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Pre-stressing Timber-Based Plate Tensegrity Structures

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Summary

Tensile structures occur in numerous varieties utilising combinations of tension and compression. Introducing structural plates in the basic tensegrity unit and tensegric assemblies varies the range of feasible topologies and provides the structural system with an integrated surface. The present paper considers the concept of plate tensegrity based on CLT plates (cross-laminated timber). It combines the principles of tensegrity with the principles of plate shells and is characterised by a plate shell stabilised by struts and cables. The paper deals with material aspects and robustness of timber-based plate shells and outlines needs, methods and effects of controlling cable stresses for secured capacity, form and function of plate tensegrity.

Keywords: *plate tensegrity; timber-based plate elements; redundancy; robustness; pre-stressing.*

1. Introduction

A plate based tensegrity structure [1,2] is composed of small plates of various shapes, e.g. triangular, square or hexagonal, which are connected along their edges to form two- and three-dimensional assemblies, see Figure 1, left and middle. Plate tensegrity is based on panels of cross-laminated timber, CLT, and utilises the high strength to weight ratio and workability of these layered timber products. To increase the structural depth, each plate is perforated by a single strut, oriented normal to the plate. The ends of the strut are connected to the corners of the plate by cables. Finally, the ends of the struts are connected by cables to neighbouring struts. The resulting triple-layer structure, to the right in Figure 1, shares many similarities with double-layer grids, especially the cable-strut grids by Wang [3] and triple-layer tensegric strut units by Saitoh [4,5]; Saitoh introduced a central strut in a wire-wheel configuration and uses classification principles based on the arrangements and resisting mechanisms of tension members in a bar frame. The main difference, however, is the middle platelayer, which functions as shear stiffening roof covering. It should be noted that Skelton refers to tensegrity plates, but then as an analogy considering an assembly of strut-based simplexes in a flat configuration [6] and not as an actual case of an integrated structural plate.

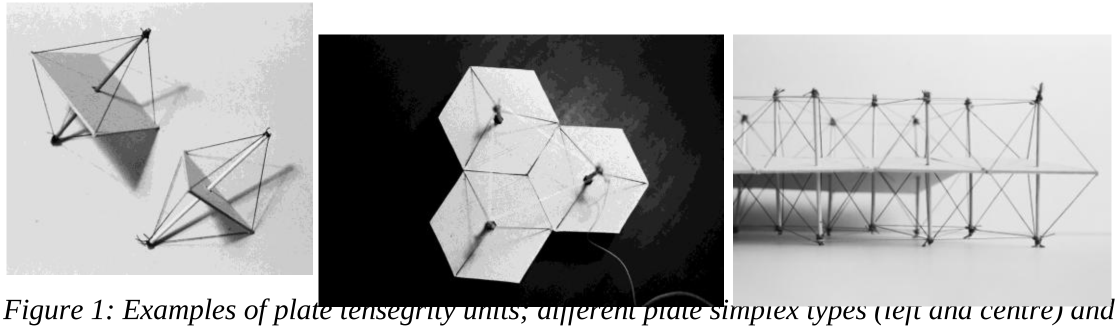

Figure 1: Examples of plate tensegrity units; different plate simplex types (left and centre) and a side view of an assembly showing the middle platelayer inscribed by cable-nets (right).

1.1 Basic typology

Plate tensegrity has so far been proposed for plane and single-curved assemblies. Three topologies have been studied and are briefly described below. The (discrete) single-curved assemblies are facetted due to the planar nature of the basic CLT elements. The tessellation decides the characteristics of different feasible topologies as well as the construction process. In both plane and curved assemblies different element shapes may be combined and the stabilising cable-nets allow for openings in the shell, and thereby elements may be removed in the structure to open it and to create varied light conditions, either with completely open areas, or with CLT elements substituted with non-structural, transparent panels.

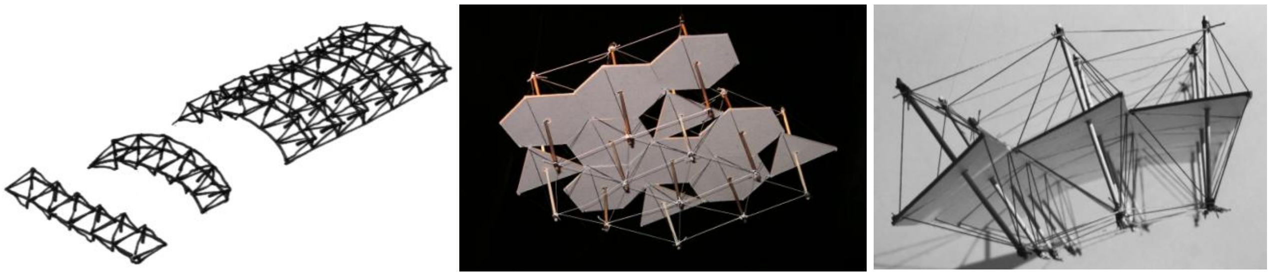

Figure 2: Three basic topologies of plate tensegrity: plan and arch shaped trusses, combinations of element shapes in plane assemblies and curved assemblies through repetition of a single element type.

1.1.1 Topology 1

The initially studied topology is composed of square CLT elements jointed together to form a plane or a single-curved assembly, as described in [2] and shown to the left in Figure 2. The structural assembly can be defined as a truss element, either plane or with an arch form, which can be repeated and combined into a shell when the truss extended in the direction perpendicular to its span. The concept furthermore describes a potential erection procedure, where trusses are assembled one by one, erected and jointed together.

1.1.2 Topology 2

The second topology is composed of triangular and/or hexagonal elements jointed together to form a plane assembly with varied architectural properties, as proposed and modelled in [1] and shown in the middle in Figure 2. The structural assembly can be defined as a plane spatial truss with variable architectural/functional properties, where the tension levels of the two cable-nets are in balance and counteract deformations under load.

1.1.3 Topology 3

The third topology is composed of triangular elements jointed together to form single-curved assemblies, as described in [7] and shown to the right in Figure 2. The uniformity of the elements is mainly an approach to simplifying the structure. The triangular shape is chosen for its geometric potential in 3-dimensional compositions. To reduce the number of cables, every second element in the assembly may be reduced to a simple plane CLT plate without strut. In this way the plate tensegrity assembly forms a spatial truss with in-fills. The in-fills could be structural or as in Typology 2 exchanged with non-structural transparent plate elements.

2. Structural Characteristics of Plate Tensegrity

A plate tensegrity system is built up by a basic unit, which could be referred to as a plate simplex. In previous studies [2] the CLT element in the plate tensegrity module was modelled as a double-diagonally braced truss, with cross-sectional and material properties to give the same in-plane stiffness as an isotropic plate. (This simplification, can be compared with the structural bar frame in the middle layer of the tensegrity unit proposed by Saitoh.) The plate and strut form a compressed core stayed by cables in an arrangement, which on the level of a single simplex could be referred to either a cable stayed strut or as a cable-stayed plate. The plate simplex is in equilibrium when strut and plate are activated as compression members as the cables are connected to fix their relative positions and act as tension members eliminating the internal mechanism. The edges of a plate simplex are constituted by the plate edges and the inscribing cables. The plate simplex is fixed to neighbouring plate simplexes by plate-plate connections transferring compression and shear, and by strut-cable connections to two parallel cable-nets, one cable-net on each side of the platelayer.

2.1 Measures and proportions

The plate tensegrity unit is composed of a plate (e.g. triangular or square) with 2.95 m side l. The plate size is chosen considering the maximum width of currently produced CLT elements (today, elements measuring 2.95 x 16.5 m are produced by one of the leading manufacturers). The plate is perforated by a strut of a certain length L and with a certain ratio of the parts of the strut length above and below the plate, h/H. The global deformations have been shown to decrease when strut-length increases [2] and a reasonable relation could be $1.5l \leq L \leq 2l$. This means a strut length L of 4.4-5.9 m. The plate-strut connection should be moment free. Therefore the joint does not fix the plate, but the joint centres the strut in the perforation of the plate and decreases the buckling length of the strut $L/2$ = 2.2-2.95 m. The relation between l and L has effect on the direction and type of forces in the plate and the strut and regarding the material properties of timber this should be taken into account when defining the final proportions.

2.2 System Action and Damping

By utilising separation of tension and compression, tensegric structures meet the basic requirements of efficient lightweight structures. Through isolation of compression members, which are prone to buckling, the concept utilises the structural efficiency of tension members, which however are prone to deform by elongation before they get fully active in taking loads. Tensegric structures rely on the stresses in the tensioned members to provide stiffness and functional static behaviour under loading and the redundancy in the structural assemblies and the large number of cables and joints have caused problems in the design and functional utilisation of the structural typology.

The introduction of a CLT plate leads to an increased self-weight of the tensegric assembly, but the plate element also provides increased stiffness through activated shell action and thereby the potentially large deformations may be reduced, and considering the effects of the stabilising cable-nets, the finite mechanisms may be further reduced. The remaining infinitesimal mechanisms can be approached by introducing actuators. Applications of actuators in a tensegric structure have been proposed in e.g. [6] to include the control mechanisms in the design and to vary the equilibrium of the structure to parry load-induced deformations, and further treated to define their optimal location in a space truss by e.g. [8,9].

The actuators can be designed to regulate the tension levels either primarily locally or more or less globally in the structure, depending on the continuity/discontinuity of cables and the type of joints fixing the structure. Due to the large number of elements in a plate based tensegrity structure, it will contain several states of self-stress, which may cause problems when the structure is to be pre-stressed, as well as post-stressed for adjustments during its service-life. The stresses in a plate tensegrity assembly can be regarded on two levels (referring to the definitions of joint levels used in [2]), internal and external conditions, referring to the cables of the plate simplex and the cables of the cable-nets respectively.

2.2.1 Internal conditions/level I

In the plate simplex, the cables introduce forces in the strut and the plate. In the case of a triangular plate the plate simplex design comprises three cables. Each cable is connected to the strut ends and between the end joints it is connected with an adjustable cable-plate connection to the plate, allowing for variations of the angle between plate and strut, depending on the topology of the overall geometry. The composition of three cables evenly distributed around the strut ($\beta = 120°$ for triangular plate units, $\beta = 90°$ for square plate units) and inscribing the plate and strut, results in a unit in internal equilibrium, as long as the cable stresses are adjusted properly. The angle between plate and strut is regulated before fixing the cable-plate connection and the cable stresses can be adjusted for an even distribution of the forces.

As the structural assembly has been exposed to loads, and to adapt the structure to different and varying load conditions, the cable stresses may have to be adjusted and varied several times during the service life of the structure.

2.2.2 External conditions/level II

Considering the basic criteria for tensegrity one should note that plate tensegrity works with compression surrounded by tension, but that the compression members of plate tensegrity are not discontinuous. In the plate simplex the strut may be in direct contact with the plate and in an assembly, the plates are jointed together to form a continuous surface. This exception from the original definitions of tensegrity has been made to fully benefit from the plate and shear-plate capacity of the CLT in assemblies. Thus, the middle platelayer can be referred to as a continuous shell structure. The shell is formed by the plate elements linked to each other with plate-plate connections, which transfer shear but not bending. The design and pre-stressing of the cable-nets decide and fix the shape of the shell through cables and indirectly through the struts. The cables interconnecting the struts may be of two types, discontinuous ones, which are tailored to fix a specific shape, and continuous ones, which enable post-stressing of the global assembly.

The strut is exposed to the in-plane forces in the plate through the plate-strut connection. Forces out of the plane, i.e. forces caused by e.g. snow-load and wind-loads on the plate surface, are transferred to the strut through the cables connected to the plate in the periphery of each plate unit. In its assembled state with fixed joints, in-plane forces are transferred in the global structure by shear-plate action and compression or tension forces in the CLT elements and the tension levels in the cable-nets fix and stabilise the shell through the cable-plate connections. This is valid for both an unloaded and a loaded state. In the case of asymmetrical loading and/or locally deforming point loads, forces normal to the plate shell are transferred by the cable-plate connections to the cables and to the cable-strut connections at the strut ends, where tension forces are distributed in the cable-nets on both sides of the shell.

2.2.3 On control of internal cable-stresses of a plate simplex

Actuators may be designed as proposed in [2] where turnbuckles are located to the lower strut ends, allowing adjustment of the cable-stresses by regulating the strut length. The turnbuckle will simultaneously increase or decrease the tension levels in all cables of one plate simplex. Thereby the function of the actuator will also affect the cable-nets; since the strut-plate connection does not fix the strut in its longitudinal direction, the change of strut length will affect both the upper and the lower cable-nets. These actuators are possible to adjust also after construction.

However, there is no closed-form solution for control command computation for control of such an active tensegrity structure. Multi-objective search has to be used to select control commands. In practice, active structures need to remain in service as loads change, i.e. maintaining the surface pitch to accommodate multiple load and control events during service-life. Since the structure may be equipped with several active struts and have several measurement points, several combinations of contractions and elongations of active struts will potentially satisfy the top surface pitch objective to an acceptable degree. This presents an opportunity to select commands using multi-objective search to control the structure while maintaining robustness. In other words, additional objectives are used to avoid limits of safety and serviceability. The following objectives are relevant for changing load conditions:

- Stress: minimise stress-ratio of the most stressed element.
- Stiffness: maximise the stiffness, i.e. balance between ideal geometry and post-stressing levels.

2.2.4 On control of global stresses in the cable nets of a plate tensegrity assembly

By regulating the cable-stresses in the two cable-nets the global shape of a plate tenegrity assembly can be controlled. To simplify construction and tensioning procedures, continuous cables are proposed on the lower side. Cables of the upper cable-net may be discontinuous. In a single-curved assembly with continuous cables in the lower cable-net actuators may be located to the end simplexes or the abutments depending on the local design at the supports. This solution may allow global post-stressing of the structure assuming that the connections between cable-net and struts do not fix the cables permanently but allow adjustments by un-locking the joints, letting the cables run with minimal friction. The control approach can be implemented as described for the plate simplex in 2.2.3.

2.2.5 When cables go slack

Under loading the forces are distributed through the compression and tension members, and due to uneven force distribution and e.g. changes of the structural conditions at the supports some cables will go slack. In previous modelling different approaches have been used, e.g. in [10], where slack cables were omitted or as in [2], where presumed slack strings were assigned a very low modulus in the simulations, rather than omitting them.

Non-compressive conditions due to slack strings/cables affect the stability properties. When cables go slack the load paths are re-arranged and the structure will transform to act under the changed loading conditions. Combining the principles of tensegrity with a plate shell structure results in a structure, which partly relies on plate and shell action, which means a potentially more robust structure than a pure tensegrity. However, robustness is related to scenarios where exposures, including unintentional and unforeseen loads and defects, result in local damage to the structural system, and where this damage may lead to further collapse of the structure. Therefore timber-plate based tensegrity structures have to be carefully designed with respect to the integrity of the CLT plates, joints, cables and the control system.

Regarding load paths reference can be made to one of the tensegric truss systems, “tensegric truss type I”, proposed by Saitoh et al. [5], where the middle layer in the basic unit consists of a frame with four bars. Based on his simulations it is found that when cables go slack, remaining active cables will still take tensile forces, while resistance to bending moment and axial forces is presumably provided by the plate acting in compression and resistance to vertical shear is provided by the strut acting in compression. The plate simplex is very closely related to the basic unit described by Saitoh, but provides higher initial redundancy through the plate and shear plate action of the CLT element, which renders the simplex increased efficiency in transferring the loads directed and re-directed through the plates from cables and strut.

3. Material Issues

The CLT plate is chosen for the beneficial stiffness to weight ratio of timber. However, by choosing a product based on timber boards, an additional complex set of properties must be regarded, which is environment and time dependent. The material strength varies with changing moisture content, and the characteristics of the timber cell structure results in anisotropy on the macro scale. The effects of these phenomena are reduced through the production of CLT but local deformation of joint zones and long-term deformations of elements still need to be considered in the design of details as well as whole systems. Time-dependent effects on timber elements under constant loading due to creep-effects and long-term deformation have direct effect on the need for post-stressing of the structure.

3.1 Properties and effects of timber and CLT

3.1.1 Local effects

In the design of joint solutions for CLT elements the anisotropy of timber has to be considered regarding the choice of fastener type, the loading angle in relation to the fasteners and the relation between fastener and material dimensions. In e.g. joint design for standard use of CLT the grain direction is to be taken as the grain direction of the facing layer of the panel. However, the CLT element in the plate simplex will be provided joints along all edges, thus, the angles between grain direction and edge surface will differ. (In this context the plate-plate and cable-plate connections are of primary importance, since the central plate-strut connection may be designed as a simple perforation without requirements of rigidity.) The layered build-up implies a variation of grain directions across the edge surface of the element and thereby a variation of properties.

Strength and stiffness are considerably lower in the direction perpendicular to grain than parallel to the fibre direction. Loaded at an angle between 0° and 90° the material shows properties somewhere between the values valid for the directions parallel and perpendicular to grain. However, already at a small deviation from 0° the properties decrease drastically. This affects the resistance to local deformation of joint zones. For plate-plate connections a combination of screwed joints and steel plates is reasonable, where loads relatively efficiently are transferred through transformation into compression forces. In the case of screwed joints, the pull-out strength is optimal perpendicular to grain and decrease with decreasing angle, thus, screws are preferably drilled not into the end grain. The plate edges are subjected to in plane compression forces by the cables and adjacent plates, bending moment by the cables and tension and shear by the plate-plate connections. For CLT general guidelines for timber are valid regarding e.g. minimum distance to edge, predrilling, screw depth etc. [11]. Furthermore design of joints and material dimensions in joint zones has to take into consideration the amount of removed material in case joint solutions implying drilling and slotted in steel plates are used.

3.1.2 Global effects

The cross-lamination implies an uneven number of board layers glued together, for structural purposes normally 5S, 7S, 9S... with varying standard total thickness from 60 up to 226 mm. Sawn and planed boards are glued together in altering cross-wise layers to obtain a 2-dimensional form stability. The angle between two adjacent layers ($45° \leq \alpha \leq 90°$) may be tailored to suit specific desired properties. Considering the data displayed in Table 1, the optimal load direction in timber members is parallel to the direction of the fibres. In 1-dimensional structural members there is an evident relation between form and force, whereas the build-up of CLT implies a more complex relation between form and optimal force directions.

Cross-lamination of the boards results in locking of the layers with the effect of reduced anisotropy on the macro level (board and structural element); the co-action between layers, obtained by rigid glued joints, provides the element capacity as plate and shear plate. However, the cross-wise build-up still causes differences in strength depending on the orientation of the plate. This means that the structural behaviour will differ slightly, depending on the orientation of the plate in the assembled plate simplex.

The duration of load has effect on the properties of timber, and especially on the relative bending strength and in a single plate simplex, bending of the plate element will occur.

Table 1: Panel strength of CLT, according to ETA-06/0138, Load applied normal to facing grain, CLT in plate action.

Mechanical strength	**Strength**
Modulus of Elasticity	
– Parallel to the direction of the panel grain $E_{0, mean}$	13 000 MPa
– Normal to the direction of the panel grain $E_{90, mean}$	370 MPa
Shear modulus	
– Parallel to the direction of the panel grain G_{mean}	690 MPa
– Normal to the direction of the panel grain, Roll shear module $G_{R, mean}$	50MPa
Bending strength	
– Parallel to the direction of the panel grain $f_{m, k}$	24 MPa
Tensile strength	
– Normal to the direction of the panel grain $f_{t, 90, k}$	0.12 MPa
Compressive strength	
– Normal to the direction of the panel grain $f_{c, 90, k}$	2.7 MPa
Shear strength	
– Parallel to the direction of the panel grain $f_{v, k}$	2.7 MPa
– Normal to the direction of the panel grain (Roll shear strength) $f_{R, V, k}$	1.5 MPa

4. Discussion and Conclusions

4.1 Discussion

Plate tensegrity as a structural system is currently under development and will need a number of modelling processes to be defined and designed in detail. The plate simplex is defined and will be applied in a number of combinations to develop and test joint solutions and study the global behaviour of different topologies. A hypothetical replacement of an existing CLT based roof structure has already been proposed and will be summed up below. The next step is to compare investigations and design procedures with the reference structure and thereby further inform the design process. To do this, further material and data regarding the applied procedures need to be collected and analysed.

4.1.1 Comparison and project aim

In 2005 the construction of an equestrian hall was finished in Flyinge outside Lund, Sweden. The roof structure was designed with a pitched roof with CLT plates, supported by a trestle and rod structure on its lower side. The span is 42 m and the apex is 8.6 m above the level of the support points. The roof structure has a structural depth of 6.5 m at the middle of the span and is composed of two CLT-elements assembled on site and lifted into place by two cranes.

The hypothetical replacement of the existing roof structure with a plate tensegrity structure has been discussed before [7] and will in the next step of the current study be further concretised. The two structural principles show similarities in the staying structure. In the Flyinge roof, there is a basic unit comprising the on-site assembled roof elements, which like in a plate simplex is supported by a trestle and a set of rods. Two basic elements are connected plate-to-plate at the apex and the trestles of two elements are connected across the span by a rod through trestle-to cable joints. This rod is mainly designed to take the lateral loads from the self-weight of the roof + snow load. The importance of controlling the stresses in the lower cable-net in the plate tensegrity assembly is comparable with the conditions for the rods connecting the trestles in the Flyinge roof.

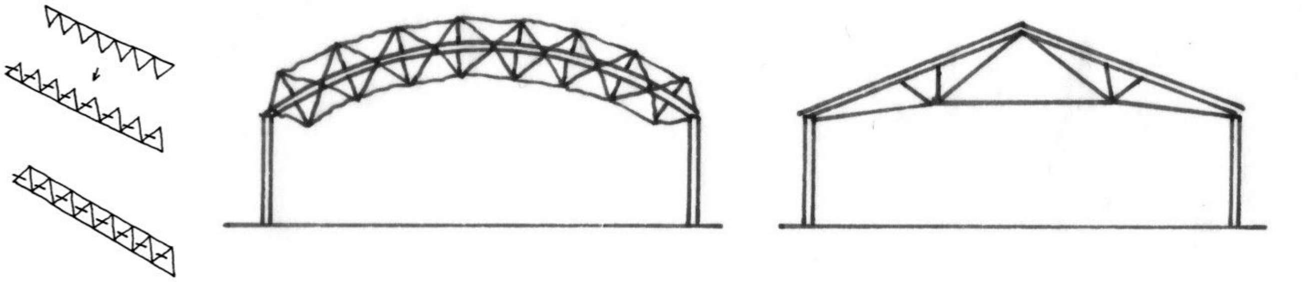

Figure 3: Principle for assembly of triangular plate simplexes (left) and comparison of structural form and architectural space, between plate tensegrity and trestle and rod solution in Flyinge (right).

With a single curved vault based on a basic triangular plate simplex with the edge 2.95 m, arranged according to the construction procedure described in [7] approximately 19 plate elements are needed to cover the span in the Flyinge project. A simplified comparison can be seen in Figure 3). The structural depth of the Flying roof is created by the trestles and rods, which means a less disturbing effect than ordinary roof trusses in timber or steel. The supporting structure is located on a distance from the surface element of the roof, which varies across the span. In comparison, the distance between plates and stabilising struts and cables of a plate tensegrity assembly is constant across the span. Using the values proposed section 2.1, the cable-nets will be fixed at a distance h/H from the plate of L/2 (2.2-2.95 m).

The long-term aim of the project is to consider an application of plate tensegrity on a free-form structure covering e.g. a railway station hall. Further modelling and analyses, and physical model tests and development of joint solutions are currently planned.

4.2 Conclusions

Plate tensegrity is a structural concept, which bears similarities, and also shares a number of problematic characteristics, with regular tensegrity. The varying states of self-stress and adjustment of cable stresses in tensegric assemblies tend to be cumbersome to handle and to analyse. For repetitive and geometric regular structures, the pre-stressing scheme is often straightforward, but for free-form structures it becomes problematic. The plate element of plate tensegrity introduces plate and shell action in the basic simplex, which does not reduce the structural complexity, but tends to reduce the deflections and results in increased robustness. The proposed timber-based plate introduces material issues, which have effect on the structural performance, detail design and the need of maintenance, above all the post-stressing during the service-life of the structure. The CLT plates are today in conventional use in construction of e.g. bridge decks and residential blocks, and general solutions and guidelines are applicable in most aspects. Still, the analyses of load paths and pre-stressing schemes are in need of developed procedures. The problem issues regarding stress-levels and analysis may be approached by introducing actuators and by applying analyses comprising multi-objective procedures to handle an increased number of factors and a range of loading and stress scenarios.

The project, which the currently presented study is part of, aims for an extensive study on structural and architectural performance of timber-based plate tensegrity structures. The potential benefits from the integrated plate element and beneficial material properties of timber encourage further development of the concept. The structural concept has not yet been tested in full scale and the range of potential topologies should be further explored.

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