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Folded plate assemblies with branching column supports – interaction and control of overall shape

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Abstract

The work described in this paper aims at developing the interrelation and overall effects of interaction between a folded plate roof structure and a system of branching column supports. In the context of architectural performance it is of interest to discuss the effects of the material on environmental conditions. The current study is complementary to a project on environmental and architectural performance of a free-form roof and will discuss modelling, environmental performance and material related issues such as material properties considering thermal and moisture buffering effects on the resulting architectural context. The currently presented paper aims at initiating a further developed study of system action in a broad architectural sense, sub-system interaction and material-specific considerations.

Keywords: plate shells, interaction, modelling, control, performance analysis, material properties

1 Introduction

In this paper the design process of modular structures based on folded plates is discussed by focusing on the interrelations among geometry, performance and material properties. In this context, the use of digital tools is discussed as a support to input into the design process information on the material behaviour as a driver in the decision making process. Analogous intentions lead a large amount of current research and innovative design processes, which aim at guiding the design based on the knowledge of material properties and behaviour as a means of the design. This demonstrated great potentials, often combined with integrated production techniques. However, when focusing on the early phases of the design process, choices about materials to be used are often still an issue that needs to be left open. The work described here tries to engage the design with the material properties without compromising this need. Specifically, it focuses on timber plates by integrating their properties into the design process while still allowing for comparison and combinations with alternative materials.
A large background of previous studies introduces the timber plates by focusing on a bottom up design approach, starting from the material properties and deriving geometrical configurations of large assembled shapes. This first set of studies has been supported by optimization techniques based on genetic algorithms. Such approach gave a solid basis for enlarging the applications toward a top down approach allowing larger

variability of the overall shapes. A second set of preliminary studies approached this aspect by using the same optimization techniques, but with the integration of parametric modelling. As a third step, the current work aims at introducing knowledge on timber plates' properties and behaviour as an integral part of an on-going project for a large roof, herein called SolSt. Besides integrating studies on material properties with geometrical, tectonic and environmental aspects, the challenge consists also in evaluating performances for design solutions based on alternative materials as well as different materials combined with timber. The successful combination of parametric modelling and genetic algorithm is currently used also in the on-going third part of the work.

2 Timber as a construction material

For the 1994 Olympics in Lillehammer and Hamar, Norway, a number of ice-skating halls were constructed where 3D-trusses in timber were used, see for example Figure 1. The design is a development in scale and technology of ordinary glulam beam trusses and frames. Timber is used for the structural system only and not in the envelope. The structural design is more or less based on conventional linear structural elements in combination and even though the spans are impressive the amount of timber is in relation to the enclosed space fairly small.

Fig. 1: Vikingaskipet ice-skating rink, Lillehammer, Norway

Shells based on CLT implies a much increased area and mass of timber exposed in the structure and to the indoor air. Examples of these structures have been presented in [1]. The increase of exposed area and mass in the structure increases the importance to regard the material specific properties and their environmental related effects. An example of origami inspired architecture constructed in CLT can be seen in Figure 4. The span in this small temporary chapel in Switzerland is of course much smaller than the ones in Lillehammer and Hamar, but the development of CLT-based shell structures show that spans steadily increase and so does the sizes of constructed spaces. In the Swiss chapel and similar objects timber is utilised as both load-bearing structure and envelope, which is also the case in the currently studied roof.

Fig. 4: Origami structure in CLT as temporary chapel in St. Loup, Switzerland

In the first Swedish CLT-based medium-rise housing block, finished in Stockholm, Sweden, in 2001, it has been noted that the moisture content of the prefabricated CLT elements is of importance, not primarily for the structural capacity and stability – which is granted – but for the behaviour of the exposed timber surfaces, which are prone to cracking caused by the drying while evening out the moisture content in the timber and the level of humidity in the indoor air. Cracks appeared in the surface layer of elements when the boards had been dried to moisture content higher than the aimed context.

3 Combination of tools, materials and systems

Previous studies have comprised system action in timber based folded plate structures with branching columns. Evolutionary computation (EC) has been utilized to develop branching patterns and parametric modelling has been introduced in a second phase in order to control complex geometries. The combination of tools enables rational handling of a complex set of aspects and issues of interest and, as was shown in the latter case, simplifies design analysis and control of complex forms. This section briefly presents both the investigated structural systems and the use that has been made of the digital tools.

3.1 Background of the study

Previous studies [2,3] have been focused on three-dimensional geometries in relation to two-dimensional patterns as means to obtain rigidity and have described variations in the branching pattern of the supports and variations of interface angles of the basic plate units respectively resulting in plane plate assemblies in the first case and curved assemblies in the second one. Issues of interest have been the relationship between elements and units, interrelations between shell and support, and resulting geometry and topology of the assembly. In the studies combinations of tools have been utilised; in the first case analogue thread models and EC and in the second case EC and a parametric modelling software. Specifically, the origin of the first study is an attempt to develop the application of cross-laminated timber plate elements (CLT) in shell structures, combined with an exploration of interaction with branching column supports and EC has been utilized to develop branching patterns using Genetic Algorithms (GA). The origin of the second study partly presented in [4], is a project on combining digital modelling tools to increase the capacity to handle complex architectural and structural forms. This combination contributes in managing a suitable number of variables that may be changed and the resulting structural form can be analyzed. In both cases finite element analysis has been applied on the digital models.

The approach is similar in the two studies, however with different points of origin. In the first case complexity of overall form is dealt with through predefinition of measures and proportions of the basic unit in the plate-based shell. The resulting geometric assembly proceeds from the design of the fixed basic unit. In the second case a free-form structure is developed using variable parameters. The structural analysis includes plates and thereby combines the previous modelling and analysis efforts, is still under development.

Results from these studies point at an interesting potential in varying the stiffness in the plate assemblies by varying structural depth and branching patterns and combining cables and bars in the supporting structure. In the context of plates, it is as well of interest to discuss modifications and combinations with bar and node systems to create variation in the system regarding structural behaviour and architectural utilization. These aspects will be focused in a later phase of the ongoing study. By studying the interdependence of the two subsystems the overall design can be optimized for structural efficiency and architectural utility.

As structural components CLT-plates provide rigid structural plate elements and an increase of mass compared to traditional timber-based building systems, as will be discussed below. The increased mass has effect on climatic control and cycling of thermal and moisture-related response and function as building envelope. By varying material and thereby element properties in the building envelope the enclosed climate and architectural space can be designed to fulfil the expected needs of the end-user. Modelling and designing of these behaviours and effects are of major interest in the early stages of the design process, treated for example in [5], when materials and systems are to be defined, chosen and prescribed.

3.2 Current study

The current part study of the project is exploring interrelations of material properties and enclosed environmental conditions. In context geometry is a key factor, not only for the aimed at space-related utility/function/perception for the end-user, but also for the material-related performance of the building, since geometry affects air-flows in the enclosed volume and thereby ventilation, the exposure of roof areas to direct sunlight, the flow of light and heat through the building and the climatic interplay between indoor air and roof and wall surfaces. Parametric modelling tools have been used as in [4] in combination with GAs, by means of a tool called ParaGen.

4 Integrated performance analyses

To enable optimisation in the construction process, while regarding a wide range of aspects that might occasionally present conflicting interests, it is gainful to integrate the analysis of several types of performance already in the early, conceptual design phases. Utilising the above-mentioned EC tools gives more capability to the designer or design team by providing a pre-defined number of reasonably good solutions. The parameterisation proposed in [4] and described in the ParaGen method makes it feasible to oversee design complexity by using EC techniques to search many solutions using a limited number of variables and calculated performance indices. To work in interdisciplinary groups currently gains interest and the integration of complementary skills in project groups and platforms for a tightly linked interactive design process results in an increased interest in and need of tools and methods that manage analyses of several factors in one procedure. The integration of complementary tools and an increased number of analyses in the conceptual phase also changes the design work from a more or less linear process to a cyclic one which supports iterative approaches managing an increased complex of needs.

The primary interactive activities in early conceptual design stages are normally those between architect and structural engineer. The difference in phases, precision of tools and balance of input at different stages of the initial part of the design process is discussed in [6]. The interplay between the players in a project might get slowed down by a mismatch of the tools utilised by the different professions. Initially in the design process there is often a primary need for qualitative understanding of the structure and quantitative analyses get too laborious and tend to deliver results of too high a precision.

To deliver the accurate response to the design issue in this context, tools based on generalising analysis of types of structural action, interpolation of curves and optimisation of NURBS frames using control points, are used.

Adding on for example environmental analyses in the early phase and initial modelling is, despite the increase of work needed, of increasing importance. The nature of the very model is defining the basis and prerequisites for the potential output and furthermore the communicative abilities to inform the discussion and development work in the design team. More factors in the analysis process lead to more complex and laborious modelling procedures and the factors chosen to scope needs to be defined with care early in the process. Selection and definition of optimisation factors decide the representation characteristics of the model and steer the output of the primary modelling, thus both degree of abstraction and precision of output and tend to fix the initial design features, which have to be managed later on. A balance is needed.

Architectural performance refer here to a large set of performances most of which have soft boundaries and belong to the domain of ill-defined problems. These include for example the satisfaction of functional requirements, aesthetic intentions, relations with the context, expressive ambitions and others. The early phases of the design confront very strongly these aspects, which have substantial power during the design conception. The work here presented does not directly face and analyze architectural performances; however these are taken into account. Specifically, they are approached in the structure of the used tools, by specific mean of the way ParaGen aims at combining both programmed objectives along with subjective selections made by the designer. Due to it, the tool uses a strongly visually oriented approach that helps the designer in exploring a range of good solutions based on numerically expressed by the performance criteria as well as making preferential selections in ill-defined problems. In this way, the program can take into account for example the visual appearance of the solutions, based on designer preference or different analysis.
Structural analyses have in previous studies been applied with results from similar modelling procedures where GA and analogue modelling have provided material for structural evaluations of the structural/architectural form. A common thread has been throughout to combine structural characteristics and modes of action and to handle combined interactive structural performance while step-by-step introducing them into the design sequence.
The scope of environmental issues can easily overwhelm the designer with complexity. The modelling tools constantly developed further but informing and making use of the designer's procedures to evaluate and creatively interact with the digital design loop is regarded by the authors as crucial for properly judging the hypothetical as well as resulting design proposals in a holistic way.

5 Design and control of form

In the design of surfaces sub-division has been applied in different ways. While previous studies included a building block approach in which the overall form proceeds from the design of fixed basic units as means to obtain rigidity, a second approach is investigated with inverse procedure. In order to allow its higher three-dimensional variability, the overall geometry is freely modelled based on a NURBS surface, and subsequently subdivided into modules. The NURBS surface is modelled based on control points with variable position. The modelling process makes use of Generative Components (Bentley Systems), allowing parameterizing the shape by means of independent parameters that regulate the geometrical outputs. Specifically, Cartesian coordinates of the control points are used as numerical independent inputs. The tessellation of such a variable NURBS surface is based on a distribution of points lying on the surface and used as nodes to define a set of polygons. The pattern of the tessellation can be of variable or fixed density. A pattern based on a fixed number of hexagons has been chosen for the current structural analysis. The hexagons generated in this way are taken as a geometrical base-layer for the configurations of the panels as well as for modelling the branching columns. Specifically, the panels are configured in three-dimensional assemblies using the polygon as a base; and the columns are branched with variable proportions, oriented toward the centroids of a number of selected hexagons. The parametric model here described is part of a larger work running for the design of SolSt, a large roof in Milan. A number of variations in the parametric approach have been developed aiming at exploring various interdisciplinary aspects of the design. A broader overview of the overall parametric design of SolSt can be found in other publications [7,8].

6 Envelope design

The envelope of the shell structure is defined by a combination of structural load-carrying plates (CLT) and a steel grid structure carrying non-structural transparent elements (glass), as shown in Figure 3. This combination responds to a wish to create a diversified interior in terms of light conditions and interior environmental effects. The tailoring of load-bearing sub-systems is also of interest as in previous studies on I) branching columns and folded plate shells and II) branching columns and a double-

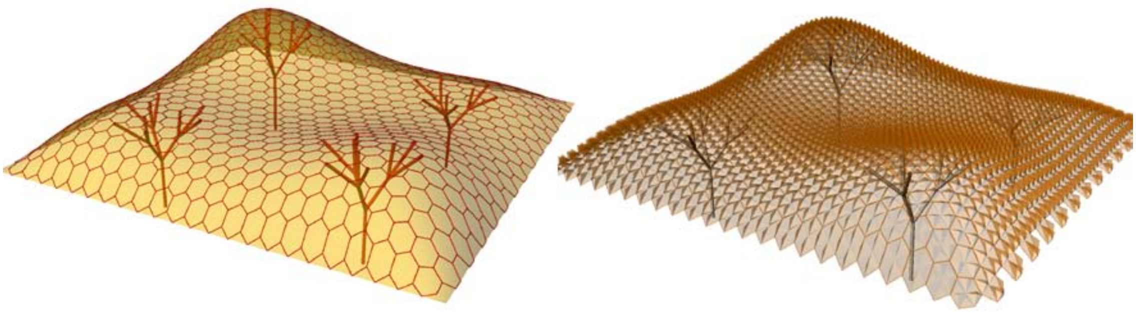

Fig. 3: View of the modelled roof structure with surface tessellation and branching columns.

curved hexagonal steel grid. A common CLT product is 146 mm thick and is built up by 5 layers, where layers 2-4 are oriented perpendicular to layers 1-3-5. The cross-section of the CLT elements may be tailored to suit specific load conditions and structural functions, such as bending moments, type and direction of loading, integration and combination with other materials and structural systems and detailing. This enables a varied use of the CLT panels, either to include both structural and environmental functions in one single member/layer resulting in the structural layer defining the enclosed space, or to separate the environmental/climatic function from the structural function as infill panels in a steel grid. This allows deviations in form from the grid, as the infill panels may be given a folded shape and provides the potential variation of opaque and transparent surfaces, which is currently studied.

6.1 Structure and geometry

The point of origin for the geometry of the roof structure is the flat square configuration of the parametric surface, sub-divided through different tessellations, as exemplified to the left in Figure 3. The roof is supported on four branching columns constructed in steel with tubular section. The cladding is elaborated through the studied parametric approach and facetted units are varied in base shape and pitch. A plane design of the facetted roof is shown in Figure 4. The roof is modelled with CLT elements of 146 mm plate thickness. In the modelling the walls enclosing the covered space have not been taken into account.

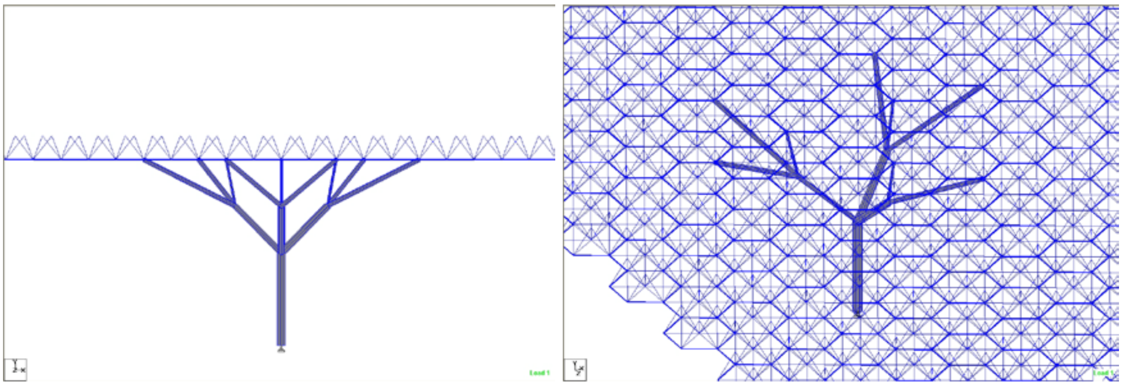

Fig. 4: Plane design version of the facetted roof, here based on CLT panels.

By changing the input values of a set number of control points distributed across the surface the overall shape/topology of the roof can be varied. This dune geometry is described in the related papers [4,7,8]. The variation of geometry of the roof surface and thereby the characteristics of the enclosed space affects the air-flows and different solutions for ventilation can be developed and applied, as in the ongoing project on SolSt.

The structural performance of the plane assembly has been studied in models based on a steel grid with infill elements as well as in models based on structural CLT panels. In the case with structural CLT panels the area of timber exposed to the indoor air can be fairly big and even increase further with varied pitches of the panel units.

6.2 Material-related effects

The CLT panels have been tested regarding behaviour with increased moisture content of indoor air where there is a risk that mould can develop on surfaces of a structure's lower side if it is not well ventilated. The mass of the timber shows buffering effects, and in the scale of residential buildings they provide an evening out of indoor climate both on a 24 h cycle and over a 1-year cycle. The penetration of moisture during taking up and releasing moisture content is approximately 1 mm in the 24 h cycle and 3 mm in the 1-year cycle [9].

The problem with mould is caused by condensed moisture on the lower side of roof elements when the surface temperature of the roof elements sinks below the temperature of the surrounding air. This happens when daytime rain resulting in increased moisture content in the air is followed by a clear night when heat radiates from the roof out into space. If not properly insulated the roof surfaces can then get far cooler than the air. The risk of repeated moisture buffering increases, whenever the combination of rainy days and clear night-time skies re-occurs. The problem has been documented in carports and on eaves. It is also rather frequent in attics where insulation is placed in the attic floor structure, thus leaving the attic space and the roof structure cold. Insulation on the upper side/outside of the roof elements minimises this effect by preventing the heat loss, storing heat in the building mass of the roof and thereby keeping the lower surface of the roof above the air temperature.

Another reason for the appearance of mould and fungi, however, might be the drying process of the timber boards [10]. During kiln drying the moisture content of the timber is reduced when water migrates to the surface and leaves the timber. Nutrients are brought to the surface and left there, leading to a concentration of nutrients in the zone near the surface where water evaporates, approximately of 2 mm thick [11], which risk to increase the growth of mould and fungi. It has also been shown that the method of drying has effect on the distribution of nutrients in the surface of timber products [12]. Also the choice of raw material influences the resulting structural and environmental performance. Timber members of heartwood normally show better properties than members from sapwood due to higher content of extractives. However, the content of naturally occurring preserving substances in the timber decreases during heating of the material from 40°C to 110°C. Normal kiln drying temperatures are 70°C to 90°C and during high temperature drying the temperature is 110°C or even higher.

Regarding fire the general burning rate of CLT with timber density of 290 kg/m^3 is 0.7 mm/Min. In residential buildings the CLT is often clad with particleboard or gypsum board to increase the fire resistance. In a shell structure like the one of current interest the lower surface may be provided such a board cladding as well. An addition of a particleboard of 16 mm thickness, extends the fire resistance under test conditions by 10 minutes [13]. Steel connectors imply sensitive zones in the timber structure and jointing technology based on dowels and slotted-in steel plates show relatively good behaviour during fire exposure since the steel is embedded in the timber.

7 Discussion and conclusions

7.1 Discussion

In the previous study aspects of light conditions, energy and material properties are approached as factors possible to use to inform and direct the design process. The effects of light, energy flows and material properties on the indoor climate depend on scale, structural systems and geometry. The choice of structural system in most cases indirectly defines the structural materials and the used amount and the properties of the utilised materials decide the interplay between material and indoor air/air quality/experienced comfort. Extensive use of timber panels in the CLT version of the currently studied roof results in a large surface of exposed timber compared to a roof structure with for example a timber-based space truss clad with other materials. Thereby the effect on the obtained indoor climate of moisture and heat buffering capacity of timber increases.

The approach to fire resistance also affects the experienced architectural space by potential additions of extra cladding materials, paint-based coating or non-combustible insulation. These issues leave the designer with another set of choices, fully feasible to handle but still decisions that have to be made. In objects like the Flyinge equestrian hall outside Malmö, Sweden, the CLT is left untreated and visible [14] and in the Brunner headquarters and showroom in Rheinau-Freistett, Germany, plywood is utilised in sandwich elements and left without further cladding [15].

Initially, the material induced effects discussed above have little or no negative effect on the structural performance of the structure, but influence the environmental result and are therefore of importance already in conceptual design phases and to include in the early design stages. They can be handled and managed through choice and treatment of materials as well as through geometric design decisions, if the early phases of the process are thoroughly informed. The use of case studies and experience from material tests is common in design work, but very often the tests are performed after the finished production and primarily utilised as documentation of the obtained result. Reports on failures or risks, especially regarding climatic/environmental issues often have little and slow effect on new projects in the building sector.

For reasons of tradition and competition object specific design and documentation might be difficult to access, but still much material is generally available and fully accessible. Existing modelling tools also show synergies when combined and interactively developed. Procedures to include important steering factors can be defined by developing the methods, tool applications and documented results from previous projects.

7.2 Conclusions

In this paper a holistic approach to the setting of preconditions for architectural and structural design is applied. The idea is to increase the action of informing the design process at early stages. Interrelations between structural, environmental and material effects on the architectural result are discussed, whereas the methods of analysis are still under development. By utilising combined modelling and analyses as well as experience and data from case studies this broad approach is made feasible even with varying sources and formats of information. Both the digital design procedures and the designers' active choices and decisions can thereby be informed and influenced in a beneficial way.

Modelling and comparisons of alternative design solutions as those mentioned above are presumed to provide useful experience for the analyses of the proposed procedures. Varying the structural solutions through combinations of structural timber-based panels and non-structural glass panels should furthermore shed light on the structural interaction of sub-systems studied in previous papers. The structural decisions, from choices of structural systems and structural materials to choices of structural and spatial geometry have obvious effects on the impact of environmental and material aspects. The amount of information increases through the extension of the procedures and in the ongoing work the design and informing steps are not yet fully developed and described. The phase needed to manage the informing steps is, however, provided by the approach in the method combining parametric modelling and Genetic Algorithms, which supports an open phase of design evaluation in the early design stages, enabling the designer to include architectural, environmental and material aspects in a geometry-based evaluation process and to regard alternative design solutions.

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