in opposite directions. Only once the last component is assembled, the reciprocal system is closed, the structure can be considered stable, and the disassembly is prevented. Furthermore, the assembly of the grillage complies with the automatic robotic assembly process developed for this project, which does not allow any triangulation in the structure. Connecting several reciprocal planar grillages together allows the development of spatial structures using only interlocking timber-to-timber half-lap connections.

In the design of the *CantiBox*, strict rules must be considered, which are dictated by the planar nature of the grillage module, by the use of square timber elements, and by the assembly process, which allows only planar connections (i.e. the plane of the reciprocal planar grillage module must be shared by two faces of the beam to which it is to be connected). Therefore, the design presents box-like structures where each face consists of a reciprocal planar grillage module.

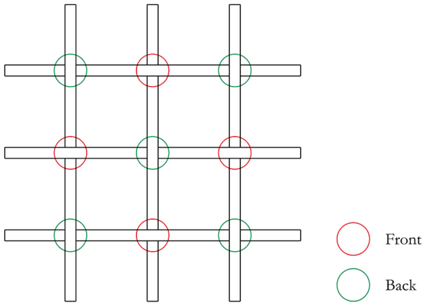


Figure 6: *Schematic representation of a reciprocal planar grillage module used in the CantiBox pavilion. In a real scenario, the assembly of this type of reciprocal structure is impossible without relying on the elastic flexibility of the elements. The interwoven composition prevents disassembly by presenting an alternating orientation of the connections. In the CantiBox pavilion, the last element to be assembled - the key element - exhibits a different orientation of the connections that allow it to be assembled without compromising the reciprocal system.*

3.2 GLOBAL DESIGN

CantiBox consists of three independent units: two lateral boxes connected to the ground and a cantilevering central box supported by the other units, as shown in Figure 7. The boxes are connected via shared horizontal planes. Each unit is composed of 20 linear timber elements of solid spruce with a cross-section of 10 by 10 cm, which are automatically assembled via robotic fabrication. The six linear timber elements of each face of the boxes are interconnected through bespoke half-lap joints arranged in the plane to generate a reciprocal system. Of these six elements, four present connections facing two opposite directions (e.g. two inward and one outward). This characteristic allows assembling each face with an interweaving pattern that ensures the correct automatic positioning of the elements within the face using a robotic arm. The sixth linear element of each face - the key element - has three connections pointing in the same direction to allow assembly by a robot. For this reason, one connection of the key element is ensured by a metal fastener that prevents disassembly [11].

For the evaluation of the global structural behaviour of the *CantiBox*, Finite Element Analysis (FEA) is used. In the analysis, each joint is regarded as a rigid connection. Since the project is built in the open air, the following external forces are considered according to the Swiss codes 260 [12] and 261 [13]: self-weight of the structure and wind load. The wind load acts in different directions. For each element, the most unfavourable direction is considered. In the definition of the support conditions, translational movement is blocked in all directions while rotational movement is allowed. The construction detail of the supports is characterized by a steel blade penetrating a notch in the timber, which is then fixed with a steel pin. The capacity of linear timber elements to resist axial forces, shear forces and bending moments is determined according to Swiss code 265 [7].

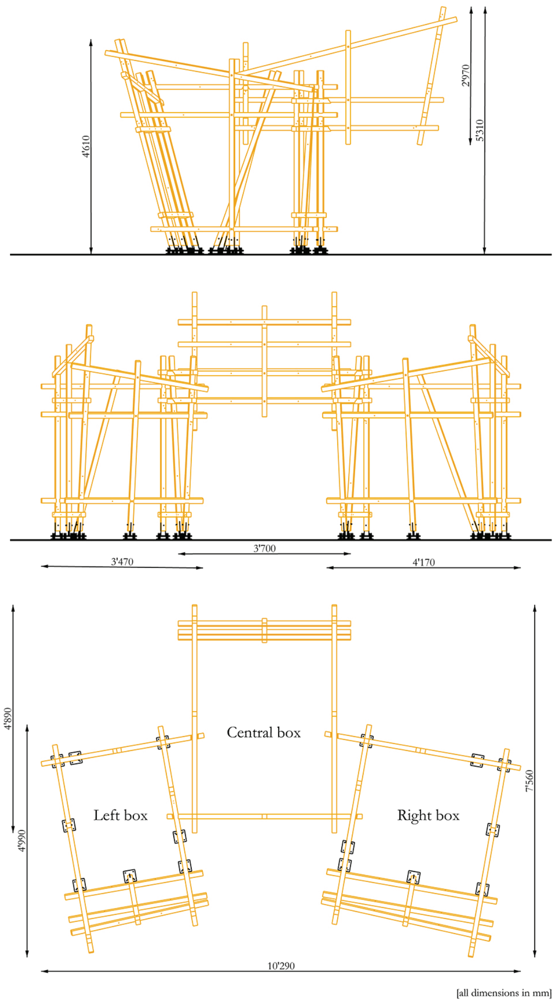


Figure 7: *The structure occupies an area in plan of 10.3 by 7.6 m and reaches a maximum height of 5.3 m.*

3.3 CONNECTION DESIGN

3.3.1 Half-lap connections

Among the many types of interlocking timber-to-timber connections, half-lap connections are adopted since these connections best meet the requirements of automatic robotic assembly. The prototypical half-lap connection is produced through a subtractive process in which half of the cross-section in each of the two elements to be connected is removed. From a static point of view, half-lap connections allow both axial forces and bending moments to be transferred. In addition, this single typology enables great flexibility in the geometry of the structure since a wide range of angles can be achieved on several planes.

3.3.2 Structural capacity of the connections

Based on plastic theory, the static method of limit analysis is adopted to determine the capacity of the interlocking timber-to-timber connections and their design (Section 2.2). The structural capacity of a connection depends on the geometry and the boundary conditions of the connected elements. Here, it is conservatively assumed that the connection has a fixed end on the left side and a free end on the right side.

Contact surfaces

In the half-lap connection, five contact surfaces are identified. These allow axial forces to be transferred in each direction except that of insertion, as shown in Figure 8. The transfer of bending moments occurs by combining in pairs the contact surfaces used for transferring axial forces (Figure 9). A bending moment can be transferred by activating multiple combinations of contact surfaces. From this first analysis, the importance of the extension of the beam beyond the connection that constitutes the free ends becomes apparent. This part activates an extra contact surface to transfer axial forces and bending moments.

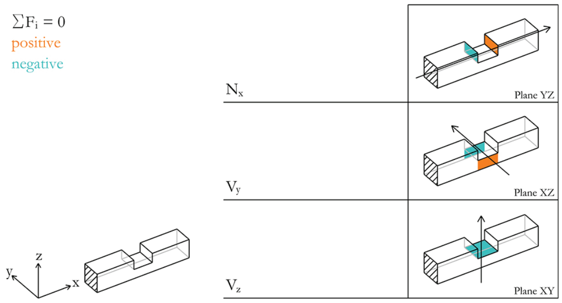


Figure 8: *Contact surfaces activated for the transfer of axial forces. Positive load transfer requires a positive surface.*

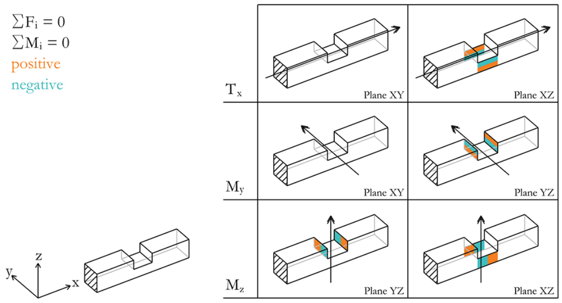


Figure 9: *The coupling of contact surfaces responsible for transferring axial forces ensures the transfer of bending moments.*

Strength of the contact surface

The internal force flow analysis aims to determine the maximum stress applicable to a contact surface. Therefore, this value represents the strength provided by the internal force flow system. It may be different for each contact surface.

As a reference, Figure 10 shows a more in-depth view of the force flow for several activated contact surfaces. A complete internal force flow analysis based on stress fields, strut-and-tie models, force diagrams and yield conditions is performed according to 2.2.2.

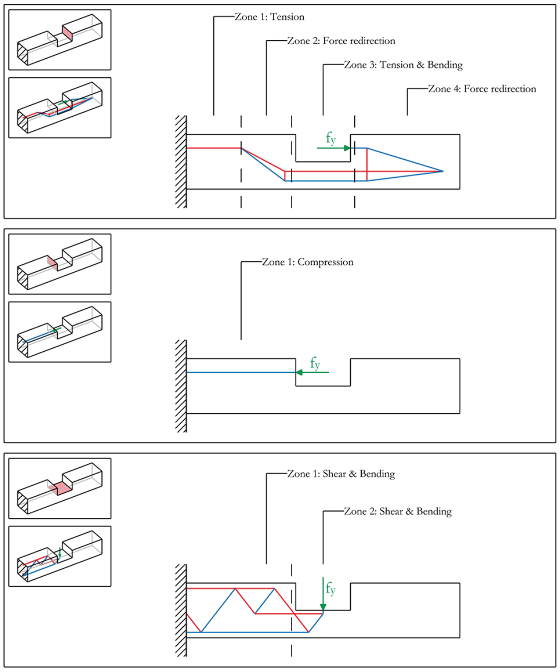
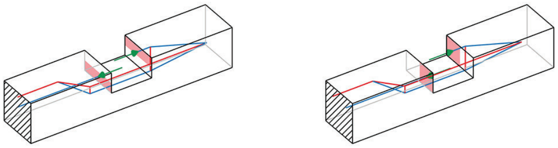
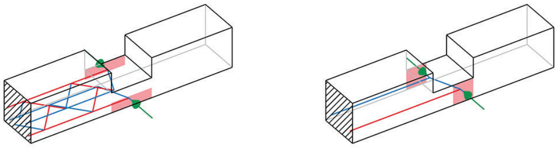


Figure 10: *Several typologies of internal force flow developing in the XZ plane are illustrated. Tension forces are shown in red, compression forces in blue and external forces in green.*



Plane YZ



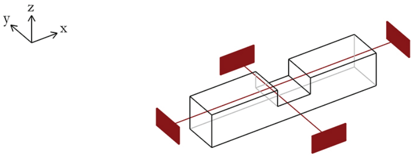
Plane XZ

Figure 11: *The transfer of a bending moment occurs by activating two contact surfaces in the same plane. This results in a double flow of internal forces that must be controlled. For example, in the case of contact surfaces activated in the YZ plane, the single flow of forces develops on the XZ plane. Since the flow of forces is double, they can interact. Consequently, an analysis in the XY plane may be necessary as well.*

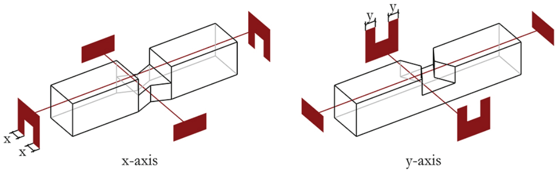
While in the case of single-activated contact surfaces, the development of internal forces develops in one plane, in the case of simultaneous activation of multiple contact surfaces, multiple flows of internal forces can develop. This happens with bending moment transfer, which occurs by activating a minimum of two contact surfaces, as shown in Figure 11. In this case, the interaction between multiple internal force flows, occurring in planes different from that of the single force flow, can cause changes in the strength of a contact surface.

3.3.3 Parametrization

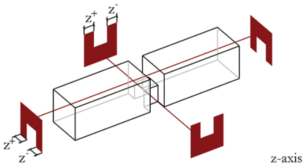
As each connection is subjected to different loads, it is possible to modify the contact surfaces required for load transfer by varying the geometry of the joints. The prototypical half-lap joint connection is customized whenever necessary to adapt its capacity to internal stresses. In the *CantiBox* project, the prototypical half-lap connection is modified via four parameters (i.e. x, y, z^+, and z^-), as shown in Figure 12 and Figure 13. In this case, the increase in the capacity of the connection is achieved through an increase in the contact surface, while the associated strength is assumed unchanged.



Prototypical



Axial forces



Bending forces

Figure 12: *The geometry modification occurs through four parameters. This allows the capacity of the prototypical half-lap connection to be changed by manipulating the size of the contact surface used to transfer the forces. As contact surface is considered the projection of the connection geometry plane perpendicular to the axes in which the acting loads are determined.*

The capacity to transfer axial forces is governed by the parameters x and y for the respective axes. Parameters z^+ and z^- govern the bending moment capacity in the z-axis for positive and negative moments, respectively. The parameters are considered independent, which means, for example, that the parameter x only influences the transfer of axial forces in the x-axis, not the bending moment in the z-axis.

The connection design process is parameterized and integrated into an algorithm that is automatically able, given the forces to be transferred and the strength of the contact surfaces, to define the geometry of the connection. The algorithm defines the geometry by a control polyline governed by the four parameters described earlier. Geometrical changes take five steps up to a maximum value for a single parameter of 10 mm. The limit is set because geometric changes involve a subtractive process that, if uncontrolled, could change the flow of internal forces and, thus, the strength of individual contact surfaces.

The digital interface developed for this project is shown in Figure 14. It allows the plastic redistribution of forces to be monitored and provides valuable information for fabrication. Concerning fabrication, acute angles are avoided. In addition, there is a real-time three-dimensional visualization of the connection generated by the algorithm. The final design showcases bespoke connections according to the different load conditions, as shown in Figure 15.

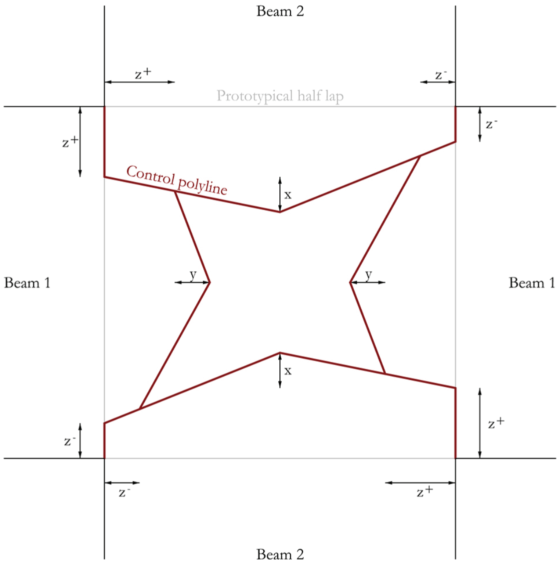
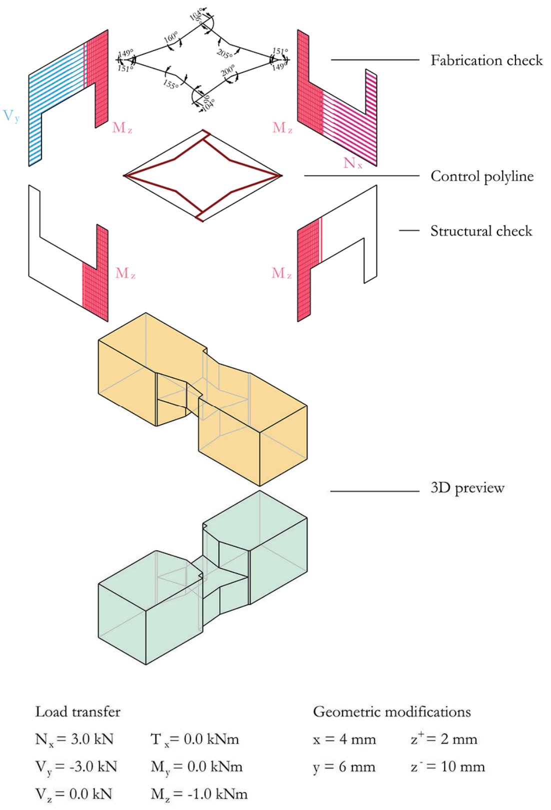


Figure 13: *A polyline defines the three-dimensional geometry of the half-lap connection.*



Load transfer

N_x = 3.0 kN
T_x = 0.0 kNm
V_y = -3.0 kN
M_y = 0.0 kNm
V_z = 0.0 kN
M_z = -1.0 kNm

Geometric modifications

x = 4 mm
z^+ = 2 mm
y = 6 mm
z^- = 10 mm

Figure 14: *The digital interface developed for designing and analyzing the connection integrates geometry, fabrication and structural feedback. The parametric space for customization is carefully designed so joints can be machinable by commonly available automatic joinery machines and assembled by our robotic tools.*

Figure 15: *CNC machines foster the design of bespoke geometry for the connections. All the half-lap connections – prototypical and bespoke - are machined with a Hundegger Robot Drive automatic joinery machine (©GKR 2022).*

3.4 ASSEMBLY

The structure is constructed through a fully automatic process [14], which involves using a set of custom-built, remote-controlled, distributed robotic clamps (Figure 16) and screwdrivers (Figure 17). Each of the three units is constructed spatially in an automatic process (Figure 18) instead of planar sub-assemblies. Robotic clamps are used for joints that do not require fasteners. Robotic screwdrivers, which can be loaded with a left-in fastener, are used for the key elements. Those operate in collaboration with an industrial robotic arm to assemble the timber structure spatially. This assembly method is explicitly developed for half-lap connections and allows for overcoming several problems traditionally experienced in the assembly of interlocking timber-to-timber connections, such as:

- The clamp provides a guide that reduces misalignment problems when inserting a new beam into an existing structure.
- Since the clamps are controlled remotely and each clamp is independent, several clamps can be used simultaneously. This allows the simultaneous insertion of a new beam in multiple connections.
- The clamp introduces a large but localized force, which the robotic arm cannot do. This exceeds the resistance given by friction during insertion, as the connections are tight-fit.

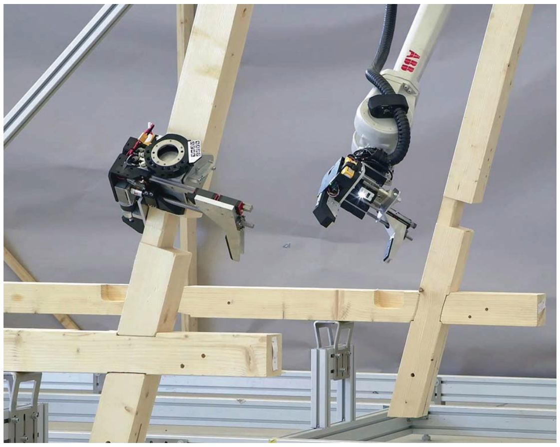


Figure 16: *The robotic arm positions two robotic clamps to insert a new timber element in the structure (©GKR 2022).*

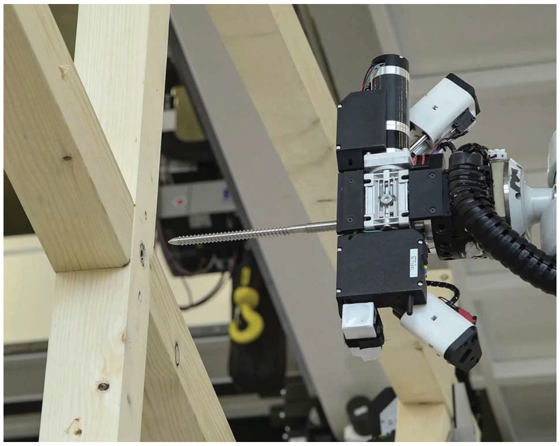


Figure 17: *A key timber element is assembled by a robotic screwdriver loaded with a left-in fastener (©GKR 2022).*

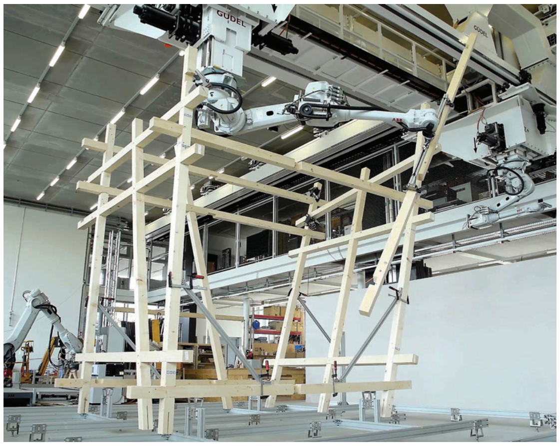


Figure 18: *One of the timber units during construction, with the robotic arm positioning a timber element following the assembly sequence (©GKR 2022).*

The assembly sequence of one face of the box is shown in Figure 19. The interweaving logic of the face allows the use of interlocking timber-to-timber connections during the automatic assembly. Only the last assembled element - the key element - requires a non-structural screw to close the reciprocal system and prevent the system from disassembly.

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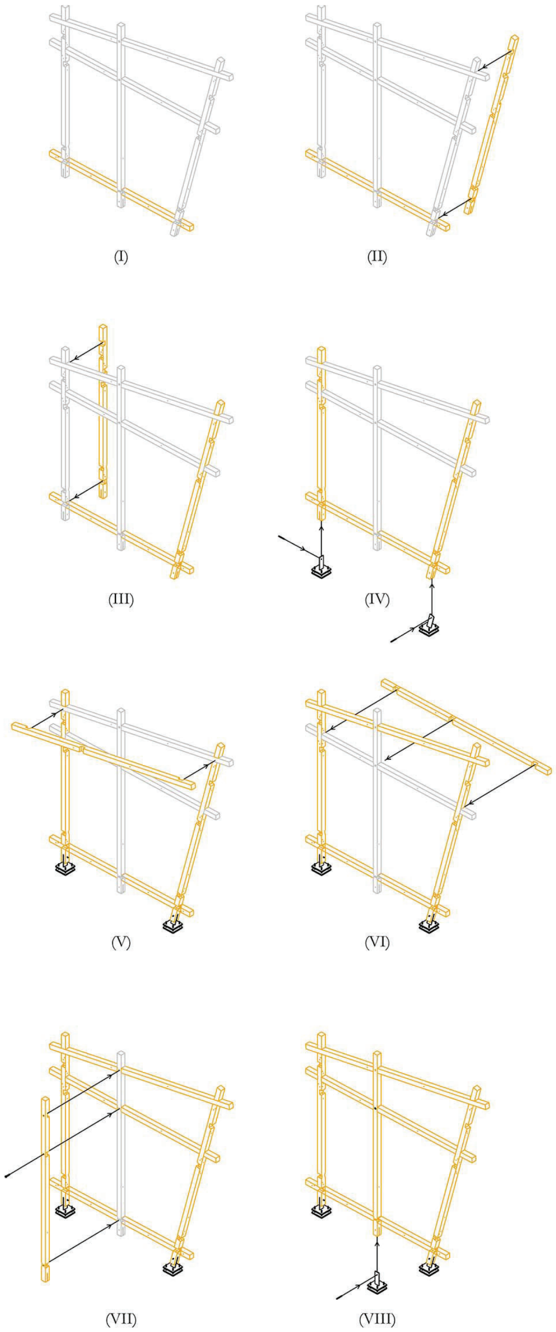

Figure 19: *The interweaving logic used during the assembly allows the number of metal fasteners to be limited to one per face.*

4 CONCLUSIONS

This paper discusses the design and fabrication of the *CantiBox*, a robotically assembled structure composed of linear timber elements and customized interlocking timber-to-timber connections. The project is made possible by the interweaving logic used in its assembly. Special attention is given to the method developed for analyzing and designing the interlocking timber-to-timber connections, which is based on the lower bound theorem of the theory of plasticity. This novel application of limit analysis to timber allows for informing the design and assessing the collapse load. The proposed static method for limit analysis uses stress fields, strut-and-tie models, force diagrams and yield conditions. Furthermore, it facilitates understanding the relationships between geometry and structural performance, thus allowing to customize each connection according to the specific load conditions. The development of a bespoke assembly set-up allows the structure to be automatically assembled in its final three-dimensional configurations.

Figure 20: *The CantiBox is partially covered with translucent fabric to provide shading (©Ali Zigeli 2022).*

Figure 21: *The reciprocal configuration allows high geometric complexity using only simple planar joints (©Ali Zigeli 2022).*

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