Proceedings of the International Association for Shell and Spatial Structures (IASS)
Symposium 2015, Amsterdam
Future Visions
17 - 20 August 2015, Amsterdam, The Netherlands

Form Exploration of Timber-based Folded Plate Domes

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Abstract

This paper presents a study on timber-based plate-shell domes with a set base diameter and a variety of topologies using different combinations of perforation ratios. Using a combination of geometry generation and performance optimization, parameters of folds, depth of folds, height of dome and the effect of perforations on structural efficiency, interior lighting and acoustics are explored. The combination of a visual database with both structural and architectural oriented performance parameters, gives the designer added insight in overall form determination. The overall geometry and its tessellation are also discussed in terms of environmental performance.

Keywords: perforated, plate shells, cross-laminated timber, ParaGen, daylighting, acoustics

1. Introduction

1.1. Development of timber-based construction

Cross-laminated timber (CLT) is a robust engineered wood product (EWP), which to date has been proposed for and applied in a wide range of structures, so far mainly due to the renewability and workability of the raw material and high element stiffness of the produced surface elements. In terms of production economy it is so far available at comparably higher cost than light timber-frame systems and corresponding prefabricated systems based on concrete elements. As environmental issues are rising in priority on the political and societal agendas globally, however, reduced resource consumption during production – compared to many non-bio-based materials and products – is getting increased recognition as well. In the cradle-to-grave perspective the energy consumption during extracting and refining of building materials have gained more interest lately and the tools for life cycle assessment (LCA) have been developed to enable true comparison between different material categories (Erlandsson et al. 2013 [1]). Through this harmonisation work considering e.g. the

agreement about system boundaries for evaluation, LCA tools at hand today which enable robust and fair comparisons of different materials for the building sector and from environmental point of view this will increase the competitiveness of bio-based materials and products in the construction sector, a condition valid even for timber-based products such as CLT, which require relatively higher energy consumption during production than light timber-frame systems.

1.2. Plate-based structural systems

The dimensional stability, rigidity and efficient force distribution in the CLT-based plate elements leads to generally good structural performance of CLT-based structures. This study uses integrated performance values based on structural behaviour, lighting characteristics and acoustic response, to explore a range of geometric solutions. The study is conducted using ParaGen, a method, which uses a GA to fill a database with well performing solutions based on a parametric model. ParaGen, allows for open interaction between the designer/designers and the computer tool regarding the comparison of multiple design factors, and the process of evaluating the generated results. Thereby performance criteria and other design considerations can be easily linked to and taken into account in the process.

Studies of the effects of perforations on the structural properties of CLT elements have been carried out on orthogonal plate structures and in experimental architectural projects. The effect of freely placed openings for e.g. windows, doors, roof-lights etc., either already in the factory or on the building site, can be seen in examples from the Wood Studio at Aalto University in Finland and in the so called “Naked House” from 2006 by dRMM architects. The robustness of the CLT elements offers many possibilities to vary both the architectural use of the plates and the level of prefabrication of the structural parts – the workability of the timber material enables perforations to be made also on site.

Structural efficiency, material utilization and resource minimizing efforts, as well as lighting and acoustic behaviour all have important impact on the design of a structure aiming for varied functions and architectural use. Both the global geometry of the panel-based system as well as the local perforation of individual CLT panels with glazed inserts impact a range of performances including structural, lighting and acoustic, areas that are currently combined in an integrated performance exploration of plate-based wooden domes. Acoustic behaviour of large open spaces is also a critical design consideration especially in sport facilities. Sustained crowd noise in an acoustically active space can reach levels, which are physically damaging to the hearing of the occupants. Both the geometry and surface composition (glazing vs. CLT) of the structure play an important part in the performance of the space. Also the design of daylighting through the use of the panel perforations brings with it another set of performance considerations. In order to evaluate the space and structure for all of these integrated performances, ParaGen stores the values in a SQL database that can be explored both with sorting and query commands as well as parallel point and scatter graphs to find Pareto optimal and other well performing solutions in all areas. Because the method is visually based and displays images of the solutions for the designers, qualitative aspects of the design can also be considered.

1.3. Folded plate-shells

In terms of structural performance, folds offer a beneficial alternative for plate-based steel structures to obtain efficiency and folded plate-based vaults have been in focus in previous studies where tessellations and depth of folds have been varied, and comparisons between curved plate shells with

supporting structures and facetted self-supported vault-structures have been made (Falk and von Buelow 2011 [2] and Falk and von Buelow 2009 [3] respectively). The performance of facetted typologies can be varied by changing the plate properties by perforating or altering the materials of the plate-elements. Changes of the resulting performance can also be obtained by truncating the folds, which opens the structure, offering insertion of elements with other properties, such as glass panels. Figure 1 shows the basic plate-shell typology, which is in focus in this paper.

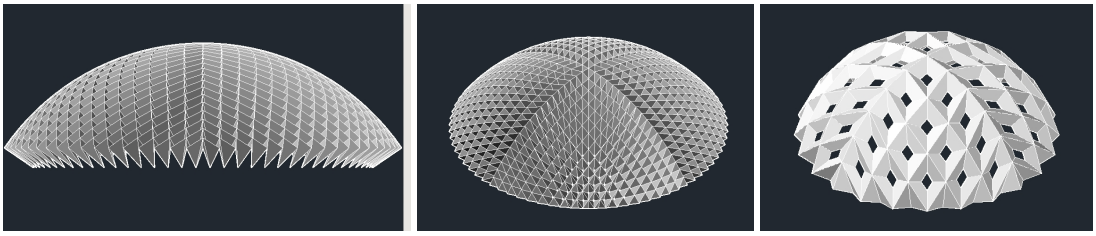


Figure 1. Basic plate-shell (left & middle); a plate-shell with fewer elements/larger openings (right).

2. Timber-based domes

Timber-based domes have been developed and studied in different contexts. Shell types offer many different solutions both for structural systems and for modifying the interior environmental performance and qualities. The traditional timber-based structural systems have been based on 1-D elements of posts and beams and as a consequence dome-shaped structures have been built up as reticulated systems. The stability issues and buckling phenomena of such systems are dependent on the characteristics of linear elements, member density and nodal joints, as studied in e.g. Pan and Girhammar 2003 [4], where the ring beam stiffness is in focus. The function as a tight roof is obtained through addition of decking, which adds to the rigidity of the dome through bracing of the purlins. Pan and Girhammar 2005 [5], discuss this in relation to the mesh density expressed as a relative timber volume, defined as timber volume divided by the timber volume of a mesh density corresponding to $n = m = k = 10$ (n is the number of sectors, m is the division of the length of the arc, k is the division of the bottom ring length). In the performed study mesh densities between 0.27 and 0.63 are considered. Increasing the mesh density, i.e. increasing the volume of used material is found to have marginal effect on the structural performance. The function as support for cladding/decking has to be considered but in case of the discussed densities, the effect is marginal.

The increase of used material volume can be evaluated in terms of added value and/or added functions. In a resource efficiency perspective the addition of material should benefit the structure in some way – preferably with more than one added function – and if it has little or no effect on the structural performance it could still have effect on other aspects of the structure and its enclosed volume. By going from a reticulated structure to a plate-based structure the material utilisation is altered and the structural elements also serve as bracing/stabilisation of the geometry, and can be potentially used for roofing function as well. The structure gains practical/utility qualities through this change within the duality discussed by Wester, 1984 [6], where lattice and plate structures are defined as interrelated anti-poles, by incorporating a surface (structurally interconnected surface elements) utilised for force transfer. Cross-laminated timber as a product offers this function efficiently but

could as well be replaced by a typologically related product like LVL, laminated veneer lumber, which is also available in the format of structural plate elements. This type was utilised in e.g. the Metropol Parasol in Seville from 2011 by J. Mayer H. Architects in collaboration with Arup, even though it is not primarily used for covering purposes in that very project.

2.1. Global geometry

Internationally, contemporary architectural trends result in experimental geometries and experiments with visual material effects, which challenge both material and structural properties of the elements and systems. The relation between architectural and structural design varies with the attitude towards structural clarity and interest in structural and construction related aspects and if the Guggenheim Museum in Bilbao by Frank Gehry Partners inaugurated in 1997 may be taken as example of one extreme, where the structure is hidden and expected to anonymously support the undulating lines and curves of the façade, Qatar National Convention Centre by Arata Isozaki and RHWL Architects finished in 2011, may represent one anti-pole, where the structural concept is exaggerated to form the main design feature of the project. Beijing National Aquatics Centre from 2008, more well known as the Water Cube, designed by a consortium consisting of PTW Architects, Arup international engineering group, CSCEC (China State Construction Engineering Corporation), and CCDI (China Construction Design International) of Shanghai, is another example where the structural system was developed as the main design characteristic of the object's visual appearance.

The relation between structural form and the geometry of the building envelope is gaining importance as architectural complexity increases at the same time as the necessity of resource efficiency becomes more obvious, for environmental reasons. The potential synergies of the utilisation of structural materials and the design of the spatial characteristics of the building skin appear in that light as both interesting and developable from a combined structural/architectural/environmental point of view.

The material properties may provide to and co-act with the environment of the enclosed volume (humidity and temperature buffering effects studied in e.g. Falk, Turrin and von Buelow, 2010 [7] and Falk, von Buelow and Kirkegaard, 2012 [8]) and combinations of different surface and material properties in the interior have potential effect on the interior environmental performance. Surface properties and geometry of the roof and wall structures have effect on acoustic and light properties of the indoor environment through the way the surfaces reflect and/or absorb sound and light. Depending on the arrangement of perforations and the local geometry, angles and surface finishing around them, both sound and light performance can be tailored differently. The structural form in the case of the CLT-based dome-shaped shells considered in this study, constitutes the form of the building envelope and thereby both the external and the internal surface geometry. The geometry and element design of the plate-shell is studied and optimized for proper structural function but also regarded in terms of their additional environmental effects on the interior space. The plate shell presents a folded structure, which combines plate and shear-plate action with increased structural efficiency obtained through the depth of the folds. The arrangement of the folds may also be used as an optimisation parameter.

2.2. Perforations

In structural perspective perforations can be made to save material and optimize the material utilisation. In architectural and holistically functional perspective perforations are made to let light in, to vary and improve the interior light conditions and ditto quality, to vary the expression of the

geometrical form, etcetera. In that way void and removal of material enables improved functional performance as spatial values are potentially enhanced. For proper structural function the optimisation of remaining mass gains increased importance and the studies of nature inspired skeletal analogies are innumerable, e.g. Wester, 2004 [9] and Phillips, 2012 [10]. Phillips among others refers to Cullmann's graphical statics from 1866 and the discussion on trajectories by von Meyer 1867. The growth of bones had been noted to develop a structurally optimized pattern in response to gravity and the patterns of the resulting inner structure were in focus of their discussion. In his study of Cullmann's and von Meyer's works, Phillips models and runs an optimisation sequence of the structural composition of the thighbone close to the hip joint as a combination of shell and beam elements, where the shell thickness and the distribution of the beams are varied. This discussion on material saving is fully driven by the aim for structural efficiency, more or less as the I-beam is saving material without making other use of the basic principle than decreasing the dimensions of the web. Architecturally however, void is as important as mass. The structural materials offer the mass and the design and location of their mass creates the preconditions and the characteristics of the void, i.e. the architectural space.

The high in-plane rigidity of CLT plates offers efficient transfer of in-plane forces and this property is efficiently utilised in folded plate-shells of CLT elements. Contemporary production technology allows cutting-patterns for minimised waste of material and the dimensions of the CLT elements are produced in more or less tailored build-ups, which can be easily chosen in response to the specific load-conditions for each design situation. Thereby a wide range of forms is enabled. The timber-based folded plate dome seen to the right in Figure 1 is based on truncation of the folds enabling openings in the structural shell, which are filled with glass panels. The point of departure is the typology shown to the left in Figure 1 and in the onward development the number of elements, depth of folds and size of truncations/openings are varied.

2.3. Additional utility aspects

The effects of perforations and variations of materials on the indoor environment comprise apart from light conditions and acoustic properties also air quality and humidity due to e.g. air streams and materials' varying capacity of interaction with the indoor air, as well as tactile experiences of the users. Tools like ParaGen allows for consideration of a wide range of aspects in the design process and different types of analyses along the process. It makes it feasible to easily include different factors for environmental performance and by that enabling encompassing of a building's compatibility with not only structural and architecturally functional requirements but also environmental aspects such as qualitative evaluation of geometry and building skin in the same procedure. Those additional aspects are not yet added in this study.

3. Results of modelling

As mentioned in Section 2, a variety of topologies and geometries were explored using the ParaGen method. In the runs made thus far, quantitative assessment has been based on geometric features and structural performance. Further planned assessments include lighting and acoustic simulations. ParaGen employs as variety of simulation software to collect performance data on solutions generated using parametric modelling software. In this trial, Formian was used to generate the dome geometries based on origami patterns. The structural analysis was performed using STAAD.Pro from Bentley

Systems. Also Rhinoceros by Robert McNeel and Associates was use to manipulate the geometry and prepare renderings together with DIVA for lighting simulation and analysis. An analysis based on Sabine's equation was used for the acoustic simulation (Sabine, 1922 [14]).

3.1. Dynamic configuration processing of folded plate diamatic domes

"A dome is a structural system that consist of one or more layers of elements that are arched in all directions" (Makowski, 1984 [11]). A dome might be a part of a sphere, ellipsoid, paraboloid or a curved surface with different patterns of braced elements or plates. There are diverse types of domes and 'diamatic domes' are frequently used in practice because of their specific characteristic. In some types of domes 'element cluttering' around the crown is a significant issue and this not only causes some construction problems but also aesthetic features, which normally are less preferable. In contrast, diamatic domes are based on such patterns within which the population of elements look almost consisting from the crown to the base. This advantage can be seen in Figure 2 in which a lamella dome is compared with a diamatic one. Two notable domes of this type are the Superdome in New Orleans and the Astrodome in Texas, see Figure 3, left and right.

In this paper, a diamatic type is opt for to avoid the problem of plate cluttering at the crown of the folded plate dome. A diamatic dome consists of a number of 'sectors' and the pattern of each sector is in a fashion that the side boundaries are along two meridians of the circumsphere of the dome and the bottom boundary is along a parallel of the circumsphere. The number of elements along a boundary of a sector is referred to as the 'frequency' (Nooshin and Disney, 2001 [12]).

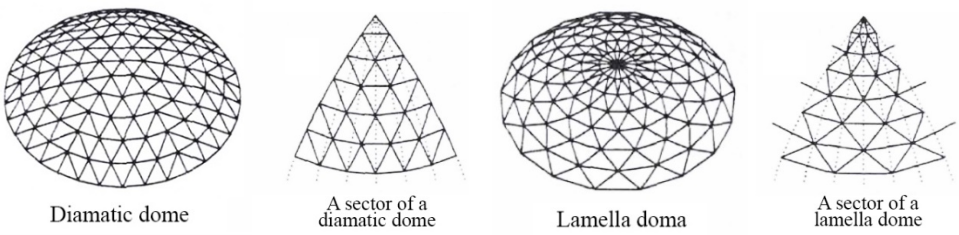


Figure 2: Comparison of a lamella dome and a diamatic dome (Nooshin and Disney, 2001 [12]).

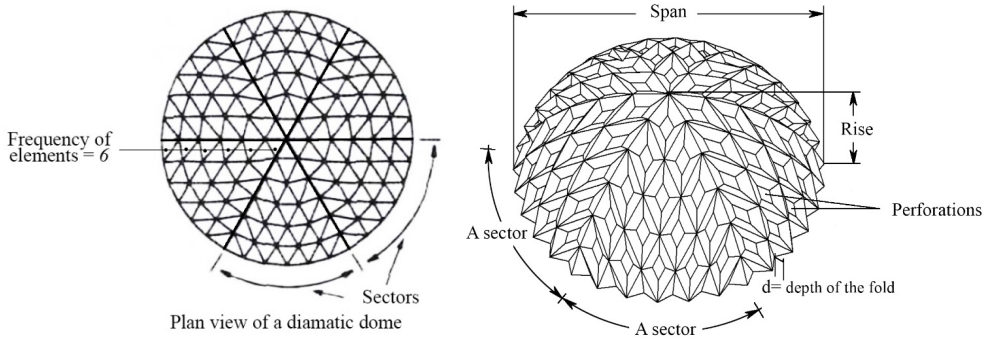
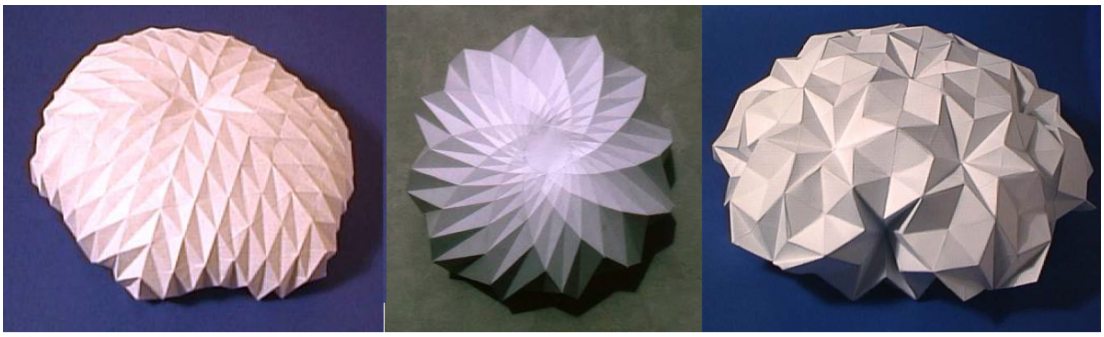


Figure 2: Sectors and frequency of elements in a diamatic dome (left). A typical form of a diamatic folded plate dome that are to be explored (right).

In this paper, the configuration of a diamatic folded plate dome with a 20-meter span is processed using concepts of Formex algebra and its associated programming software, Formian. Formex algebra is a mathematical system that allows a designer to define the geometrical formulation of forms through concepts that effect movement, propagation, deformation and curtailment ((Nooshin, Disney, and Champion, 1997) [13]). Within this mathematical system the plates are defined as descrete surfaces, which are arranged besides their edges.

The domes investigated in this paper have perforations for providing daylight to the interior. The proportion of perforation area is defined in percentage. The geometry of the dome is exported in two separate DXF files, one for the structural timber plates and the other for the non-structural glazed surfaces. The folding pattern of the dome in this study is inspired by origami patterns (see Figure 4), with one pattern forming the base topology of the dome. In Table 1, constant parameters, variables and also their acceptable intervals, used in the parametric formulation of the dome are described.



http://www.flickr.com/photos/elelvis/

Figure 4: Some origami-based forms, Yoshimura Pattern variations.

Table 1: Geometrical parameters of the folded plate diamatic dome.

Parameters	Sign	Constant/Variable	Acceptable interval/ value
Span of the dome	S	Constant	20 m
Rise of the dome	H	variable	[3,10] m
Number of sectors	m	variable	m should be integer. [2, 10] is recommended.
Frequency of plates along the left border of the each sector	n	Variable	n should be integer. [5, 20] is recommended.
Depth of folds	d	Variable	[0.2, 2) m
Percentage of perforations within each diamond	t	Variable	(0-100%) is recommended.

3.2 Structural simulation

The dome is simulated using two materials: CLT panels based on softwood properties (Spruce-Pine-Fir) and plate glass. STAAD.Pro uses 3 or 4 node planer plate elements with variable thickness. For this analysis the CLT thickness was set to 9 cm and the glass thickness at 0.5 cm. The stiffness of the glass panels was turned off during the analysis assuming that the glass would not transmit stiffness to the system. In addition to self-weight, an imposed downward vertical load of 2.0 kPa was applied to all plates. The performance values, which were taken from the analysis included the modal frequency; the calculated weights of panels and their relative proportion by area (CLT to glass); the von Mises stress values for plates (including a stress contour plot); deflection values; and total reaction loads.

Using the ParaGen interface, the results could be explored based on these performance parameters. For example, Figure 5 shows a grouping of solutions sorted by the panel complexity. Below each image is a short list of other parameters that describe the dome.

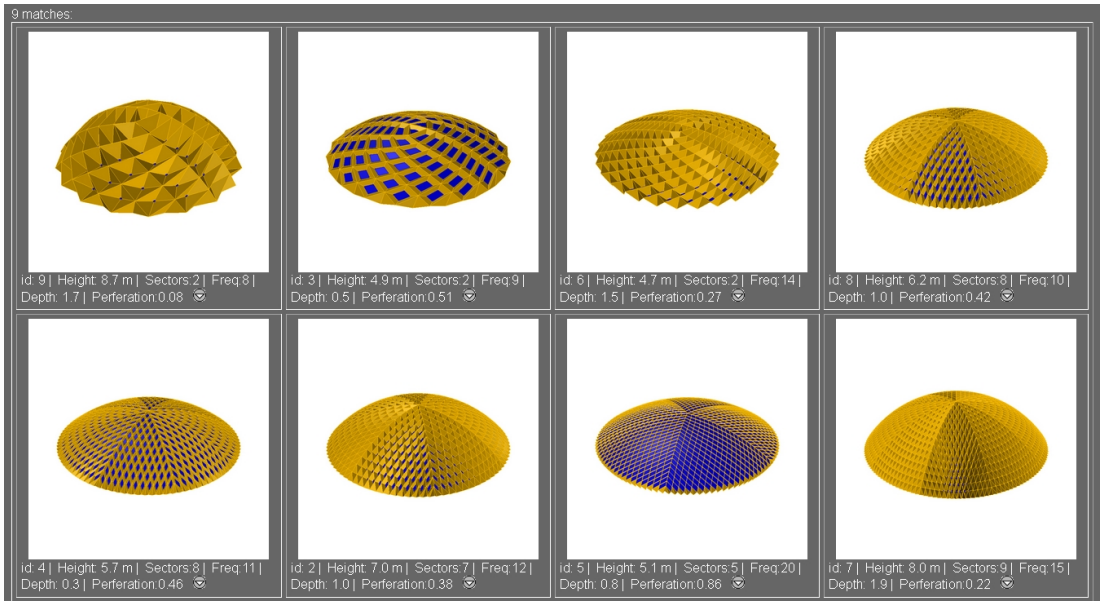


Figure 5: An array of solutions sorted by numbers of panels.

3.3. Simulation of lighting

The daylight analysis, see Figure 6, begins with setting a surface as the ground, and then importing the DXF file of the dome into the space model. A point along the central axis with a height of 80 cm is defined as a station point in calculating the daylighting factor and solar irradiation value of the models. Furthermore, another surface at the same height of 80 cm is created to survey the light distribution and illuminance quality. This surface has the same dimensions and location for all the dome models. Next, appropriate materials are assigned to the structural parts and perforation surfaces.

DIVA daylighting simulation factors are set as follows: ambient bounces (ab) = 3, ambient divisions (ad) = 1500, ambient super-samples (as) = 20, ambient resolution (ar) = 300, ambient accuracy (aa) = 0.1. The simulation then yields the solar irradiation, daylight factor and illuminance values. The location is taken as Amsterdam, Netherlands (52.37° N, 4.90° E).

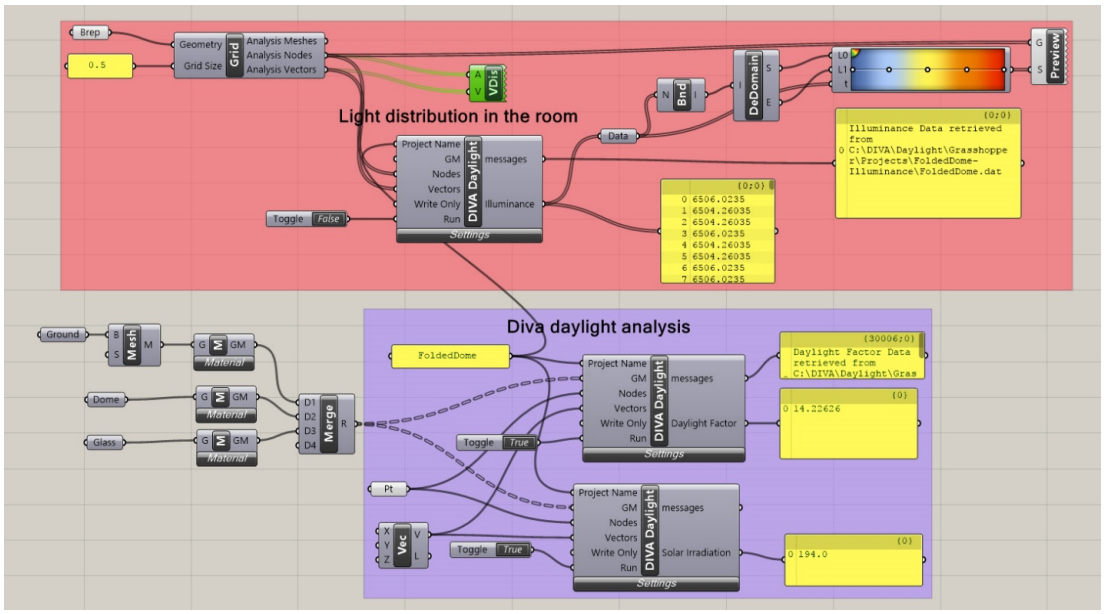


Figure 6: DIVA daylight analysis.

Table 2: Definitions and effects of different Daylight Factors.

DF and appearance, thermal performance		
Average DF	Appearance	Energy implications
< 2%	The room looks gloomy	Artificial lighting is required
2% to 5%	The room looks lit, but supplementary artificial lighting is needed.	Artificial lighting may be required for some times.
> 5%	The room appears strongly lit	Daytime artificial lighting rarely needed, but glare and solar gain may cause problems due to overheating in summer and heat losses in winter.

Daylight Factor is a ratio that represents the amount of illumination available indoors relative to the illumination present outdoors at the same time under overcast skies. The DF may influence our choice of suitable design solutions more than other factors. Daylight Factor is typically calculated by dividing

the horizontal work plane illumination indoors by the horizontal illumination on the roof of the building being tested and then multiplying by 100. Table 2 above, describes the quality of different range of the DF. Comparing the value of daylight factor at a certain point within the solutions allows us to make suitable design decisions accordingly.

4. Discussion

This study considers dome-shaped structural systems comprised of a combination of flat CLT and glazed plates. A sampling of solutions is generated based on a parametric model that ranges in topology from a nearly smooth continuous surface to a reticulated shell composed of beams. Regarding the typology with a curved plate-shell and a reticulated dome as anti-poles, it is obvious that the material can be distributed – and utilised – in completely different ways. In the study the solutions are each evaluated primarily for structural performance characteristics, but also acoustic and daylighting quality are considered. The structural performance follows the range of the topology – surface-active systems versus section active systems. Figure 7 shows this range and the corresponding von Mises stress plots. In the analysis the stiffness of the glass panels have been set very low (assuming they would be gasket mounted) which forces the CLT panels to provide the overall rigidity.

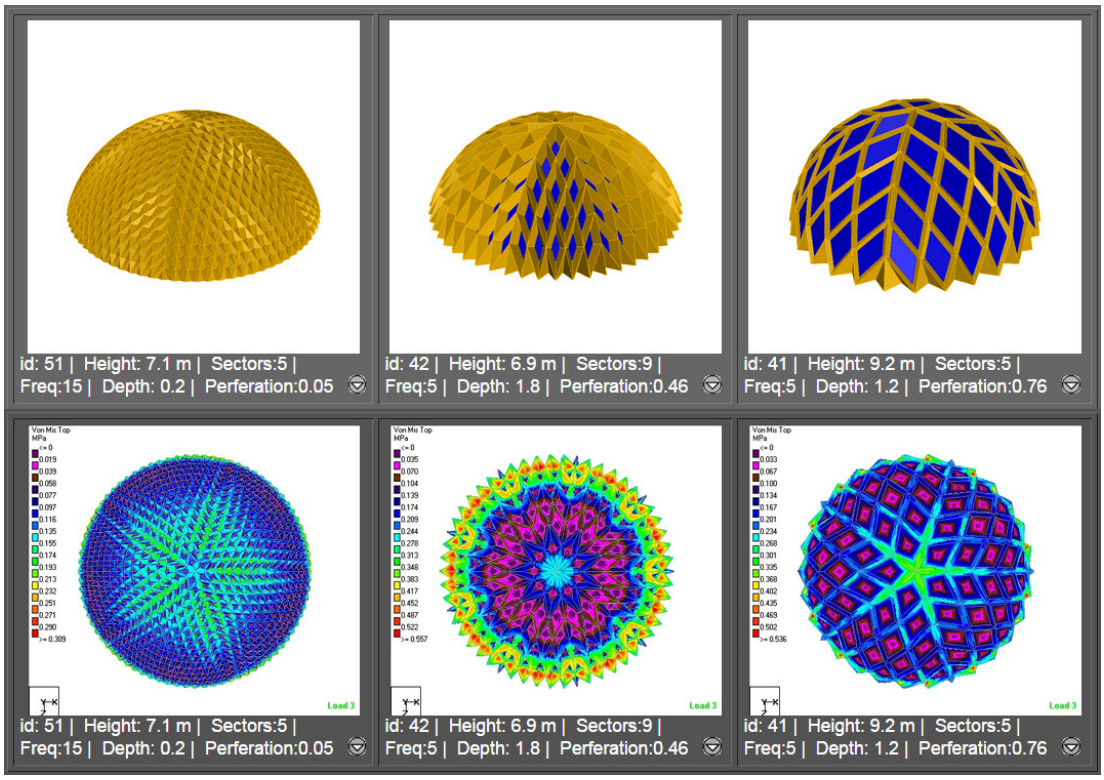


Figure 7. A comparison of the range of perforation and its effect on topology and structural behavior.

When perforating the plate-shell system (valid also in case of perforation of individual elements), shear-plate action will remain and the system can be structurally optimized as a surface-active system. This enables the designer to model the relation between opaque and transparent parts of the structure, an option, which clearly differs it from the reticulated dome. In the design procedure the designer may include several optimization aspects, which should be handled in relation to each other, such as structural efficiency, material volume and utilisation, qualities and effects of lighting, acoustic performance, actual view through the perforations establishing the experienced relation between indoor and outdoor environment. Other aspects not explicitly considered in this study are e.g. efficiency of production and deployability.

By varying the parameters and depth of folds and the height of dome the enclosed space is varied markedly both in terms of enclosed volume and in terms of preconditions for sunlight penetrating through the openings. Deeper folds will result in a structurally more efficient system and may enable certain reduction of the plate-element thickness. Fewer facets, i.e. larger scale of the tessellation will result in a relatively smaller number of openings with larger dimensions. An increased height of the dome changes the angle of the shell surface towards the sun, and as the pitch of the dome surface increases the lower parts of the dome change nature from mainly roof function to mainly wall function. Sunlight will thereby penetrate the structure not only midday when the sun is high, but also during morning and evening hours. This will increase the amount and intensity of daylight entering the indoor volume.

As a final note: The perforated folded plate-shell offers an architecturally variable typology where the enclosing structure also forms the geometry of the building envelope. Practical aspects such as water drainage of the folds and additional layers protecting the timber elements from moisture and weathering as well as sealing joints and insulating layers ensuring a comfortable indoor climate of course have to be added. Furthermore, as a built structure with intended structural use, larger openings for entering the structure are usually also needed. The entrance location may change the boundary conditions for the dome. These aspects have not yet been considered in the current study.

5. Conclusions

So far, the results of the modelling are limited, since the simulations have been just recently started, but the procedure of ParaGen is under steady development and show very useful results, not the least when adding environmental performance and compatibility to the set of considered design aspects. The potential to add different softwares and designer's qualitative input to the optimisation process provides a robust design process where the designer is in full control throughout.

The CLT-elements are not yet used in practice for the studied structural typology, but this type of engineered wood product demonstrates both developable potential of CLT-based structures and a potential to innovate and develop new bio-based structural elements and systems. The workability enables fast processing of the material both off and on site and the environmental aspects of prefabrication and CAD-CAM supported production with high level of resource efficiency and low waste, and of materials interacting with the indoor climate, could be further utilised.

The variability of the building system for the studied dome type offers interesting possibilities to develop the structural efficiency and material utilization in relation to their effect on the desired environmental performance, providing a wide range of options with tailored indoor spatial properties. These interrelations will be further modelled and analysed through the upcoming stages of the study.

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