FOLDED PLATE STRUCTURES AS BUILDING ENVELOPES

Andreas Falk[1], Peter von Buelow[2], Poul Henning Kirkegaard[3]

ABSTRACT: This paper treats applications of cross-laminated timber (CLT) in structural systems for folded façade solutions. Previous work on CLT-based systems for folded roofs has shown a widening range of structural possibilities to develop timber-based shells. Geometric and material properties play, however, an important role also for the enclosure, and climate and conceptual design procedures have been utilised to include these issues in early design phases. A current architectural trend proposes increasing complexity of the façades and in this context the paper proposes the application of folded CLT-based systems, which are studied and analysed by using a combination of digital tools for structural and environmental design and analysis. The results show gainful, rational properties of folded systems and beneficial effects from an integration of architectural and environmental performance criteria in the design of CLT-based façades.

KEYWORDS: Cross-laminated timber, Building envelopes, Folded structures, Indoor climate, Performance criteria

1 INTRODUCTION

The currently presented work is based on an explorative study on applications of cross-laminated timber (CLT) elements in shell structures.

Recent steps of development in contemporary architecture raise demands on increased complexity of the building exterior, and even tend to separate the façade from the actual building as a more or less autonomous system, thereby increasing the importance of technical solutions which complement and support free-form shapes that are capable of providing clear and visibly strong forms as parts of the overall exterior architectural design. Following this trend the exterior design tends to be disconnected from the interior design of spatial structures, thereby also changing the requirements on environmental performance (e.g. issues concerning energy and light) of the façade system and of the building envelope as a whole. The façade may also be designed with reduced climatic function, like e.g. in Figure 1. This entails increased protective function of the layers behind it, i.e. one façade layer for the architectural image and a second layer providing the technical function, and may lead to an envelope with two parallel structures. Thus, the architectural development gives rise to a need for structural solutions, which provide the requested complex geometries while handling both static and environmental requirements.

As a response to this the current paper implements the design and analysis of folded CLT-based structural systems for building envelopes by using a combination of parametric tools and a genetic algorithm (GA) for generation, sorting, selection and development, complemented with additional tools for structural and environmental simulation and analysis. The procedure comprises form-finding and utilisation of performance criteria regarding architectural utilisation and indoor climate in the design of complex geometries for building envelopes.

Figure 1: *The rattan façade of the Spanish pavilion at the Shanghai World Expo 2010.*

[1] Andreas Falk, Dept of Civil Engineering, Aalborg University, Sohngaardsholmsvej 57, 9000 Aalborg, Denmark. Email: af@civil.aau.dk
[2] Peter von Buelow, University of Michigan, 2000 Bonisteel Blvd., Ann Arbor, MI 48109-2069, USA. Email: pvbuelow@umich.edu
[3] Poul Henning Kirkegaard, Dept of Civil Engineering, Aalborg University, Sohngaardsholmsvej 57, 9000 Aalborg, Denmark. Email: phk@civil.aau.dk

The paper furthermore discusses the relation between climate skins, shell structures and free-form as well as engineered architecture, and proposes an integrated performative design solution using a geometrically complex CLT-based façade system.

2 PERFORMANCE-BASED DESIGN

Following the development of computer tools in the practice of building design more and more parameters are by need and necessity being included in the modelling, analysis, optimisation and evaluation procedures in the creation of structures. Terms like performative morphogenesis demonstrate ambitions to integrate numerous factors into the designing function itself, in the very function of the tool. Great potential is furthermore defined in the automation of the design evolution, in the quest for new architectural form. Still the designer interactivity is often stated as a key issue.

According to Kolarevic, *Performative Architecture* utilitises digital technologies of quantitative and qualitative performance-based simulation, covering multiple realms from spatial, social and cultural to purely technical structural, thermal, acoustic, etc. [1]. In this context performance-based design can be given different meanings. It may be applied as a way of devising a set of practical solutions to a set of largely practical problems. A performance-based design approach in architecture may also, however, be defined as *Performative Tectonics*, which links the contemporary development of digital tools to the tectonic tradition of architecture [2]. I.e. the term performance-based implies a major shift of positioning in architectural theory and practice from what the building is to what it does. An architectural object is defined, not by how it appears, but rather by the object's articulation and capability of affecting, transforming and doing, i.e. by how it performs, which parallels the approach in contemporary building regulations.

2.1 ARCHITECTURAL PERFORMANCE

The approaches to performance-based design in practice may differ, however, and currently the quest for renewing and developing the designs of architectural icons follow different lines. One theme is highly technological façade solutions focusing on properties of a more or less integrated building skin. Another trend generates sculptural free-standing designs, as can be seen in the above mentioned examples from the recent World Expo in Shanghai. Both these trends aim at creating eye-catching symbols, which are focusing on the form per se or the mere experience of form.

The application of adaptability on the built environment is a trend of which the Institute du Monde Arabe, constructed in Paris in 1981-87 with design by Jean Nouvel is an early tentative example, where mechanically adjustable shutters regulated the sun shading function of the façade. Programmable facades can be seen in more recent projects, e.g. on the Louis Vuitton's Lippo Plaza Store on Huaihai Road in Shanghai, or the Galleria Hall West in the Apgujeong-dong district of Seoul. The technology with iridescent foil and custom designed lighting systems provides aesthetic effects varying with factors, which can be predefined – weather, number of visitors or any other aspect – i.e. an example of responsive architecture. Another example is the so-called BIX Electronic Skin applied on e.g. Kunsthaus Graz by Peter Cook and Colin Fournier, 2003. The most striking aspect of this "skin" is not the development of its climatic function but rather its design as instrument and platform for artistic presentations. Different contemporary interpretations do exist of terms like performance, responsive and interactivity and it is in the light of projects like those above mentioned and, e.g. Heydar Aliyev Centre in Baku, Azerbaijan, by Zaha Hadid Architects, that contemporary architecture is being developed.

Architectural performance may refer 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. It is evident that architectural performance borders to and thereby has effect on much more than the pure artistic and aesthetic, and it is of ever increasing importance to develop the environmental design issues in construction, especially considering the strong icon oriented design trends. Some of the examples above demonstrate that the aimed at aesthetic aspects of architectural performance are integrated in a structure, which also provides climatic shelter for the contained interior spaces, some do the opposite and separate the artistic and the technical function.

2.2 ENVIRONMENTAL PERFORMANCE

Environmental performance of a building is a complex dynamic situation, and environmental design of buildings needs to include building physics and simultaneous interacting factors to secure acceptable climatic conditions. Environmental requirements on a building envelope include: to minimise heat losses in winter and to capture sunlight, to minimise heat gains in summer and to avoid sunlight, to use natural sunlight efficiently, to provide thermal mass, to allow for sufficient natural ventilation without maximising thermal losses and to keep moisture out. In addition to this, behaviour and patterns of the users of the building have an effect on the environmental sum.

In this context the performance of the building envelope may be divided into active and passive functions, i.e. responsive and/or mechanically adjustable functions e.g. the degree of sun protection, and built in static architectural and/or structural properties. In the second case, which is the focus of this paper, the architectural and structural design should manage a wide range of conditions in one single state. Technology allows almost anything to be constructed today, and it can be argued

that we should proceed with precaution [3]; the importance of input from modelling of material, structural and environmental performance cannot be underestimated in the design procedures. As discussed in e.g. [4] the flow of information and the timing of input and decisions are crucial for the quality of the output. A part of this timing and information issue is in the current context approached through the combination of tools applied in the conceptual phase.

Both architectural and structural design relate to form. Thereby systems, which through efficient utilisation of materials and a robust design show good structural and environmental capacity enabling a varied range of structural forms and architectural typologies, is a prerequisite and in this context regarded as highly beneficial to develop.

2.3 GENERATION AND QUALITATIVE ANALYSES OF CONCEPTUAL DESIGN

In the conceptual phase of the design process the amount of information is normally reduced, but the impact of decisions to be made steers the design and performance considerably during the continuation of the process. To minimise the negative effects of these preconditions, a range of different performance criteria are possible to regard and proposed to include in a qualitative analysis enabling interaction of the designer when optimising the structure at the early stages of the design. In recent works on folded plate structures [5], different topologies of roof structures have been studied by using parametric form generation with performance design guided by a genetic algorithm. Currently applied on systems for complex roof structures, these modelling and analysis procedures, while incorporating an increased number of decisive factors, show a morphological sequence, which exploits the structural capacity of CLT-based systems where the internal form and aspects of material and indoor climate are included in design and evaluation procedures through a multi-objective approach, described in e.g. [6].

The proposed strategy is aiming for a cyclic process where the designer or designer team directs a breeding process iteratively whereby complementary skills and experience in an interdisciplinary group can be utilised to generate input for design, analysis and evaluation. Hereby architectural and environmental performances are approached in the structure of the used tools, combining both programmed objectives along with subjective selections made by the designer. The communicative abilities to inform the discussion and development work in the design team thereby gain importance and 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.

3 BUILDING ENVELOPES

The concept of a building envelope is basically a protective layer, a climate skin, which covers the building and/or the enclosed space. During the 20th century there was a general development of building envelopes of common use from types comprising one or a few components into cross-sections composed of a complex set of layers, which makes the climate shield relatively sensitive. If one layer fails, the environmental function of the entire wall runs the risk of failing. Considering this, CLT-based structures provide potential simplification of a timber-based wall structure.
Plate elements of CLT provide a set of material properties – shear capacity, high strength to weight ratio, workability, tightness, heat buffering capacity etc. – which enables a wide variety of potential forms while maintaining structural efficiency, along with a potential reduction of sensitive wall components such as wind and vapour barrier, depending on the build-up. The need for insulation may be found to be similar with a CLT structure compared to a stud-frame, depending on the local climate conditions, but the overall build-up tends to be more compact and robust in the CLT case, see schematic comparison in Figure 2.

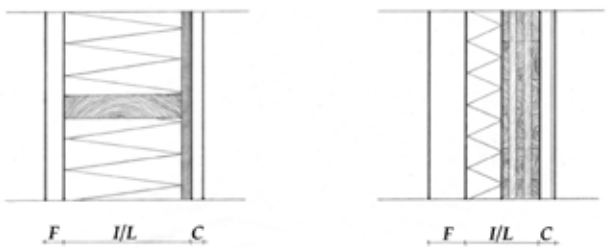

Figure 2: *Comparison between stud-frame (left) and CLT-based (right) external wall. F: façade, I: insulation, L: load-bearing, C: inner cladding/lining.*

Regarding the contemporary quest for novel and experimental architectural expressions through expressive and complex facades, folded plate structures provide several architecturally as well as structurally interesting possibilities, like efficient force distribution, potential mechanisms, subdivision of surfaces, etc. Thus, there is a potential to build up a façade geometry incorporating open and closed panel locations and geometrically tailored passive environmental control functions. A 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 becoming more common and more experimental.

3.1 FOLDED PLATE-SYSTEMS

Previous studies of timber-based plate elements in folded or facetted plate roofs interacting with stabilising steel-based systems, plate tensegrity and studies inspired by origami show a widening range of structural possibilities to develop timber-based shells and new architectural typologies. Folded plate structures may originate from

repetition of a simple element type or be composed of uniquely tailored parts, depending on the chosen tessellation. Both extremes may provide efficient utilisation of plate and shear-plate action and may be designed with stabilising systems or without supporting structure, as fully rigid shells exemplified by Figure 3.

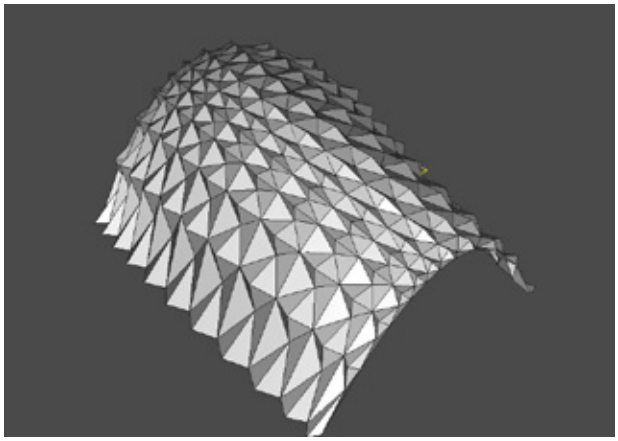

Figure 3: *Example of a CLT-based folded shell.*

Folded structures of CLT enable structurally robust, expressive geometries, which can be utilised in both exterior and interior architectural design, as shown in e.g. [7]. Consequently they offer potential solutions, which re-connect the façade to the building behind it. Regarding structures, the concept of tectonic refers to a tectonic building design, which makes use of its structural principles as part of its architectural design, and in this perspective the folded plate system may provide rational solutions with architectural-structural synergies.

3.2 A CLT-BASED FOLDED FAÇADE SYSTEM

The concept of building envelopes implies exterior and interior climate-related considerations. Environmental issues are globally of steadily increasing importance, primarily regarding energy consumption, and material properties add to the environmental effects of ventilation, heating and light, on the created climate conditions inside the enclosed volume.

The exterior effects of the structure depend on exposure of structural material and properties of products used for cladding and fenestration in the design of the outside of the shell. The effects of the structural material on the interior environment vary depending on the building geometry and whether the material is exposed or covered with cladding. Timber may, depending the design case, be exposed in the interior, and by including climate and energy aspects while analysing the design results of form-finding procedures in the conceptual design phase, these aspects can be managed and included in the design decisions and be utilised for environmental control.

In comparison with previous studies of folded plate shells in arch-shaped structures, the application in façade structures implies change of main load directions where the main direction of gravity appears in the plane of the assembly and the wind pressure causes the major forces to act normal to the surface. The faceting provides rigidity through its 3D geometry, and the angles between the folded planes stiffen the plates against buckling.

3.3 OPTIMISATION OF ELEMENTS

Elements for prefabrication are designed for optimised off-site production, handling and logistics and finally assembling on-site. The assembling of prefabricated elements into functional components on-site raises demands for two types of load conditions and thereby eventually different joint solutions, one joint type to be fixed in the factory during prefabrication by assembling planar elements into bigger 2D-elements or 3D-components and one joint type fixed on-site connecting adjacent panel components. The production sequence thereby calls for two levels of subdivision, one cutting pattern for production of the planar elements and one for the preassembled parts. Predefinition of the cutting patterns for the element production is logistically easy with CAD and CNC tools. Studies presented in e.g. [7], show evidence of high material efficiency during tailoring and prefabrication of CLT-panels to dimension with high tolerances.

Systems are also under development for retrofitting [8] where in a life cycle perspective timber is lowering the environmental impact compared to other conventional methods.

3.4 GEOMETRY AND DEVELOPED TYPOLOGIES

Regarding contemporary modelling tools and procedures as well as subsequent construction processes, many of them imply designing of bar frameworks, nodal joints and tiling to obtain first structurally sound systems for load transfer, then visual and climatic enclosure of the architectural volumes. It can be seen in e.g. the Strand Link Bridge project in London, with architectural design by Future Systems and structural design by AKT [9], where the hull of the bridge is designed as a twisting free-form envelope consisting of a hexagonal mesh. The structure is realised as a lattice system carrying polycarbonate panels. This design approach normally results in the nodes providing the highest fabrication costs since they are being fabricated one by one. In this case the design process resulted in a uniform joint solution, which was possible to combine in a multitude of modules.

Considering origami, like in Figure 4, as source of inspiration for and geometric parallel to built structures a development of building typologies is close at hand. A structure like the nunnery of St Loup in Switzerland, shown in Figure 5, is an obvious example of the development of 3-dimensional form and the topologies of facades as facetted building components. This piloting project, constructed with 40 mm CLT in the walls and 60 mm CLT in the roof elements, also includes jointing solutions matching the strict format of the aesthetic image of pure folds [7]. (The folded roof structure spans approximately 9 m, which gives an example of the structural capacity of the folding principle.)

Figure 4: *Example of a Miura-ori based origami-pattern.*

The context enabled use of on-site jointing of pre-cut planar elements with angled steel plates of 2 mm thickness screwed to the timber, a procedure, which considerably facilitated the construction in practice. The temporary chapel project is an offspring of a study aiming at facilitating the production of free-form surfaces [10], applied to CLT.
The preconditions for a temporary structure cover the static and to some extent climatic aspects, however with reduced requirements regarding weather protection and durability. Weathering of façade surfaces due to sunlight and moisture and of joint zones due to leakage as well as deterioration of joint zones along the foundation may be accepted for a building with a short-term usage. In the St Loup project the CLT-elements were covered on the outside with a membrane to shed water, and 18 mm thick, layered timber panels. For more permanent structures these effects decreasing the performance of the structure have to be more carefully considered and prevented through structural protection and tightening of interfaces and joints.

Figure 5: *Interior view of the chapel in St Loup.*

In previous studies of single-curved roof structures like the one shown in Figure 3, a range of related topologies were produced and among these the one shown in Figure 6 is in the current context used for further studies of wall structures and light conditions.

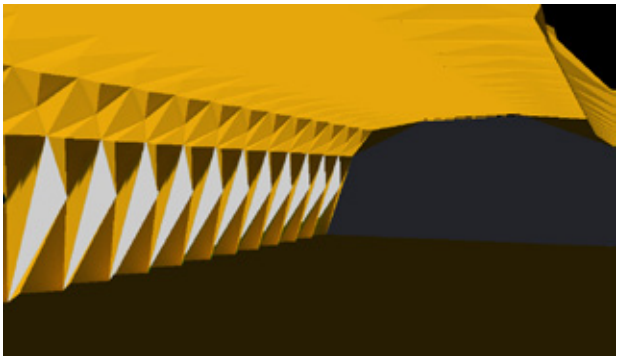

Figure 6: *A model-image of the interior in a CLT-based folded structure.*

3.5 LOAD PATHS AND OPTIMISATION OF FOLDS

The CLT-based envelope can be modelled as a parameterised surface with a predefined tessellation defining its typology. The relative positions of the vertices and thereby the depth of the folds can be varied and adjusted for satisfying geometric properties of a topology, which fulfils the structural and architectural requirements of the façade. A folded structure provides potential rigidity through plate and shear-plate action providing efficient in-plane load-distribution and robustness regarding wind loads. The key issue for this capability is the optimisation of angles and joint solutions between plate elements to ensure efficient load paths, which with the currently applied strategy is modelled, analysed and evaluated in the cyclic generation-breeding-analysis-evaluation procedure.

3.6 TIMBER PROPERTIES AND CLT

Timber is a versatile material with a manifold of uses in construction and interior design. The tactile properties are often appreciated and the aesthetic properties highly valued in an architectural context. The structural properties include a beneficial strength to weight ratio and the development of cross-laminated timber products have further widened the range of purposes for which it can be used.
In the design of joint solutions for CLT elements the anisotropy of timber has to be considered regarding the loading angle in relation to the fasteners and the relation between fastener and material dimensions. Strength and stiffness are considerably lower in the direction perpendicular to grain than parallel to the fibre direction. Loaded at an angle between 0° and 90° the material shows properties somewhere between the values valid for the directions parallel and perpendicular to grain. However, already at a small deviation from 0° the properties decrease drastically. This affects the resistance to local deformation of joint zones.
In relation to climate and energy issues timber provides when exposed heat and moisture buffering capacity, which enables an interaction and a certain evening out of changes of moisture content and temperature of the surrounding air.

Also negative effects should be mentioned. Depending on species and production means emissions of volatile organic compounds (VOC) occur, e.g. terpenes, which are naturally emitted primarily from timbers from conifers and formaldehyde from glue and other bonding agents. VOC can also be produced by organisms like mould, resulting in microbial volatile organic compounds (MVOC). The risk for mould to appear inside a poorly ventilated structure or on indoors-exposed surfaces depends on the orientation on insulation thickness.

Mould on exposed timber surfaces is normally caused by condensed moisture on the lower side of e.g. roof elements when the surface temperature of the roof elements sinks below the temperature of the surrounding air. In the context of facetted façade structures similar situations may occur on wall surfaces, with the slope of the exterior designed with an orientation more or less towards the sky. 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 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 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 might be the drying process of the timber boards [11]. 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 [12], 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 [13]. This effect varies with the degree of product refining; in the case of CLT the exposed surfaces are normally planed, whereby the layer with increased content of nutrients is removed in the process and the risk of mould to appear is reduced.
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.

3.7 FIRE PERFORMANCE

Tests have shown a risk of stepwise substantial loss of load bearing capacity as a consequence of the burning off of the CLT layers. Due to the anisotropy of timber the compression strength is higher in the longitudinal direction and with a conventional build-up of a CLT panel of an uneven number of layers – e.g. 3 or 5 layers for conventional applications – there will be a considerable loss of strength of a plate in in-plane loading when one of the outer layers is lost due to fire. Board thickness and type of adhesive used for the cross-lamination (Melamine Urea Formaldehyde, MUF, versus Polyurethane, PUR) have also been shown to affect the behaviour [14]. Increasing the thickness of the outer layer compared to the general board thickness may compensate for this [15]. Board layers are typically between 18 and 33 mm thick, depending on the fabrication. Thicker board layers in the build-up prolong the resistance to fire through better insulation properties obtained by remaining coal layer. After the loss of a protective layer – a coal layer or an added protective board – the burning rate tends to increase due to enabled exposure to generally increased global temperature in the room.

Regarding fire the general burning rate of CLT is approximately 0.7 mm/min. In residential buildings the CLT is often clad with particleboard or gypsum board to increase the fire resistance. An addition of a particleboard of 16 mm thickness extends the fire resistance under test conditions by approximately 10 minutes [14]. Thus, the common design for increasing the fire performance of a CLT structure counteracts the passive performance of a buffering structural mass. Another solution, which is increasingly used on the market is sprinkling systems, which is regarded one of the safest ways to save lives in case of residential fires. Joint solutions with steel connectors imply sensitive zones in the timber structure. An approach to this is jointing technology based on dowels and slotted-in steel plates, which show relatively good behaviour during fire exposure since the steel is embedded in the timber. In case of internally exposed CLT of a facetted structure joints should preferably be of embedded types for aesthetic reasons, and in potential combination with sprinklers the fire performance should be realistic to solve in a suitable and efficient way.

4 CLIMATE ISSUES

4.1 PROTECTION OF ENCLOSED CLIMATE

In general, as described in the previous sections, a well-insulated building with sufficient fire resisting capacity is obtained by adding layers on both inner and outer side of the load-bearing structure. The function of an external wall structure as climate shield normally further includes the design of a rain-screen cladding combined with wind barrier, a ventilated cavity and an insulation layer of a certain thickness (even though the needed insulation capacity of a building envelope may differ between different climatic regions and contexts). Due to the

relatively exact tolerances of the prefabricated CLT panels, air tightness can be achieved through the use of pre-compressed foam and/or vapour permeable tape across outside joints.

Exposed materials on the exterior, e.g. structural mass may contribute to the potential heat buffering in the building or reflect light. The effect of light reflections may be beneficial if prevention of heat buffering is desired in the building. On the other hand it may also result in disturbing spreading of light in the surrounding environment. The addition of insulating layers makes utilisation of these effects from CLT difficult. There are external wall solutions designed with a double CLT structure with insulation in between the layers, a solution, which is sometimes ordained by architects wanting the materiality of the load-bearing CLT structure to characterise the façade expression. Normally, however, the effects of weathering on exposed CLT elements make this less desirable considering issues of maintenance and durability.

4.2 INSULATION OF A CLT STRUCTURE

There are different ways to fix the insulation layer in practice. In the early CLT based projects an additional timber stud frame was fixed on the outside to carry the insulation. This of course increases the amount of used material – in some early examples the structure that carries the insulation would be capable to carry the entire building, i.e. making the CLT superfluous. The use of studs furthermore makes irregular and facetted wall shapes difficult to realise in terms of acceptable function of the layers in the climate shield as well as regarding transfer of loads imposed by the façade itself. One solution to this problem is to replace the studs with e.g. a system of fasteners as shown in Figure 7, which are designed to penetrate and fix a layer of high-density insulation to an inner structural surface-element and provide support for an external rendering net. This solution has been developed for concrete construction and is also used e.g. when refurbishing existing brick buildings in need of additional insulation to be fixed externally. This system was applied to carry a rendered facade on the first Swedish three-storey building constructed in CLT in 2001 [16].

Figure 7: *Fastener for rendering and insulation layers.*

The system could be adjusted to carry battens or another support system for any façade material, even a timber based panel with ventilated air cavity on the inner side. The system thereby makes supplementary more material intensive stud structures redundant and provides increased geometrical flexibility as the fixing device can be rationally applied in different angles and at basically any point where extra support for the façade is needed.
The fixing device does not require a main load-bearing direction and is more or less neutral in orientation, which means that the direction of e.g. battens and thereby façade boards or lamellas may be varied on different facets as well as on different parts of the building.

4.3 INTERACTION OF ENVELOPE AND INDOOR ENVIRONMENT

The capacity of the CLT to buffer moisture and heat is of evident interest for potential regulation of the indoor climate. The buffering effects of the mass of the timber in a CLT structure has been shown to provide an evening out of indoor climate both on a 24 h cycle and over a 1 year cycle, given that the CLT is exposed in the interior. 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 [17].

Recently the thermal performance of CLT and the impact of increased peak temperatures have been analysed in relation to the standards of Passive house construction, based on the Murray Grove housing project in London [18]. This is nine-storey CLT-based building was completed in 2009 with 29 apartments located at corners surrounding a double core. On-site measurements were performed in two apartments with different orientations to calibrate a dynamic thermal model. Comparative modelling of the thermal performance of the CLT construction and a similar concrete construction was performed.
The results obtained in the study indicate that CLT-based buildings due to a high degree of air-tightness and high level of insulation in combination with a lightweight construction type (relatively lower thermal mass than concrete) are sensitive to summertime overheating. The data obtained for peak conditions showed that the concrete construction reduced overheating more efficiently compared to CLT, but also that both structural types show sensitivity regarding this aspect.

Passive house as a concept has been frequently debated during recent years, however also studied and applied primarily in residential projects in Europe, and the concept was considered also in the Murray Grove project. The concept is most frequently based on heat retention and thereby proposing sealed buildings without means for passive cooling. The ability of the thermal mass to regulate the internal environment is in the CLT case in the study referred to above reduced due to 15 mm plasterboard lining on the inside and in all 85 mm addition on the upper side of the floor decks (15 mm floor boards + 55 mm screed + 25 mm insulation). This solution is a consequence of regional building traditions, how ditto building codes are interpreted and subsequent

solutions are approached in practice. The situation can be compared with the design of many Swedish residential projects, where the upper side of the CLT-floors are left visible, thereby enabling activation of thermal mass.

4.4 DESIGN OF LIGHT CONDITIONS

The substitution of CLT panels with transparent panel elements means a potential to vary both the external architectural design and the internal light conditions and the design of daylight effects in the interior.
Prefabricated CLT-panels are possible to combine with e.g. window cassettes, which are integrated in the folded structure of the façade and/or roof providing integrated roof lights. Either the transparent panels are integrated in the load-bearing structure or the folded timber shell is designed to provide load-paths around the transparent

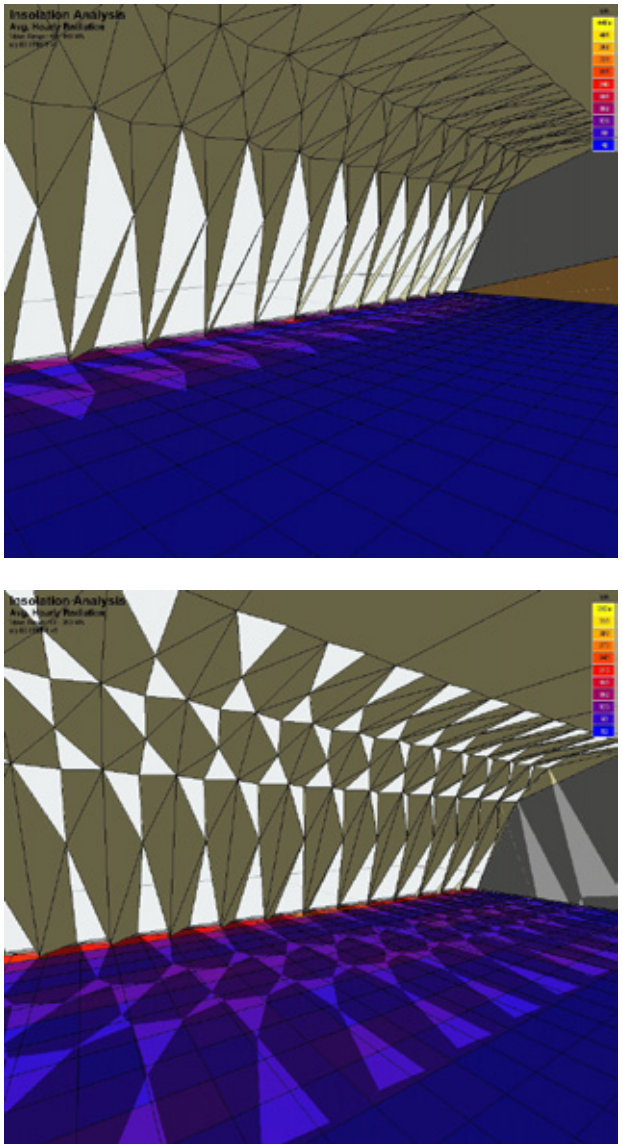

Figure 8 & 9: *Interior light studies of the folded shell with a combination of transparent and opaque element types. Two examples of different panel combinations. (Lighting studies with Ecotect [19] are at 12:00 noon on 21 June in Detroit, Michigan.)*

parts. The facetted internal surfaces, seen in Figure 8 & 9, provide means for varied transmission of daylight and different effects of reflected light in the indoor space.

Improving energy efficiency and reducing energy consumption by using daylighting can be a difficult task to solve due to the many and often contrasting performance parameters. Even if increased daylight can be beneficial in reducing the need for artificial lighting and subsequently increasing electricity savings, it may also increase the indoor temperature. This effect may be desired during the winter season, but is most often regarded a negative effect in the summer period when use of cooling systems needs to be limited to save energy. The actual performance of daylighting will depend on how daylight is penetrating the building surface. Therefore the designer faces the challenge of not only meeting quantitative requirements, but also, and more importantly, to solve them spatially, i.e. to design those elements and devices that allow the control of light penetration (both active and passive functions may be considered).

In the current case the interplay between transparent and opaque elements can be actively utilised as a variable factor in both architectural composition and environmental design optimisation of the structure. Additional shading effects may be obtained through the arrangement of folds adjusted to suit local conditions, protecting the interior from direct sunlight during certain periods of the year. With prefabricated elements for a facetted structure, an opening may be designed to replace one of the facets, as exemplified in Figure 10, where the edges defining the opening are constituted by the surrounding structural elements. Practical issues include form and angle of window openings, angles of edges and structural members surrounding openings, material and surface properties/finish of the lining. The degree of prefabrication and the edge design and finish then has a direct effect on how the light is transmitted

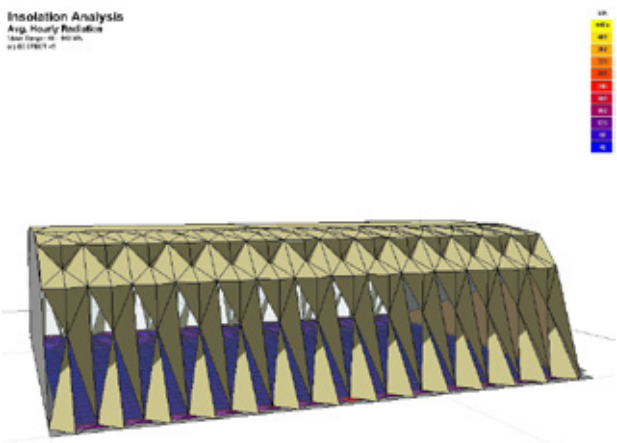

Figure 10: *Exterior view of a folded single-curved structure with a combination of panels. (Renderings are at 12:00 noon on 21 June in Detroit, Michigan.)*

through the façade and into the building. When solving this problem there is a delicate balance between quantitative performance and geometric variables whereby the integrated optimisation strategy applied in this study, has so far shown to be efficient.

As can be noticed, performance-based design procedures can be relatively complex for a CLT based building skin, and will furthermore demand considerable design co-ordination before building erection starts on site, if all openings are to be cut off site. Cutting of openings in the CLT panels on site is feasible but not realistic in all cases, due to lower quality of precision and edge finishing. The decision of the degree of prefabrication is an issue of logistics but also affecting the ways of how to meet the demands for a certain product performance.

5 DISCUSSION

In the current context the relation between climate skins, shell structures and free-form are of interest for further elaboration. These issues imply three partly conflicting factors in the design of building envelopes: For optimised function the *climate skin* requires a certain set of properties and a certain overall dimension of the cross-section. For optimal structural function a *shell structure* pre-defines restrictions regarding overall form and edge design. The current development of *free-form architecture* raises demands for structural solutions to meet the requirements of experimental and highly complex 3-dimensional freedom of challenging artistic expressions.

5.1 THE CLIMATE SKIN

Considering the need for rain-screen and insulation layers on the outside of the load-bearing structure it could in an architectural/expressional perspective be argued that the actual shape of the structural core will loose its expressional precision. If there are additional layers on one or even two sides, what is then revealed of the resulting form of the structural design effort? In temperate climate zones it is not realistic to create a fully protected indoor climate with only one single layer. There are numerous parameters that need to be considered and included in the problem solving process ending up with a complex structure no matter what structural solution is chosen for the project.
However, the structural solution and its properties remain a prerequisite for the possibilities when designing the form of a building. Form and detailing of geometries and fenestration are direct consequences of the utilisation of the structural capacity of the chosen system. Thus, it can be argued that the characteristics of CLT can be explicitly utilised in the architectural design, and the properties regarding building physics can be utilised if the design procedure allows for an iteration of multi-objective criteria, resulting in a metaphorically speaking multi-facetted analysis and evaluation. Then the issue is broken down into questions referring to efficiency in a great number of aspects, and in this context the CLT product flora is, as can be seen, beneficial, considering their structural robustness, buffering capacities, tightness and workability.

5.2 SHELL STRUCTURES AND FREE-FORM

Shell structures are interesting both for their structural capacity and ditto behaviour, the positive effects of their structural indeterminacy and for the clearly expressed architectural features of their structural function. Most well re-known examples from the 20th century are concrete shells like those designed by e.g. Heinz Isler and Felix Candela, which show with brilliance the pure designs of structurally optimised shells. The function as a complete envelope can be difficult to obtain though, due to properties limiting the range of form options for wall structures. The ideal performance of a shell is linked to its ideal form, which in concrete means a certain range of vault varieties and crucial boundary conditions. The search for free-form architecture implies challenges of form-finding and calculation and several theoretical models to study and determine the flow of forces – e.g. trajectories, thrust networks and rain flow – have been developed, in search for facilitating utilisation of the beneficial properties of shells.

Shell structures have steadily been gaining interest over the years, and have been developed also in other materials than concrete, like gridshells in steel and gridshells based on green oak as seen in e.g. the Savill garden entrance building and the Weald & Downland open air museum in the UK. These shell types provide variation on the theme of shells both regarding use, structural form and characteristics and architectural function. Plate-based shells entail another group of typologies, which widens the range of possible architectural forms.

In this way free-form architecture can be realised by choosing different means and systems for the construction, depending on the desired building performance. In the case of CLT it can be seen that the cross-laminated products provide a range of optional structural solutions with potential functional benefits and corresponding architectural expressions, which may be an answer to some contemporary design concepts and maybe even, if further developed, extend the boundaries of architectural concepts through a material based design approach. A project like St Loup already shows the potential in practice and further studied the CLT-based folded structures may further develop applications of folds and facets in construction as well as the transfer of origami into construction of complete envelopes.

5.3 EXTERIOR AND INTERIOR CONDITIONS

The relation between exterior and interior has changed through history, and the difference in approach has developed with the gradual transformation of the cross-section to become more and more heterogeneous. This has subsequently led to a differentiation of properties of inner compared to outer layers of the wall, and thereby the use of different materials and products for the different conditions. In that perspective, architectural

diversification of the inner and outer wall expression is a natural consequence, and once that is recognised it might not be too big a step to completely separate the two structurally. However, material, resource as well as structural efficiency may advocate the opposite approach and furthermore interesting challenges can be found in developing systems and designs making use of an explicit architectural-structural interplay like in the case of CLT-based systems.

6 CONCLUSIONS

Architecturally the concept of utilising one structure for both external and internal spatial form means that the structure defines the architectural form and identity and this may not be suitable in all contexts, but when e.g. a unique, iconic expression is the aim, it could be argued from a tectonic viewpoint that the interior would gain from following where the exterior and its structure go.

Timber based folded structures show potential to provide robust systems for applications as façades. Rational production and construction are recognised aspects of CLT-based designs and the utilisation of CLT in folded assemblies makes efficient use of material and element properties. To be able to manage effects of material properties on the environmental result relating to an object-specific geometry, the envelope design needs to be analysed as a multi-objective problem, and tests of hypothetical character like those currently described may generate principles of general validity.

REFERENCES

[1] Kolarevic, B. and Malkawi, A. (2005). *Performative Architecture: beyond instrumentality.* New York: Spon Press. 2005.

[2] Holst, M.K, Kirkegaard, P.H. and Mullins, M. Performative Tectonics. *Proceedings of the 1st International Conference on Structures & Architecture,* Guimarães, Portugal. pages 1004-1011, 2010.

[3] Majowiecki, M. Architecture & Structures: Ethics in free-form design. *Proceedings of the International Association of Shell and Spatial Structures (IASS)* 2007, Venice, Italy. IL11

[4] Toratti, T. Quality of timber construction Guidance for buildings and load bearing structures. *Proceedings of the 10th World Conference on Timber Engineering (WCTE 2008)*, Miyazaki, Japan. 2-166p, 2008.

[5] Falk A. and von Buelow P. Form Exploration of Folded Plate Timber Structures based on Performance Criteria. In *Proceedings of the IABSE-IASS Symposium: Taller, Longer, Lighter - Meeting Growing Demand with Limited Resources,* P-0229, 2011.

[6] von Buelow P., Falk A and Turrin M. Optimization of structural form using a genetic algorithm to search associative parametric geometry; *Proceedings of the 1st International Conference on Structures & Architecture,* Guimarães, Portugal. pages 609-706, 2010.

[7] Buri, H. and Weinand, Y. Origami – Geometry of Folded Plate Structures. *Proceedings of the 1st International Conference on Structures & Architecture,* Guimarães, Portugal. Pages 675-682, 2010.

[8] Ott, S. and Winter, S. TES EnergyFaçade – Sustainability and Environmental Impact. *Proceedings of the 11th World Conference on Timber Engineering (WCTE 2010)*, Trentino, Italy. paper no 499, 2010.

[9] Mostafavi, M. Between Engineering and Architecture, in H. Kara, editor, *Design Engineering*, pages 287-291, Actar, 2008.

[10] Stotz I., Gouaty G. and Weinand Y. Iterative Geometric Design for Architecture. *Journal of the International Association for Shell and Spatial Structures, Vol 50 (2009) No. 1*., pages 11-20, 2009.

[11] Samuelsson, I and Nilsson, I. *Missfärgande mikroorganismer på råspont,* SP Energiteknik, SP RAPPORT 2006:43. Borås 2006.

[12] Rosenkilde, A and Glover, P. High Resolution Measurement of the Surface Layer Moisture Content during Drying of Wood Using a Novel Magnetic Resonance Imaging Technique, *Holzforschung 56*: pages 312-317. Vienna 2002.

[13] Terziev, N. *Low-Molecular Weight Sugars and Nitrogenous Compounds in Scots Pine*, Doctoral Thesis, Acta Universitatis Agriculturae Sueciae Silvestria. Uppsala 1996.

[14] Schickhofer, G. et al. *BSP Handbuch – Holz-Massivbauweise in Brettsperrholz, Nachweise auf der Basis des neuen europäischen Normenkonzepts*, Institut für Holzbau und Holztechnologie. Graz, pages D-43-55, 2009.

[15] König, J. Load-bearing structures. In B. Östman, editor, *Fire Safety in Timber Buildings – Technical guideline for Europe.* pages 101-103, SP Technical Research Institute of Sweden, SP Report 2010:19, Stockholm 2010.

[16] Falk, A. *Architectural Aspects of Massive Timber – Structural form and systems*, Doctoral thesis 2005:41D, Luleå University of Technology (SP Trätek SP External Scientific Publication) Luleå 2005.

[17] Hameury, S. *The hygrothermal inertia of massive timber constructions,* Doctoral thesis, KTH. Stockholm, 2006

[18] Jowett, O. The Thermal Behaviour of Cross-Laminated Timber Construction and its Resilience to Summertime Overheating. *Proceedings of PLEA 2011 - the 27th Conference on Passive and Low Energy Architecture.* Louvain la Neuve, Belgium. 339-344, 2011.

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