EXPLORATION AND OPTIMIZATION OF COMBINED TIMBER PLATE AND BRANCHING COLUMN SYSTEMS USING EVOLUTIONARY COMPUTATION

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ABSTRACT

In contemporary architectural design new and experimental forms are constantly searched for and in the interaction between structural and architectural design a readable structural function adding to the architectural experience can be of interest. Cross-laminated timber plate elements show a high stiffness to weight ratio, and provide a wide range of possible structural applications. They have been analysed in structural systems for multi-storey residential buildings and in tensegric assemblies forming plane roof surfaces and single curved structures [1,2] based on a reduced number of element shapes. The application in faceted structures is possible by combining plate elements with linear edge joints or nodal joints, where the relation between wish for complexity in overall shape and desired production rationality and assembling simplicity decide the geometric character. The current work takes a plane roof structure with square elements as a point of departure for development of 3-dimensional plate structures and a study of interplay and result of combinations with branching column structures.

By modifying square elements into rhombuses and combining them four together simple pyramid roof units and repetitive structures with rigid behaviour are easily obtainable. By varying the rhomboid proportions different pitches of the roof unit are obtained. By regarding physical modelling the effects of development from 2-dimensional to 3-dimensional units are studied concerning assembly stiffness and preconditions for interplay with supporting column structures. Branching column structures [3] can support the plates either at the centre of plates, which then cantilever, or at inter-plate nodes. Optimizing studies are applied on plate assembly geometry and design of supporting column structures.

Using Evolutionary Computation (EC) methods [4], geometric relationships between the shells and branching columns are optimized for least weight. Parameters of shell geometry and the related branching column geometry and topology are explored. Examples of systems with good performance under load are shown and compared in terms of efficiency and stiffness.

INTRODUCTION

The currently described project studies combined action between a faceted plate assembly and a branching column support system. Cross-laminated timber, often referred to as massive timber, is a refined timber based product with relatively high stiffness to weight ratio (Figure 1). The currently available production lines in Europe provide cross-laminated elements of up to 2.95 m in width and up to 16 m in length; for larger elements finger jointing can be used.

Figure 1. Cross-laminated timber plate elements pre-cut for on site assembly.

To keep production simple and costs and complexity of element design low it is regarded interesting in the context of this paper to define as small a number of general elements as possible to be assembled in a repetitive layout. Focus has been set at a simplified layout with one single element type building up a faceted basic unit, which can be combined into a folded or faceted structural assembly.

A basic issue regarded in the current context of plates concerns their potential as structural surface elements, providing both function and stability in structural systems and a tight building envelope. Earlier studies of tensegric structures with struts/posts and cables have shown that the introduction of a covering membrane often increases complexity in modelling and analysing of load sharing. The issue of enclosing systems has also been addressed regarding blob structures, where technology and means to produce the skin affects the structural layout [5]. Cross-laminated timber elements can be easily precut and adapted for different designs (so far double-curved plate elements are not feasible) and give a wide range of possible applications. The plate elements offer potential in geometric elaborations and combinations. The element type has so far been rather little used in structures with large spans and there is a noted need and interest on the European market to widen the perspective on the element type and its structural and architectural typologies.

In its geometrical appearance and principles for structural assembly the plate structures discussed here are related to polyhedron packing and hereto related space frames [6]. By tailoring the element design the structural layout and the architectural utility and impact can be varied and adjusted to different needs. This has been utilized in the current project to study the structural and architectural result of plate-based 3-dimensional structural systems for large spans co-acting with branching column supports.

ELEMENT AND ASSEMBLY DESIGN

Characteristics of Elements and Units

The structural assembly of timber plate elements utilizes the stiffness gained from I) basic material properties, II) the tailored build up of the layered plates and III) 3D-characteristics given by folding or faceting of the surface, creating a structural depth of the assembly and a vertical bending stiffness.

I: The basic material properties of timber are generated by the natural growth of trees, developing a fibre-structure with often very good tensile strength to be able to withstand the shaking of the branches and leaves when the wind blows and to compensate in the trunk for gravitational effects in sloping terrains.

II: In the build up of the cross-laminated timber plates, sawn and planed boards are glued together in altering cross-wise layers to obtain a 2-dimensional stability by locking the fibres in different directions in a plane. On industrial basis a series of layered products are currently produced, with uneven numbers of layers – 3S, 5S, 7S… with varying standard thickness from 60 up to 226 mm. The angle between the layers is normally 90°, but 45° appears in use, and other angles are fully possible if necessary to suit specific desired element properties.

III: Through folding, the surface elements are loaded not only perpendicular to the surface but also in plane, and the utilization of shear-plate action increases. By folding or faceting the surface of the assembly, by applying angles on the elements deviating from the orthogonal grid, the corresponding lattice structure in analogy with structural plate-lattice dualism [7] will form a 3-dimensional space truss with increasing structural depth.

The currently studied pattern is based on a square plate element measuring 2.95 x 2.95 m. When such elements are combined four together (into a 2x2 unit) edge to edge the assembly is flat and stiffness out of the plane relies at large solely on the joint stiffness. The sides of the basic flat assembly measure 5.9 m; the maximum area covered by one element is 8.7 m^2 and by an assembled 2x2 unit 34.8 m^2

In a 3-dimensional assembly the angles between the plates decide the area covered by each unit. If supported at the centre of each plate the distance between nodal supports is in the flat state 2.95 m, and as the pitch increases, the distance becomes something less than 2.95 m. By increasing the pitch the cantilevering from centre-plate nodes loose in structural and architectural use since the inter-node distances decrease and shear-plate action increases whereas plate action decreases. It becomes more interesting and rational to increase the utilization of shear-plate action by using inter-plate nodes.

For reasons of rationality and to decrease the number of supporting elements it is regarded interesting to assemble 2x2 units to be supported at their four corners. If supported at the corners of the 2x2 units the intermediate distance between support nodes is 5.9 m in a flat state, and again less than 5.9 m with a pitch. By utilising branching columns the number of supports reaching the ground may be reduced, and the distance between these increased, thereby increasing the structural scale and enabling wider areas free for flexible use.

Structural Plate Assembly

A slight modification of the basic element results in rhombic elements, as seen in Figure 2 from a = 90° (left) to b = 85° (middle), and when equal rhombuses are combined four together the resulting composition/unit shows a pitch and a geometric stiffness. By varying the rhombic character of the basic element (Figure 3, above, showing element angles: a = 90°, b = 89°, c = 85° and d = 83°), the pitch of the unit and thereby the structural depth of the assembly can be altered (Figure 3, below, showing the resulting pitch angles: I = 0°, II = 5°, III = 15°, IV = 23°), while the plan, i.e. the horizontal projection shows an orthogonal grid with stepwise decreasing distance between the grid lines.

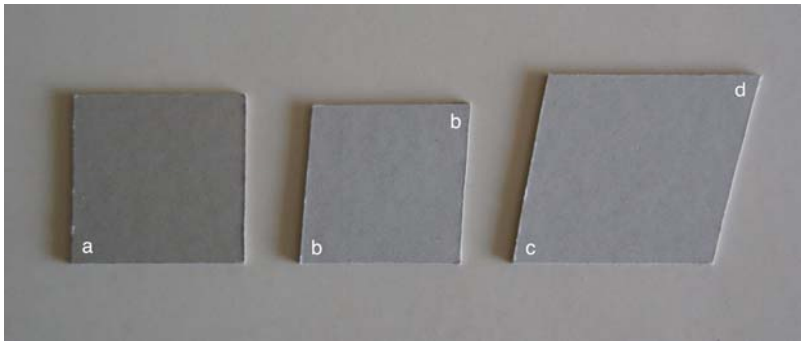

Figure 2. Varied element geometries regarded in model studies.

Thus, a number of different element angles were tested and evaluated considering the relation between the structural depth/utilization of shear-plate action and the area covered by one unit. From cardboard model studies an element angle of 85° was chosen for further model studies of plate assemblies. Rhombuses provide in such an assembled unit zigzagging edge lines on the vertical plane interfaces. As the peak angles become more acute, the pitch becomes steeper, and the structural depth increases. These geometric features relate to the assembly stiffness, which is helpful when designing the joint details. Utilizing symmetrical elements the interface angles are perpendicular to the base plane resulting in a plane assembly. If one of the pointed angles of the rhombic elements is changed, the interface angles of the units will deviate from 90° and the resulting assembly will be curved.

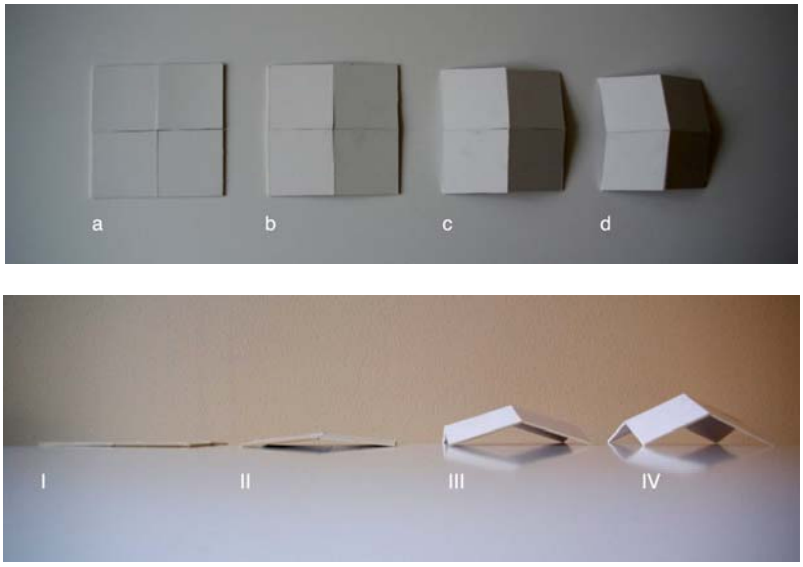

Figure 3. Transformation from flat to pitched unit assembly.

The pitch transfers loads from self-weight and seasonal snow-load to the support points of the unit at the joint nodes (Figure 4). The structural composition of the faceted plate assembly and the branching column support system shows a dual system where the plate elements form the primary horizontal load carrying system and secondary beams are redundant; the assembly is supported directly by the column structure with nodal joint connections.

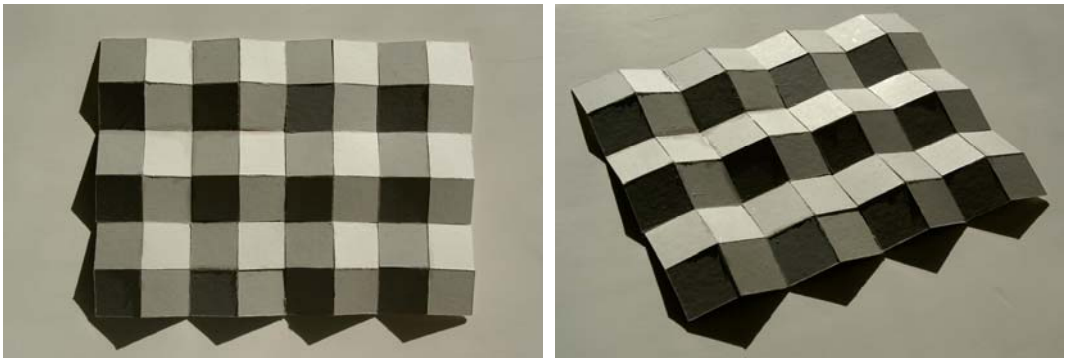

Figure 4. Cardboard model of a rhombic based plate assembly, in plan and in perspective.

A related method to define the geometrical basic unit is to study the folding patterns described by Miura in the early 1970's. With a trapezoid element (Figure 2, right) where two sides are parallel and two sides diverging a related folding pattern appears, which can be applied as design key to a folded roof assembly. Originally conceived for swift folding of maps and other paper products, this pattern follows a grid, which allows in plane unfolding in two directions without deformation of joints or joint zones. The pattern produced through the folding shows a single element shape, mirrored and repeated over the surface. To produce a plate model a sheet of stiff paper was folded according to the Miura-Ori principle (Figure 5). Then the folding marks were used as a pattern for cutting the model plates of cardboard. A basic trapezoid element as seen in Figure 2 (right), with angles of c = 80° and d = 75°, was used. The generated model plates were then glued together (Figure 6).

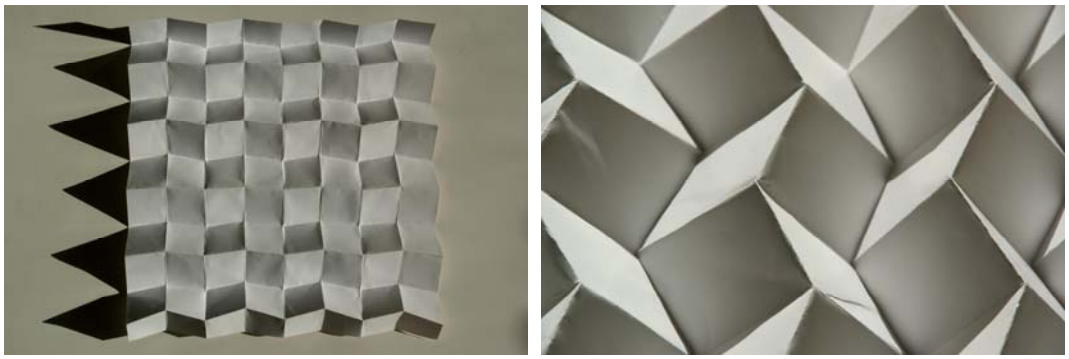

Figure 5. Miura folding of paper in plan and in detail.

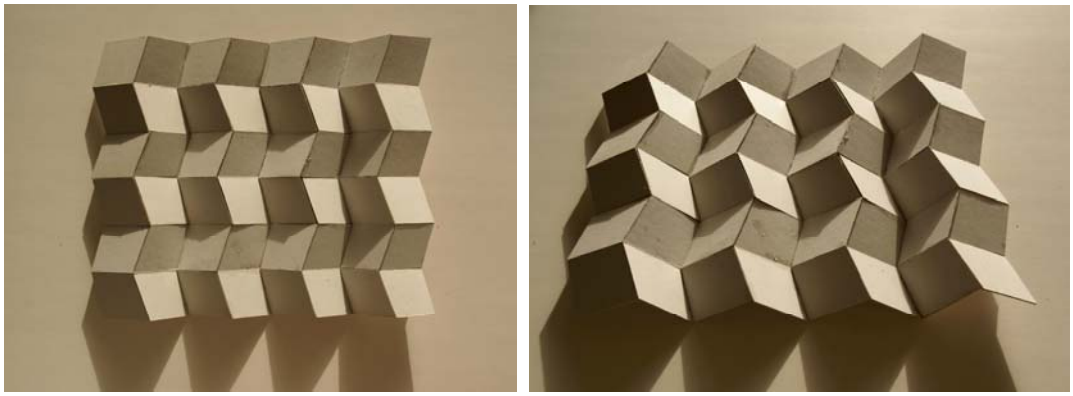

Figure 6. Cardboard model of a Miura-Ori based assembly design, in plan and in perspective.

In the family of origami folding there are numerous variations showing different geometries and spatial characteristics. The Miura version of origami was considered for the element design in the present structural study. The first aimed at assembly case is a non-curved one, used for structural and architectural analyses and the planar extension of Miura-Ori suits this aim. The Miura element geometry allows, however, varying angles between adjacent elements, thus no geometric stiffness is gained in the assembly. This property is a reason why it is so suitable for easily deployable map sheets. For structural uses this feature raises other and higher demands concerning inter-plate joints, fixing to the supporting structure, or an additional secondary structure, locking the assembly.

A small-scale reference object of interest here was constructed for the Chelsea Flower Show in 2002 [8], with design by engineer Jane Wernick and architect Sarah Wigglesworth. The ambition was to design a small pavilion to demonstrate water recycling and conservation practice, and it resulted in an accordion folded roof supported by tree-shaped column structures, with three branches each, on an irregular grid. The design work was carried out as a close cooperation between architect and engineer under prerequisites demanding production of a proposal far in advance and then a very short time of usage after construction, all with a very limited budget. This directed the choices of materials as well as technical solutions.

The pavilion roof covers an area of 5 x 3.5 m. Its shape and profile were developed through folding of paper, and the final materials chosen were altering glass panes and plywood elements. Through the material combination fixation of the glass panes could be rationally solved without additional ties and tension wires to handle forces from wind uplift. The plates of plywood and glass were in a number of locations deliberately designed to overlap each other, thereby handling tolerances at intricate plate intersections. The supporting structure consists of three branching tree-structures of steel plates, which carry a primary horizontal steel lattice system, which fix at the valleys of the roof, thereby locking the overall folding of the system. The lattice structure was needed to transfer the loads from the roof to the columns since the valleys of the roof did not coincide with the positions of the ends of the branches. The steel columns were welded together into a triangular cross-section for the trunk and with T-sections for the branches. The lattice structure was reduced to three intersecting triangles.

Brief Theoretical Structural-Architectural Analysis

The square elements provide plane conventional structural and architectural solutions where altering of the primary support system creates the architectural, visual impact of the structural design. The plates are primarily loaded perpendicular to plane and plate action is utilized for vertical loads and shear-plate action is utilized in stabilising against lateral forces. Either joint solutions need to be moment rigid or a primary support system is required to fix the shape of the plate assembly.

Rhombuses assembled four together edge to edge provide a 3-dimensional unit with geometrical stiffness and moment capacity. The resulting pitch of the 2x2 pyramid units changes the load path conditions for the plates. The plates are utilized as shear-plates and an additional horizontal load-bearing structure becomes redundant.

With trapezoid shapes like in the Miura-Ori, the plates need either joints with moment capacity or a supporting primary load-bearing structure to keep the overall shape. The structural pattern and its visual appearance is more intricate than the one obtained with rhombic plates, but 2x2 units can still be defined and the branching structures can still be affixed at nodes coinciding with the corner nodes of each such unit.

In the current structural study, simplicity of structure and stability is aimed at by utilizing the geometrical properties of the assembly. The regular pyramids, which in their assembled state form a 3-dimensional shell structure acting as a stiff plate-based space truss, were chosen for further studies.

Joint design

The timber material is easily cut and adjusted, and the plates offer a variety of possible joint solutions. In studies performed in Aachen [9] a number of joint types have been tested on plate structures based on Laminated Veneer Lumber (LVL). Joint types that have been tested were based on mitred edges glued and screwed together, edges glued and screwed to a steel tube, edges jointed with dowels and washers, and stiff joints with bent steel plates. The wish for simpler on site assembling methods resulted in tests of plate structures with foldable textile joints. The LVL was produced with a glued in middle textile layer, acting as a bendable joint when slots were routed through the LVL. The textile then provides force capacity in shear and tension, whereas the timber acts in compression. The method was tested for a number of different structural elements and shapes, beams and dome segments [10].

In the Chelsea pavilion referred to above the project context required prefabrication, rational assembly on site and swift dismantling. To obtain out of plane stiffness and in plane shear stiffness the joints in the stabilising lattice structure needed to be rigid. Steel profiles for fixing the glass were screwed into wedged timber fillets along the plywood edges. The alteration of glass and plywood in the folding enabled surfaces for fixing the glass and sealing the joints in the valleys.

Prototypes of origami assemblies have been studied in a project on timber structures at IBOIS (Ecole Polytechnique Fédérale de Lausanne), [11]. The basic elements in this project were produced as trapezoids with angles of 20° and 40°. Pinned and rigid joints were considered without satisfying results. Focus was put on the development of elastic joint solutions and a number of connections based on self-tapping screws were tested for jointing the cross-laminated plate elements: single and double rows of screws as well as slotted in steel plates. The joints were shown to be the weak point in the prototype at proof loading. The small distance between the screws and the edge resulted in joint failure.

The plate edges are easily cut in angles suitable for fitting the geometry. To obtain satisfying joint properties, however, the current structural context requires thorough studies. Between the plate elements, in-plane shear joints are easily obtained, and there are several versions already in use on the market [12]. Joint solutions, which also provide bending stiffness in the connection between plates, demand more attention. When the angles between the elements provide structural stiffness the joints in the faceted structure do not need moment capacity since the overall form is fixed. They do not have to be movable during construction, nor do they have to be structurally flexible in the service state, but they need to allow movements in response to internal forces caused by the timber's moisture related variations in dimensions. The joints in the faceted plate structure can be of a relatively simple design with lap joints along the roof ridges, transferring the shear forces with screw joints. As discussed in an earlier example in the context of plate tensegrity [1], the edge zones also require joint solutions, which provide water tightness. In the plate tensegrity assemblies, it was proposed to cover the joint zones with rubber sheets. The joints between the plate structure and the column structure at the corner points of the plate units, as well as the joints at the column bases, are designed as nodal pinned joints. Steel branching columns of this type often have cast joints, which join the branches. This simplifies welding and cutting of pipe, and with sufficient repetition can be an economic solution.

COLUMN SUPPORT DESIGN

Evolution of the Column Support Design

Figure 7. Thread model photos of the assembly and its column structure.

In combination with cardboard models of the faceted plate structure a number of thread models have been produced and studied. The materials used for these thread models are synthetic fibre thread, and steel washers and miniature lead wire-locks as adjustable nodes kept in place by friction. The plate units provide four base points for nodal supports. Assembled over an orthogonal grid layout, a 4-branched column structure supporting every second unit provides supports at each base point (Figure 7). In this way the support points are equally distributed on the lower side of the roof, and a minimal number of branches in the uppermost branching level is needed. In the thread model, two, three and four node/branching levels were investigated.

Evolutionary Computation Methods

The thread models shown in Figure 7 were chosen for further development using computational analysis. First the geometry was further investigated using an optimization program developed by the second author [13], which uses a Genetic Algorithm (GA) to explore a range of good performing solutions. The program used a 3D truss element (pinned connections) and sized the members as hollow steel pipe sections based on the AISC – ASD steel code (9th edition). Parameters of both total weight and total length of members were calculated for each tree structure. Figure 8 shows a selection of results from the program.

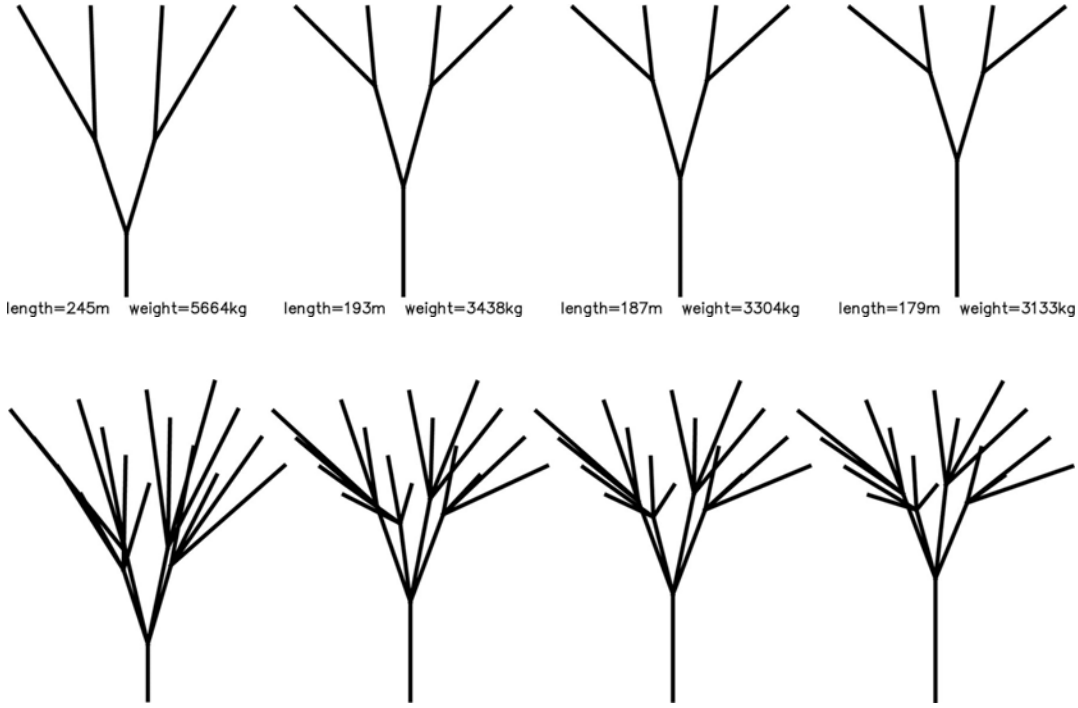

Figure 8. A selection of 4 geometries found by the GA based program.

Because the program only contained a truss element with pinned joints, the structure had to be fixed at the top and loaded from below to maintain stability. This is of course an inaccuracy compared with the actual loading from above, but it was considered to give better results than introducing triangulating members, which would be the other alternative. Also, only one loading was investigated, 1.0 kN/m^2 (20 psf), plus the weight of cross-laminated timber plates and steel. The timber plates were taken as 146 mm thick, which is a span/thickness ratio of about 1/20.

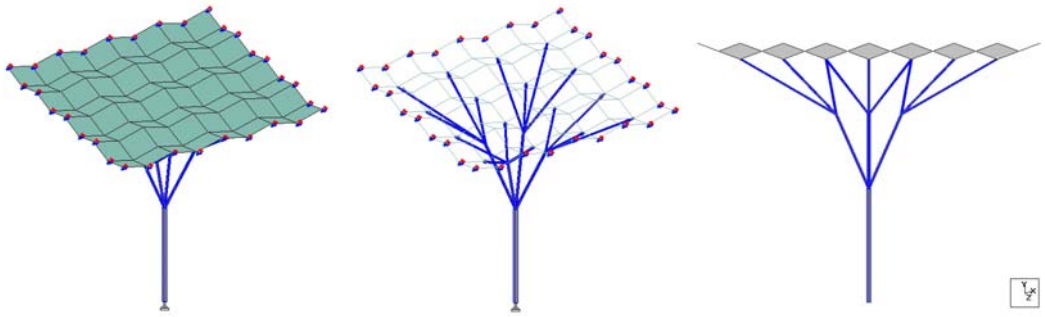

Figure 9. Isometric and elevation of STAAD FEA model. Branching column is to scale

Figure 9 shows the combined plate and tree structure, which was analyzed using STAAD-Pro, a commercial FEA software package. For this analysis, the branching column on the far right in Figure 8 was combined with the folded plate geometry shown in Figure 4. The plates were supported in the horizontal direction (vertical roller planes) on the 4 outer edges to model an interior column condition.

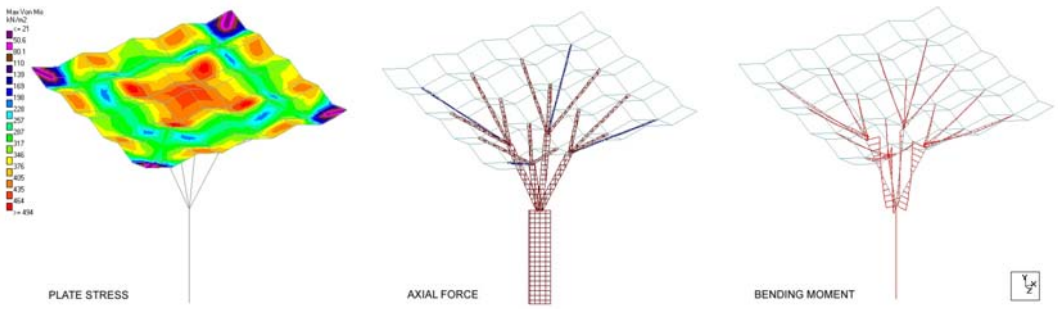

Figure 10. Force distribution in the plates and branching column for interior condition.

Figure 10 shows the distribution of forces in the model. The combined (top and bottom) maximum von Mises plate stress is show on the left with a peak value of 494 kN/m^2. The axial force is shown in the center with values of 998 kN on the base column, 267 kN on the middle branches and between 130 and 50 kN on the top branches. Pipe sizes used ranged from 32 cm square tubing at the base, to 27 cm pipe for the middle branches and 22 cm pipe for the top branches. The total weight of one branching column comes to 4872 kg (10740 lbs). The end moment in the middle branches reaches a peak of 9.6 kN-m (7.1 ft-kips). The maximum deflection of 15 mm (0.59 in) occurs at the outer corners of the plate structure.

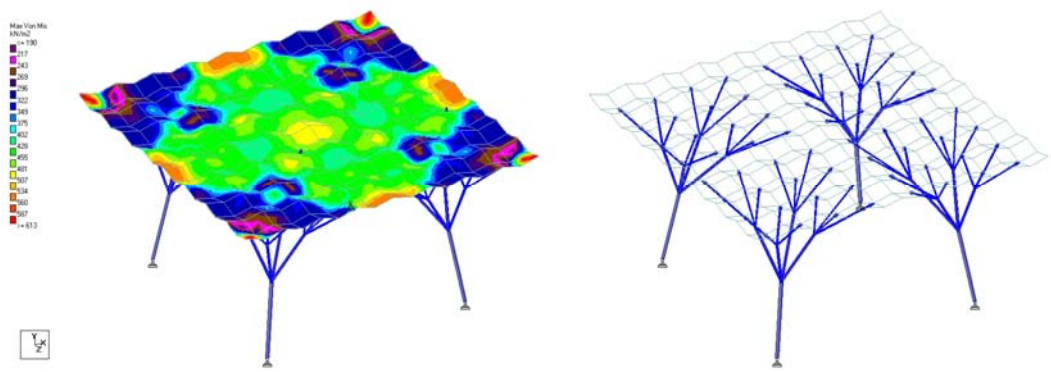

Figure 11. Plate stress and member sizes and geometry of the corner condition.

Exterior column conditions were also modeled. The column geometry changes in response to the free edge conditions at the exterior edges. Figure 11 shows the corner condition. Axial force in the column is slightly higher in this case due to the side thrust. Deflections are also about 4 times higher using members sized for forces. The total weight of one column is 5820 kg (12800 lbs). The leaning columns, as apposed to vertical design shown in Figure 10, reduced the deflection in the free corner area.

ARCHITECTURAL AND STRUCTURAL FEATURES

Impact and Utility of Structural Form

The structure is composed of a plate based roof and a branching column system providing a building envelope with large unobstructed spaces. The structure has been studied through a number of analyses regarding structural, utility-related and architectural performance and impact, aiming at a structurally efficient solution with architectural flexibility.

The visual experience of a large roof surface is often vague, depending on a number of factors. The surface may lack in concrete scale, caused by the surface itself not being load carrying,

eventually visually subordinated to the rhythm described by a visible load carrying structural system. Rhythm and scale can be experienced from primary and secondary beams and or trusses and from column supports. The visibility and readability of the load carrying system has bearing on the sense of safety in a building. A building where the load paths are detectable, explains in itself how and why it works, which can be satisfying and enriching for an observer and user. If utilised and elaborated in the architectural design it can also in a rational and economical way provide to the overall design concept.

In a flat 2-dimensional assembly the structure will show in-plane shear stiffness through joint connections, either nodal or linear, but leave stiffness out of the plane to the support system. A transformation into a 3-dimensional assembly provides stiffness out of the plane, and a more efficient load transfer to supports. The rhombus based pyramid unit is a geometrically regular structural solution, which makes the structural scale and function readable, and describes a structural simplicity. The Miura Ori based unit is basically as simple in its structural approach to shear-plate action as the pyramid system, but describes a more complex structural result with more varied angles and a somewhat more complex repetition. Already in plan a more complex tessellation is noticed in the Miura folding (Figure 5, left), compared to the pattern of assembled pyramids (Figure 4) where the spatial character is obvious only viewed at angle. The Miura folding describes the scale in the same way, but not as simplistically. Furthermore, it requires, as already mentioned, additional means to fix and stabilise the system.

Wide unobstructed areas could be obtained by using straight columns without branching and enable an increase of their intermediate distances by increasing the rigidity of the plate assembly. However, the structural design work regards the dual system as a whole aiming at an optimized relation between measures, detailing and structural performance of supports and plate assembly. The branching columns provide a large number of support points changing and simplifying the requirements put on the capacity of the plate units. Further analyses with asymmetric load cases would be required to fully design the columns and plate thickness.

The geometry of the faceted surface requires that water be lead away from each valley. At each base point between the pyramids a drainage pipe is needed. The upper surface of the roof needs weather protection. Covering the upper surface with asphalted paper and eventually sheet metal cladding solves this issue. The weathering protection can be fixed on the separate elements before delivery to the site or on the assembled basic units on site.

CONCLUSIONS

In the work described in this paper the relation between structural complexity and production/assembling rationality has been of interest. Element shapes may be varied in numerous ways, and two shapes, a basic rhombus and a trapezoid were chosen for and tested in 3-dimensional assemblies with branching column supports in model studies. The rhombic elements have so far shown potentially simpler characteristics considering production, construction and structural function, and are proposed for the structural assembly where geometrical stiffness is obtained without additional locking beams or lattice systems. The joints between plate assembly and branching columns can be defined and located directly at nodes on the plates at base points on the structural units.

Through the 3-dimensional unit design the utilization of the shear-plate capacity of cross-laminated timber-based plates can be increased compared to the force conditions in plane assemblies. Plane assembly solutions with centre-plate nodes can be of interest to develop cantilevering structures. With pitched plate units it becomes more interesting, however, considering structural and architectural functional utility, to regard edge nodes/inter-plate nodes instead of centre-plate nodes. The geometrical/topographical features of the unit can then be utilized to a wider extent.

The studies hereby presented have considered plane plate assemblies and relatively few branching topologies. By changing the angles of the rhombuses in the periphery of the 2x2 units curved structures should be feasible. This potential is not further looked into here but needs further studies. Other topologies such as a higher number of branching node levels are certainly feasible.

The geometry exploration using the Genetic Algorithm program was limited to 3D truss (pinned) elements. Better load and structure modelling would be possible using a ridged frame type element in the analysis. This might ultimately introduce other geometry or topology options.

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