Form Exploration of Folded Plate Timber Structures based on Performance Criteria

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Summary

This paper presents an explorative study on applications of cross-laminated timber (CLT) elements in shell structures. Previous studies of plate tensegrity, folded plate roofs interacting with stabilising steel-based systems and studies inspired by origami show a widening range of possibilities to develop timber-based shells. Steadily rising interest in rationality during pre-fabrication, transport and on-site construction in contemporary industrialised production increases the competitiveness of CLT-based elements and systems and the architectural applications are getting more common and more experimental. Folded plate structures which are the focus of this paper present several issues of structural importance – potential mechanisms, subdivision of surfaces etc. – and the hereby presented study aims at exploring developed typologies, using computer tools for developed optimisation procedures with interaction from the designer.

Keywords: folded shells; plate structures; cross-laminated timber; genetic algorithm; geometry optimization.

1. Introduction

Timber-based plate elements are commonly applied in orthogonal building systems, and have during recent years also appeared in novel structures inspired by origami. Timber as a structural material presupposes a certain member thickness and the folds of paper-based origami need to be translated into facets or folding patterns with suitable properties. Results from previously performed studies on folded plate roofs point at potentials of folded shells regarding structural behaviour and variety of spatial and architectural form [1,2]. Timber is an easily workable material and the elements show a high strength to weight ratio, which makes them rational and efficient in prefabricated lightweight structures and building skins [3,4].

Load-paths, patterns of folds, structural and architectural behaviour, and production constraints concerning elements and assembling methods are issues of current interest. This paper presents a study on a variety of elements, folds and folding patterns for a range of curved timber shell roofs without additional support structures where the timber elements provide both load-bearing structure and envelope. The developed topologies are explored through modelling and analyses of production, structural and architectural criteria, using a tool, which combines parametric form generation with GA guided performance design. The design tool, ParaGen, also allows for human interaction in the selection of parent solutions used by the GA for breeding children solutions. The tool is intended to expose the range of solutions both in form and performance to the designer, and thus provide a tie between performance criteria and other design considerations.

2. Shells as Structural Surfaces

2.1 Translation of Morphological Principles

Fig. 1: A bar/node system in a 14 m^2 foldable mock-up by Ture Wester, presented at the SMG 2, the 2nd Structural Morphology Group colloquium, in Stuttgart 1994.

Lightweight structures are often designed for adaptable functions and foldable applications. As with paper-based folding patterns like the Miura-Ori this implies the presence of mechanisms. Combinations of bar and node systems and light surface elements are used for quick and efficient transport and deployability, and there are several examples of conceptual studies of structures of a relatively temporary character (*Fig. 1*). A locking function may be obtained by fixing the base points to the foundation and/or locking the hinges, which provide the deployability. Structural surfaces of CLT or other rigid 2-dimensional elements normally increase the self-weight of the structure but also increase its robustness, which depending on the aimed use might be beneficial. A phenomenon which has dawned simultaneously with the development of CLT is the interest in free-form architecture with more or less autonomous building skins, a trend which is intimately linked to the development of parameterising design methods and tools providing NURBS surfaces [5] where the use of splines in the digital design procedures enables an infinite range of curved forms with varying continuity.

It is necessary to define the area of application when sorting and making use of the inspiring input, since different aspects of interest are defined in widely varying fields, where input and understanding iterate between paper folding, engineered structures and naturally appearing surfaces such as self-unfurling leaves and stress patterns in compressed elastic membranes [6]. Paper folding is a source of inspiration of current interest and especially the translation of the folds from paper to a structural material like timber. The folds are easily obtained in paper due to small material thickness. The material may be bent and folded without breaking, and when folding a piece of paper without cutting it, joints are redundant. In the structural scale, paper-based products may be utilised, but the structural function requires a considerable material thickness compared to paper. Paper may still be used but then in a refined state gaining structural properties, not only in cardboard tube gridshells by e.g. Shigeru Ban for the World Expo in Hannover, but also in plate-structures, e.g. the Monsanto Geospace Dome, a plate-based structure constructed with foam core board of approximately 13 mm thickness, manufactured in the 1960's [7].

Focusing on surface elements for structural applications, material thickness and stabilising geometry are key factors. The stabilising effect may be obtained by either 1) assembling flat elements into stable 3-dimensional modules to be further combined producing a rigid structure or 2) developing a folding pattern for the overall structural surface which renders it a locked, rigid nature.

2.2 Building Skins

Building skins need to fill sealing purposes to work as climate shields; structures forming the envelope need to shed water and to provide insulating properties. Deviations from this are frequently made in contemporary architecture (*Fig. 2*) and non-structural façades transfer the requirements of a sealing function to the inner (actual) skin. In some of these cases the façade design incorporates self-supporting structural elements, like in the French pavilion for Shanghai World Expo, in other cases the façade elements providing the main expression are mere cladding fixed on a hidden structure, e.g. the rattan façade of the Spanish pavilion. This design approach results in an increased complexity since climate issues and energy consumption are- of increasing importance for environmental and resource management. Every design step has a cost and therefore it needs a well-defined purpose. In some cases the architectural gesture and/or symbolic impact is of primary value – it depends on the choice of the prioritised aspect(s) during the optimisation procedure [5,8]. In other cases the interplay between architectural function and expression and structural efficiency must direct the design, and a building skin which manages aesthetic, sealing, stabilising and load carrying purposes through synergies between the architecture and its structural system is better suited to do this in a rational and economic way.

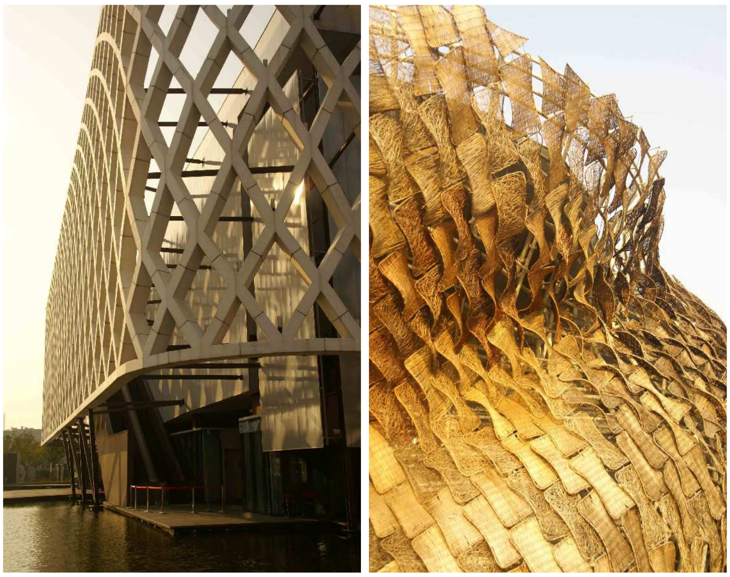

Fig. 2: Façades designed as envelopes with reduced climatic function: the French (left) and the Spanish (right) pavilions at the Shanghai World Expo 2010.

2.3 Design of Structural Skins

CLT panels can be produced as plane elements or as single-curved elements with a relatively large radius. When building parts designed with curved or compound global forms are to be constructed, it is more rational from a material and production point of view to work with facetted or folded assemblies combining standard or tailored elements. Exploration of regular and uniform elements has been carried out in previous papers and was extended in [5]. To develop the study, this paper explores a widened range of tailored cutting patterns for more varied folded geometries (*Fig. 3*). Structural skins may be designed for free-standing, self-supporting applications oriented horizontally, such as facetted roofs like in Figure 3, or as vertically oriented elements mounted on a building's superstructure to work as façade. In both cases structural and climatic functions are combined and the applied cutting pattern and angles of folds will decide the structural depth as well as the structural efficiency of load paths, geometry based rigidity and production rationality.

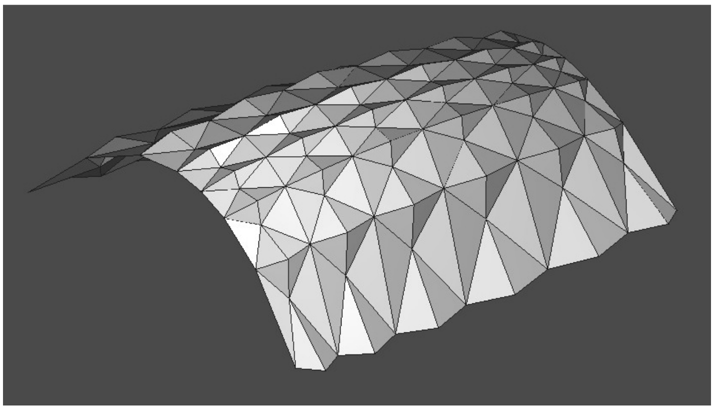

Fig. 3: Example of a folded CLT-based geometry.

Several authors have explored buckling behaviours in the design of folding patterns e.g. Tarnai in [9] and several mathematical efforts have been made to investigate and develop principles for tessellations, e.g. by Roger Penrose and later described in e.g. [10,11]. To evaluate their structural potential, the principles originating from mathematical points of departure need additional efforts, thus applications for structural use need further studies beyond the virtual morphology. The rigidity and strength of the shell is a result of the global geometry, the element dimensions constrained by production, material properties (this paper utilises standard values for CLT) and the efficiency of the load-paths. The load-paths in a facetted shell are dependent on the overall facetted/discrete curvature (global scale) and the on angles between the plate surfaces and the properties of the element edges (local scale).

3. Timber-Based Plate Shells

The basic material is CLT elements with a defined thickness of 107 mm, which defines the material properties and the edge conditions for joint design and load-transfer. The contemporary production lines offer many possibilities to tailor the CLT elements with CNC machines and the prefabricated elements may also be swiftly adjusted with hand tools on site. Even though timber is not an isotropic material the accuracy of element dimensions in CLT is high, which renders the material competitive when compared to e.g. concrete, especially of course when concrete is cast in situ, but also steel, since timber is more easily adjusted in states of post-fabrication. The logistics and means of transport steer to a large extent the design and prefabrication possibilities, and also have effect on potential interface design. The edge conditions need to stand transport and handling and may – depending on their intricacy – need to get their final shape on site.

In contemporary construction practice a number of different joint types are used, such as glued in rods, self-tapping screws, nailed connections, slotted in steel plates and dowels, depending on the load case. In a folded shell the design of the load paths defines the required properties of joint types and thereby directs the choice of jointing technique. The geometry may eliminate the potential mechanism in the folds/facets, and thereby the need for moment stiffness in the joints, while the joint still needs to manage varying compression and tension forces, depending on the load case.

If the joint may be left visible on the surface of the folded shell, angled steel plates fixed with nails or screws can be applied. Joints based on steel plates fixed on the surface or in slots, provide continuous joints increasing the in-plane shear stiffness between the elements, which increases the robustness of the assembly. Stepped joints would be another method, which however requires transformation of the element shapes and on the local scale increases the complexity of their tessellation.

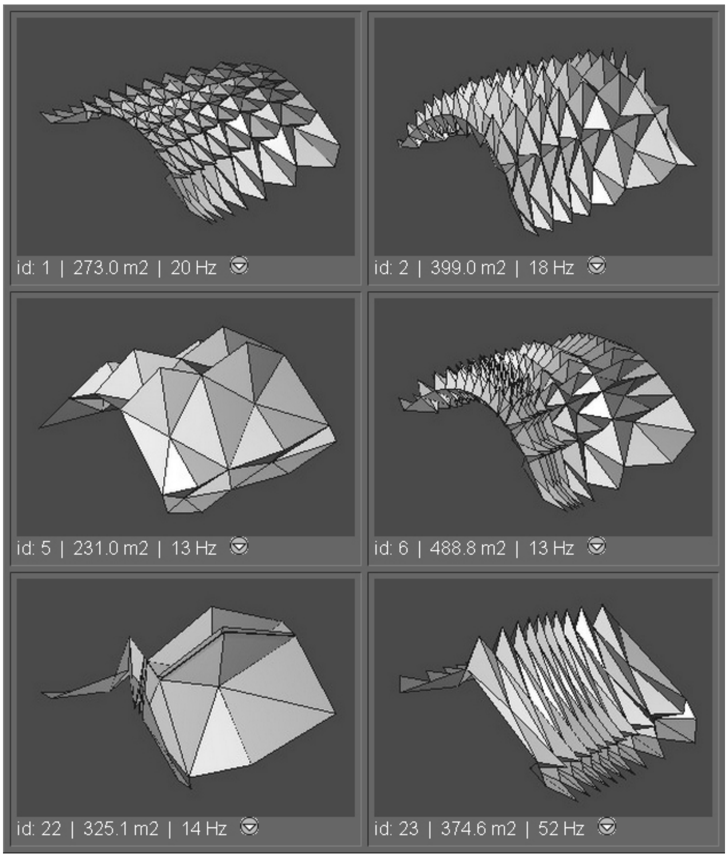

Fig. 4: Sample geometries from the initial random population.

3.1 Developed Topologies

This study is based on material and element properties typical to CLT panels using spruce lumber. The topology exploration was made using ParaGen, a design tool developed at the University of Michigan, which combines parametric geometry software with analysis software and a search procedure using a genetic algorithm. In this case the parametric software used was Generative Components by Bentley Systems, and the analysis was made using STAAD.Pro also from Bentley Systems. ParaGen runs on a web server, and uses a web page to display the discovered solutions. The interface allows users to further explore the solutions using a myriad of sorts and filters. Full performance information as well as images and even animations of modal behaviour are stored for each solution and can be instantly retrieved through a SQL database. In this way a designer can browse through the database graphically to explore and compare possible solutions. Details of ParaGen have been published in previous papers [12, 13].

For this trial the parametric model was based on a known folded plate geometry used in vaulted structures. Examples of the system can be found in Heino Engel's book *Structure Systems* [14]. A wide degree of variation was allowed while maintaining the basic barrel vault form. Figure 4 shows a small sample of the range of variation. The parametric model (developed by Colin Richardson at the University of Michigan) contains 12 variables, which control the depth of folds, the numbers or density of plates in both transverse and longitudinal directions, the height of the arch as well as non-uniformity factors.

3.2 Design Criteria

In a complex system such as a folded plate vault there are numerous criteria, both structural and architectural, that need to be considered in the complete design. In this example a structural analysis was performed which looked at aspects of the whole system rather than details. This at least relates more directly to the exploration of the global shell geometry. In terms of structural performance a modal analysis was performed and the first modal frequency was recorded as a gage of overall system stiffness. Also, maximum deflection under selfweight was recorded. Geometric data such as the overall surface area, the number of plates and the number of joints was also recorded. In addition to the quantitative values, much qualitative information can also be gathered from the images of the different solutions. Using the web interface it is easy to scan down the array of solutions or search for specific performance characteristics using the sorts and filters available.

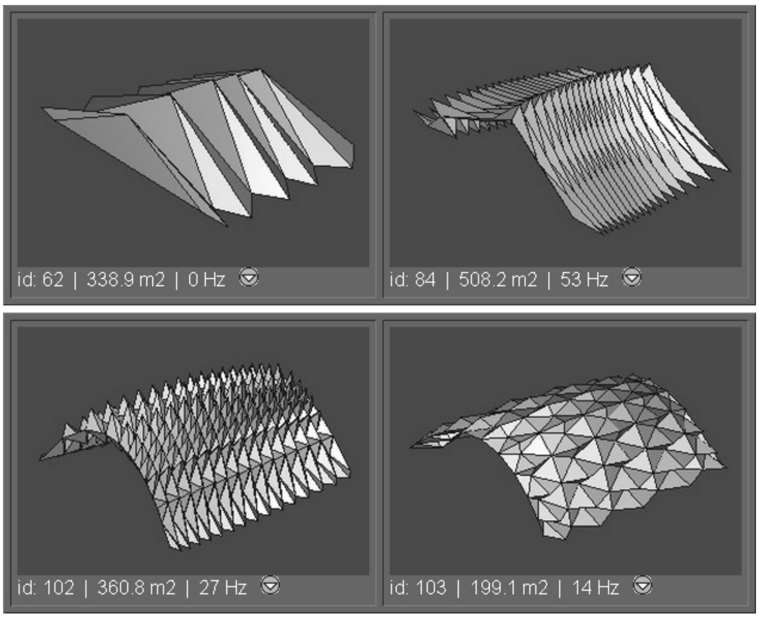

Fig. 5: Initial emergent patterns.
Top: low triangle type. Bottom: uniform arch type.

In addition there are other areas which the designer may also want consider closely:

- Evaluation of the tessellation of the surface/sub-division of the shell is of interest when considering available means for production and mounting, utilisation of the material when cutting the elements from a raw panel. The element properties depend on their shape in relation to orientation of the board layers that build up the panel cross-section.

- Evaluation of the global geometry of the structural system and the external properties of the building skin is of interest when analysing the structural behaviour and the interaction with outdoor climate, especially regarding e.g. adaptive skins regulating the influence of solar radiation.
- Evaluation of the enclosed space or covered area is of architectural and functional interest. Spatial geometry as well as size, arrangement and orientation of internal surfaces have effect on architectural function, air flow, energy consumption and material effects on the enclosed climate.

4. Analysis

The ParaGen process starts with the generation of solutions based on sets of randomly generated values, which are fed into the parametric modeller. Initially, 50 solutions were generated in this way, and they covered a wide sampling of form and performance. With this initial population the program then uses a genetic algorithm to breed pairs of solutions based on given criteria as a fitness function. In this example the modal frequency was used to search for solutions with stiffer geometry. In breeding two solutions, a new solution is produced in the form of a set of values for the input variables. The input variables are then entered into the parametric modelling software to generate the geometry.

After the program generates a range of good performing solutions the designer can sort them from best to worst, and see which geometric configurations perform best. In this case two general patterns were observed: one, which collapsed into a low triangle and the other that formed a more uniform arch (*Fig. 5*). The low triangle forms were judged as undesirable for functional reasons (poor interior space). In this way, the procedure allows simultaneous evaluation of architectural and climatic performance, based on the designer's experience of material properties and geometric forms. To steer the search away from the low triangles a height limit was added to the fitness function. Later in the run, another trend was visible in the solutions: some were very spiky while others were more uniform in depth (*Fig. 6*). Again a filter was added to the fitness function to refine the search criteria and the result yielded what was judged to be more acceptable solutions (*Fig. 7*).

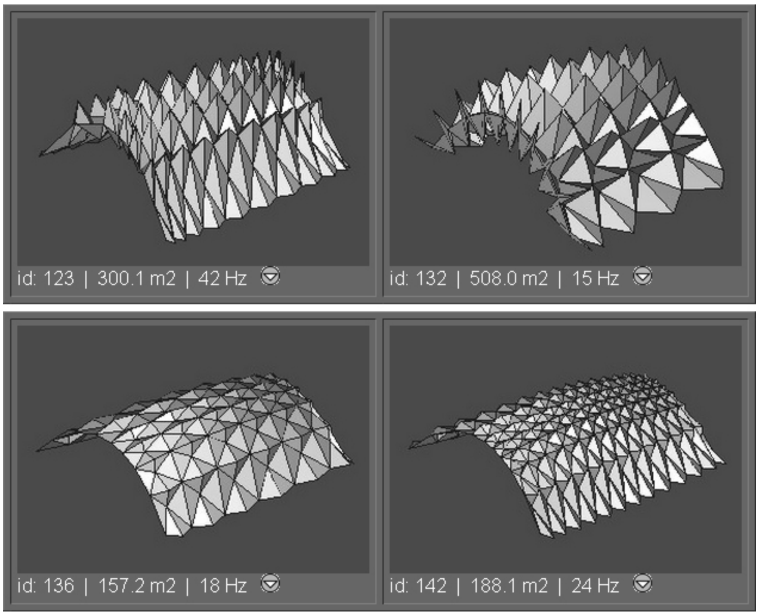

Fig. 6: Top: spiky arch type. Bottom: smoother arch type.

5. Discussion and Conclusions

It can be seen that the ParaGen method does aid the designer in finding good solutions. In Figure 7 it can be seen that several solutions were found that are satisfy the criteria and with high modal frequencies.

5.1 Discussion

When designing, analysing and evaluating architectural structures there are a considerable number of aspects and factors of importance for the result of the process. Timber as a structural material adds further design criteria, among them the anisotropy and properties often referred to as "soft" and which are difficult to assign exact values. The procedures applied in the current study are useful in this perspective, and support development in two areas; the nature and characteristics of timber based plate shells and designer aided computerized design processes.

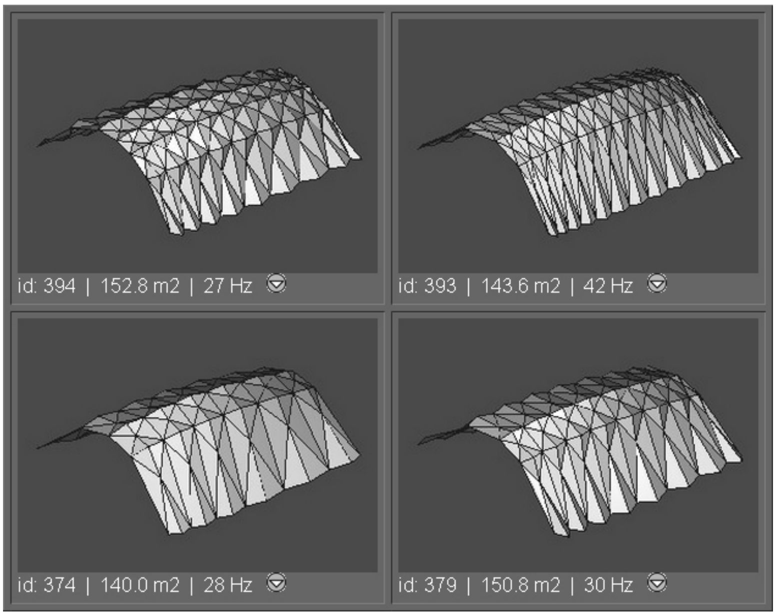

Fig. 7: Top: spiky arch type. Bottom: smoother arch type.

The main advantage of the ParaGen method is that it works both visually and interactively with the designer. Unfortunately, within the limits of the graphic format for this paper it is difficult to display how this works. The designer is initially presented with a page that contains many rows of solutions that can be scrolled through. As the number of solutions becomes cumbersomely large, they can be sorted and filtered by any of the input variables or performance output. In addition, as the designer learns more about the design space, the initial concept for the fitness function may shift or be supplemented to focus the results. In the example presented here, this was done by adding area and height limits to the original criteria of modal frequency. The effect can be seen in Figures 6 and 7 to produce more focused results. This in effect is similar to traditional design exploration procedures: 1) Some sort of brain storming produces a pallet of options. 2) In exploring the options the designer better understands the design space and may refine the design criteria. 3) Subsequently more options are generated and so on. In a design problem that involves physical forms (such as architecture) it is important for the designer to be able to see and deliberate over the options in order to better understand the problem. This is an advantage with ParaGen.

5.2 Conclusions

In the design and analysis process architectural/utility criteria are, as previously shown, easily included when opening a phase in the conceptual design stage where a holistic perspective may be applied. ParaGen allows introduction and managing of aspects related to production, material properties and structural behaviour on a global as well as a local scale, which enables the designer to evaluate and steer the process while elaborating the outcome in an iterative procedure. In the study, issues like e.g. joint detailing have not been specifically studied, but the procedure allows for steering of e.g. joint preconditions by defining number of plates and nodes and elaborating the tessellations and through the breeding process extracting and refining the needed characteristics. The architectural utilisation of the structural performance of CLT in folded structures can hereby be further developed. It can be seen that the ParaGen program was successful in discovering better solutions and helping the designer to explore a range of possible solutions. In later cycles, many viable solutions were produced with modal frequencies in excess of 30 Hz. The range of solutions was seen as useful in helping to expose patterns or types that also have associated performance characteristics. In this way the ParaGen tool was useful as a tool to aid the designer in the early phases of design exploration, in this case specifically folded timber-based plate shells, whose properties are shown to be developable and well suited for applications as structural envelopes.

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