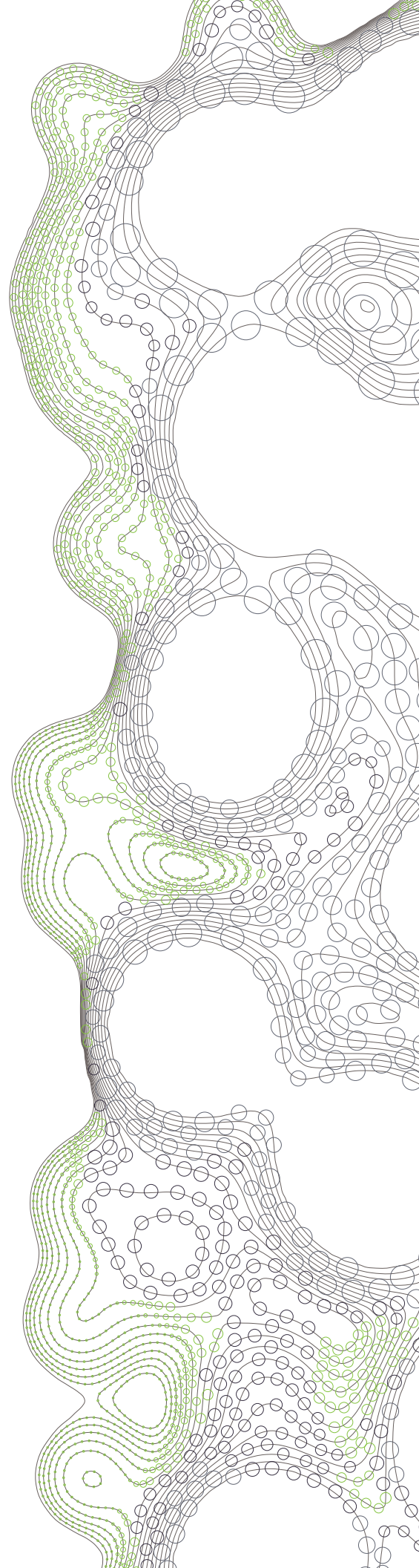# acadia2011
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PROCEEDINGS OF THE 31ST ANNUAL CONFERENCE OF THE ASSOCIATION
FOR COMPUTER AIDED DESIGN IN ARCHITECTURE (ACADIA)

Edited by Joshua M. Taron, Vera Parlac, Branko Kolarevic, and Jason S. Johnson

INTEGRATION THROUGH COMPUTATION: PROCEEDINGS OF THE 31ST ANNUAL CONFERENCE OF THE ASSOCIATION FOR COMPUTER AIDED DESIGN IN ARCHITECTURE (ACADIA) 2011

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FORM, GEOMETRY AND COMPLEXITY

Form, Geometry and Complexity

From *Post*- to *Plus*-Digital

Marc Swackhamer

University of Minnesota
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The 2011 ACADIA Conference theme positions architecture's present condition as "post-digital." This term calls to question the relevance of an organization like ACADIA, whose focus is precisely on the digital in architecture. Paradoxically, it is the work of ACADIA and digitally-oriented designers that has facilitated the gradual dissolution of the digital. In reality, we of course know that the computer has never been more present and relevant to architecture than it is today. The barriers to entry are lower than they've ever been. Digital technology is more pervasive and flexible. But, its ubiquitous integration has rendered the computer itself, with its legacy of opaque user interfaces and inaccessible language, ostensibly transparent. Through this transparency, an array of designers and collaborators previously relegated to the sidelines of computation discourse are now active participants in it. The papers in this session point to five ways in which the boundaries between the digital and non-digital, between architecture and non-architecture, are quickly eroding, and thereby allowing each to influence the other in profound and surprising ways.

First, visualization software increasingly thinks like designers think. How we interface with it closely mirrors how we draw and build with our hands, how we think about space and material, and how we manage complexity through the integration of words, numbers, and lines. In their paper "Potentials for Multi-Dimensional Tessellations in Architectural Applications," for example, authors Celento and Harriss discuss the reasons why theoretical mathematical explorations in multi-dimensional space have not gained traction in architectural venues. One of those reasons is what the authors call "the challenge of visualization." Today, robust computational programs allow for the visualization of higher mathematical concepts that were previously inaccessible to fields outside of mathematics. Concepts that were opaque and discipline-specific before can now be visualized through software that most designers have installed on their computers. This allows those concepts to infiltrate and contribute to the discourse of other disciplines, like architecture.

Second, there is a transparency to current software that allows architects to understand what is happening under the hood and how to control it. This means that they can focus more on "why" they make certain decisions and less on "how" they get software to work. For example, in "Free-form Grid Shell Design Based on Genetic Algorithms," authors Dimcic and Knippers develop a methodology for applying a statically efficient, optimized grid structure over any pre-defined free-form shape. This opens building shape back up to the possibility of being defined not by what the computer dictates (typically referred to as "form-finding"), but by issues external to the computer, like program, site, or more qualitative conceptual strategies.

Third, contemporary parametric software allows for a combination of bottom-up and top-down design processes. Up to now, most computationally-intensive design

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processes have privileged a bottom-up approach where form is "grown" from a set of mathematical equations. This form may or may not address issues of site or program in a way that works for a particular project. This method's potential efficiency, constructability, and clarity are its advantages. But new developments in software allow for work to emerge from a combination of bottom-up mathematical considerations as well as top-down non-mathematical considerations, where the ratio of one to the other is fluid and project specific. The paper "Irregular Vertex Editing and Pattern Design on Mesh" by Kobayashi develops a tool for designing components for a given form that emerge from a more top-down starting point. It takes a form that may have been developed from a study of prevailing breezes or the shape of a site and imbues it with the same level of geometrical and structural efficiency as a form that was developed from the bottom-up.

Fourth, advancements in design software allow for considerations like function, program, or use pattern to be treated as data. In other words, software can anticipate behavior and model systems after it. For example, in the paper "Tetrahedron Cloud," the author develops a stochastic system that embeds particular tendencies in a component's behavior. Their system eschews a model of optimization, where a "best" solution is pursued, in favor of a series of behavioral studies in which every outcome of a deployed system, with its embedded rules, presents a new scenario of behavioral variation. The architect then chooses an array of outcomes to develop further, rather than a single optimized solution.

Fifth, it is easier than ever for architects to customize software to fit their particular needs or those of a specific project. The ability to program, write scripts, or generate plug-ins that modify existing software capabilities is rendering the computer more relevant. It results in work that can precisely respond to its own particular, nuanced constraints. In their paper "Just Passing Through: Integration in Computational Environmental Design," authors Davis, Tsigkari, Iseki, and Aish conclude that integrated approaches to highly complex design problems require a "significant degree of custom programming to solve a specific class of problems." Further, in "Seeking Performative Beauty," Dominguez, Schimek, and Wiltsche write about the development of a software tool that seeks to reveal the hidden complexities in computational geometry and thereby render the whole process more manageable.

In fact, in virtually every paper from this session, the authors have cracked open their software to either render its processes more visible, or to customize its capabilities, or to bring digitally-challenged collaborators into a position of greater participation with a project. This is perhaps the most intriguing finding presented in these six exceptional papers. The digital interface has eroded to the extent that we can now make software our own. Perhaps architecture is moving into an era that can be categorized not as "post-digital," but as "plus-digital." The definition of what is or is not digital is no longer relevant. It is now the material residing outside the field of computation that is returning to exert its impact on the computer, rather than the other way around.

Seeking Performative Beauty

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ABSTRACT

With digital design and fabrication becoming ever more common in architectural design, the computational geometry topic of discretizing freeform surfaces into flat panels has become a common challenge. At the present, most approaches to the issue of preserving a 2D-tessellation on a freeform surface are focused on optimizing the shape of the structure by approximating geometric "equally-sized" flat patterns. In doing so, these strategies treat the approximation of the desired shape as the primary goal, leaving aside the aesthetical aspect of the paneling, which can be seen as having an ornamental quality. In contrast to these common strategies, the project presented in this paper pursues a more holistic approach that tries to integrate aesthetical as well as structural issues by using more complex as well as more performative patterns for the discretization. In the present paper, we present algorithmic strategies that were designed to integrate from the aesthetics of an exposed timber structure, through analysis of structural loading feedbacks to a detailed level of the physical joint system, as part of the fundamental early design decisions. The consequence of the overall negotiations relies fully on their physical integration through computational design. The present paper discusses both the algorithmic techniques and the joint systems through a series of case studies. At the end of the paper we provide an overview to upcoming tasks including the production of a major structure.
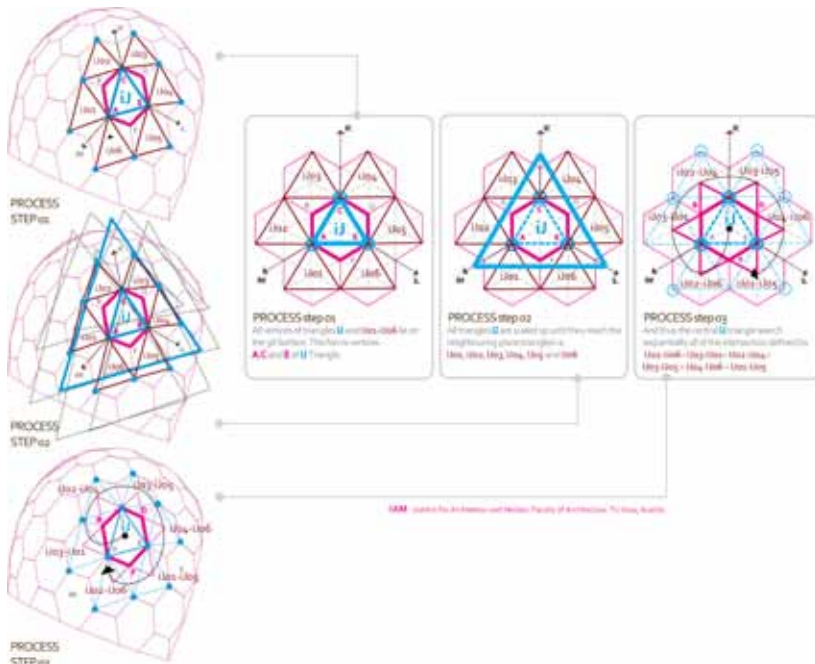
Fig. 2

1   Introduction

Architectural design aesthetics play a major role when designing a building. However, the aesthetics of a digital design are frequently altered when it turns into building construction (Ruffo Calderon and Hirschberg 2011). In order to approximate a digital design, and due to material and physical constraints, a double curved freeform structure needs to be divided into curved components or flat panels. However, the physical constraints of nonstandard geometries are frequently a post-rationalized concern rather than early design integration (Scheurer 2010). Altogether, the extensive digital revolution has exposed an urgent need for a fundamental integration of digital design, fabrication processes and building construction technologies.

The present paper discusses a series of strategies for preserving the aesthetics of ornamental 2D patterns in order to discretize a positive double curved transitional surface through computational algorithmic design and building construction technologies. This ongoing funded research project (Ruffo Calderon 2011) introduces different techniques for approximating a desired pattern and for visualizing complex systems of tessellations to envelop freeform geometries.

In terms of building construction, any freeform surface can be approximated by using plane triangular patterns (Glymph et al. 2004). However, a complex geometrical issue arises if the approximation of the desired shape should be divided into ornaments of four or more sided elements. Unlike in the case with the triangular elements, where the preservation of the exact 2D pattern in the 3D environment is a straightforward process, for more complex paneling patterns this becomes a problem. To preserve the aesthetics of the 2D pattern, shape approximation operations must be performed through advanced computational geometrical algorithms.

The aesthetic control faces a twofold issue: since the 2D-pattern may be distorted -depending on the complexity of the shape- when it is mapped onto a freeform surface we need to integrate a live simulation model in order to keep the decision of the aesthetic control of the computed pattern in the designer's hands. Second, when the algorithm is calculating the geometry of an individual panel, our intention is focused on preserving the designer's control throughout the design, fabrication and construction processes. In other words, our work focuses on allowing designers to control the overall meaning of a digital building based on aesthetical enhancement right from an early stage of the design and to follow it through to actual building construction (Ruffo Calderon and Hirschberg 2011).

The building material we are using is cross-laminated timber board or CLT. CLT material has an excellent reputation as a sustainable and regenerative material and CLT boards can be easily machined with a large variety of robotic tools including CNC milling machines. As per the structure, the joints between CLT boards have to transfer positive and negative axial forces, lateral forces and bending moments, since these
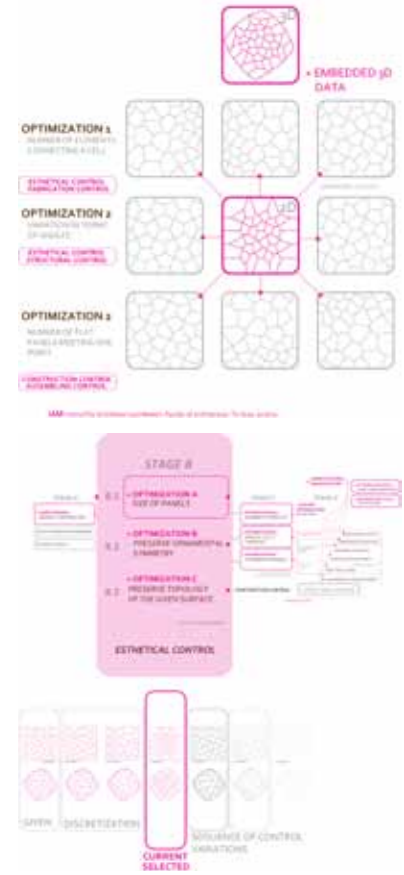

Fig. 1

Figure 1. *An overview of the interface of the platform showing interactively how to select a pattern and the population of the flat components*

Figure 2. *Process of the 3D plane components*
Left: *A double curved surface with the so-called Honeycomb pattern*

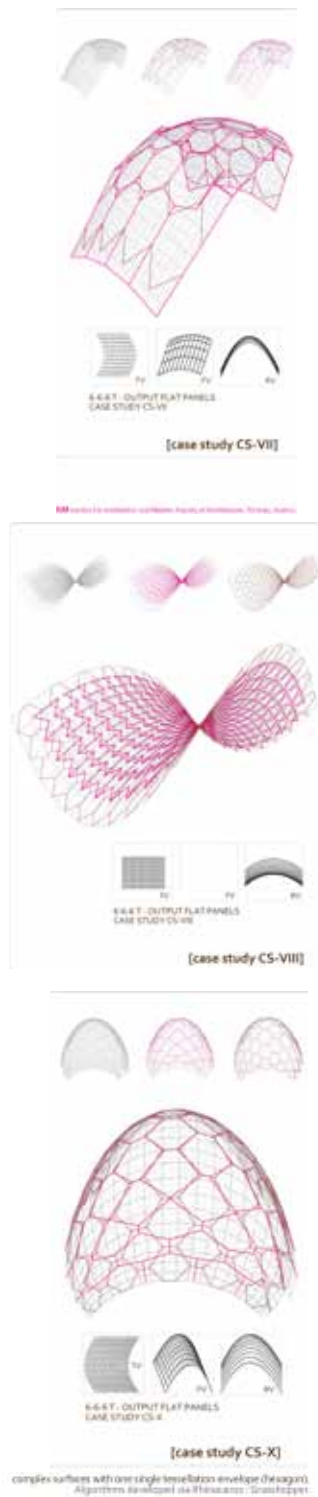Right: *The concept of the algorithmic approach based on triangle negotiations*

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[case study CS-VII]

[case study CS-VIII]

[case study CS-X]

complex surfaces with one single tessellation envelope (hexagon).
Algorithms developed via Rhinoceros : Grasshopper

Fig. 3

Figure 3. *The honeycomb pattern applied into -left and right- positive double curvature surfaces (parabolic) and center on a hyperbolic surface. Note that the honeycomb pattern is transformed into a non-convex pattern in negative curvature*

Figure 4. *A Graphic system is designed in order to set up different permutations and variations between tessellations*
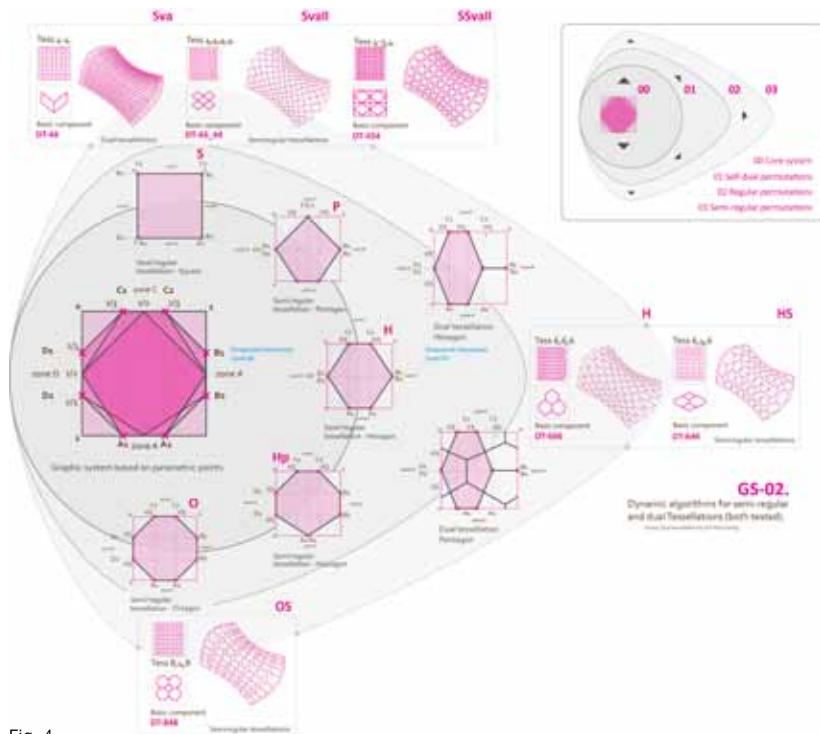

Fig. 4

CLT structures are intended to be self-supporting, thus carrying all loads without any additional support structure. At the present, there are no built examples that use such joints for CLT structures (Schickhofer et al. 2010). Consequently, this paper proposes a new joint: the "sewed" joint, whose stitch pattern is similar in appearance to the stitches of a seam. Since these joints will be exposed on the exterior of the building envelope, they will have a dominant influence on the appearance of the structure. Hence being able to control the relationships and the distribution of the connectors is not only a question of load transferring between the panels but also a creative and intuitive process carried out by the architect.

Here our approach becomes significant, as it fully relies on the use and design of fundamental computational means in order to hold all the stages of the construction life cycle from the initial architectural design, through to the actual construction of the building. The core aim of our ongoing research project is both the design of software capable of dealing with the geometrical and physical constraints, and the design of a major structure. The latter is meant to demonstrate that the integration between a digital design and the physical constraints, when dealing with a complex freeform geometry, is possible.

2   Exploring Different Algorithmic Possibilities

Regarding related investigations to the problem at hand, there exist two main known solutions in the international   research community. The first solution is focused on the optimization of the desired design based on computational progressive approximations (Cutler et al. 2007; Pottmann et al. 2007; Eigensatz et al. 2010). The second approach is based on the 3D tangent plane intersection (Hans 1993; Almegaard 2003; Bagger 2010; Stavric et al. 2010, 2011). While making use of the mentioned algorithmic knowledge, the main advantage of our approach, is that it is based on live explorations of the discretized shapes **(Figure 1)** in order to visualize the entire optimization process. This allows us to test the sequential advances and the aesthetic results in a dynamic and faster form. This particular form was a way to crack the complexities hidden in computational geometry and mathematical form finding into more manageable processes in order to make them more suitable for designers (Ruffo Calderon and Hirschberg 2011).

2.1   COMPUTATIONAL GEOMETRY DESIGN: A CORE ISSUE

One major issue within computational geometry design (Mount 2002) is that of tessellating either partially or entirely a given freeform surface out of planar components. The overall task becomes progressively complex and demanding to solve as it involves a major cross-multidisciplinary task (Ruffo Calderon and Hirschberg
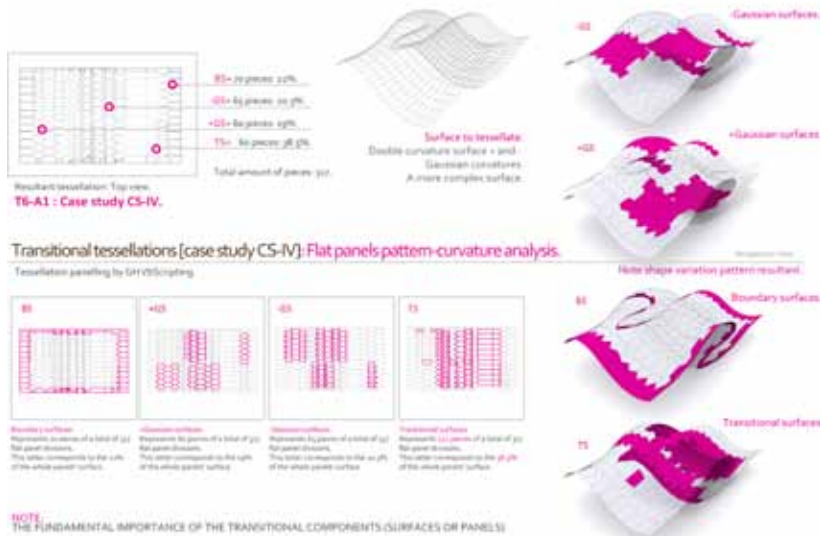
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Fig. 5

Fig. 6

Fig. 7

2011). The issue demands different background knowledge such as mathematical, geometrical, form-finding techniques, physical and material constraints and moreover associative and parametric design, algorithmic or scripting knowledge.

This paper focuses on positive and negative double curved surfaces that may manage complex curvature variations. It also considers the issue of working, in the same design form, with parabolic and hyperboloid curvature variations.

3 Algorithmic Design Strategies Based on Realtime Explorations

Our algorithmic approach, takes in the first instance the UV values of a 2D plane and, in the second selects three points that rely on the desired 2D ornament, which eventually form a plane triangle on the 3D surface, the IJ plane **(Figure 2)**. The IJ and the neighboring planes intersect each other in order to find the pattern of the central cell. We repeat this process several times through the whole surface in order to aim the desired pattern.

The three points on the algorithm strategy keep no deviation from the desired design to approximate, since they already rely on the 3D surface. The latter is a major advantage that allows the smoothness of the design to discretize very similar to the given one. However, we are also in the process of approximating more complex non-uniform shapes with the intention to keep the ornament defined in the 2D plane as similar as possible. **Figure 3** showcases different possibilities for double curvature variations concerning both parabolic and hyperbolic surfaces.

In order to integrate multiple tessellations, we propose a 'graphic system' in which the algorithm semi-automatically negotiates the points that describe the 2D desired ornament **(Figure 4)**. This opens up further possibilities to integrate multiple and complex tessellations on the UV plane and out of it too.

After a tessellation has been selected and the resultant flat panels are found, a major question arises: how to deal with strong curvature changes, especially when the desired surfaces continuously describe positive and negative Gaussian variations **(Figure 5)**. We have explained and shown in **Figure 3** that negative curvature surfaces will result in non-convex patterns. However the major problem that we are currently facing is the continuity of the properties of the algorithm when it meets strong curvature variations, especially those beyond transitional surfaces.

During our investigations in computational geometry design, we noticed a major relationship. The rules that govern the desired surface, either by building it or manipulating it, need to be coded within the algorithmic solution. One major constraint is the geometry to approximate but another one is the geometric rules that describe the desired design curvature in the first place.
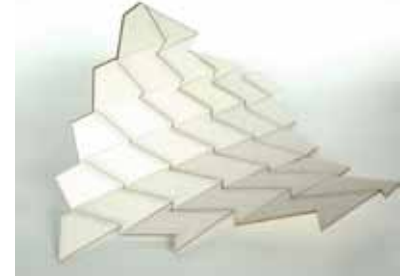
Figure 5. *This figure analyses the fundamental importance of the transitional components i.e. the patterns (panels), which change form when the local curvature diverges from positive to negative Gaussian values*

Figure 6. *This figure showcases different possibilities for hexagonal tessellation permutations mapped on a positive double curved surface*

Figure 7. *Left ornament (Srf00) seeks a hexagonal patter all the way through the surface whilst right ornament (Srf01) is based on the FEM feedbacks and then re-designed for a better distribution of the loading joints that hold the structure*
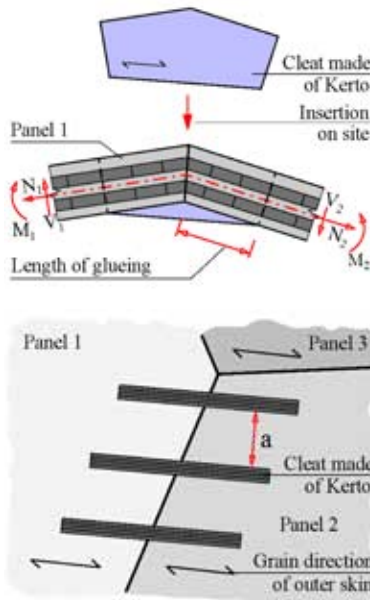
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Fig. 9

Fig. 8

Fig. 10

Figure 8. *Structural ornament based on FEM feedbacks*

Figure 9. Top: *Serpentine Gallery Pavilion, 2006, Architect: Álvaro Siza and Eduardo Souto de Moura with Cecil Balmond – Arup*

Bottom: *Chapel for the Deaconesses of St-Loup, 2008, Architects: Localarchitecture + Danilo Mondada, Structure: IBOIS – Hani Buri, Yves Weinand*

Figure 10. *Top: The "sewed" joints, cross section showing axial forces N1 resp. N2, lateral forces V1 resp. V2 and bending moments M1 resp. M2*
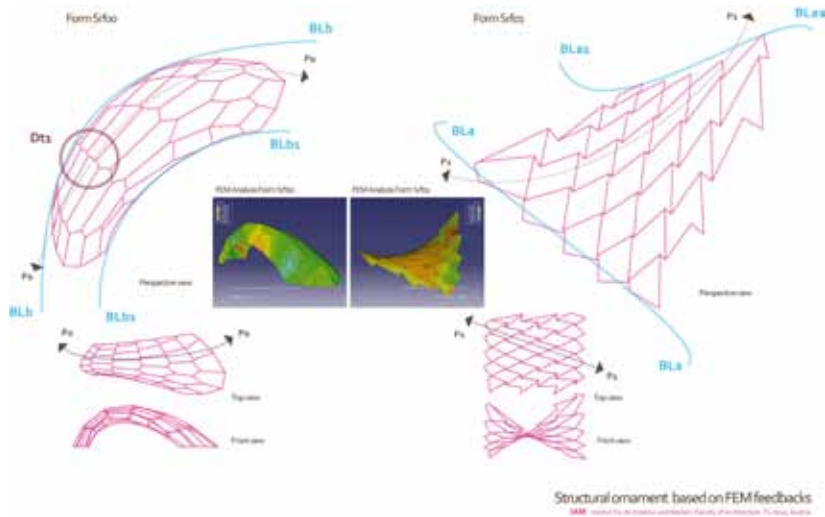
Bottom: Top view

4   Algorithmic Design Realtime Potentialities

Presently, the potential of our algorithm is determined by the following variables: a) the possibility to vary the number of elements in either U or V values, b) the possibility to change the scale of the components in a local, regional or global scale, c) the possibility to change the topological structure of the tessellation, d) the possibility to approximate a desired pattern by interfering in the properties of the local curvature, e) the possibility to interactively negotiate all the above potentialities in live fashion.

Different honeycomb ornamental possibilities are demonstrated in **Figure 6**. The potentialities described earlier are enhanced; by changing v-ery simple rules at the core of the system to control the aesthetics of the 3D ornament. Certainly, these aesthetics are not only related to the ornament itself but also to the changes of the curvature to meet **(Figure 5)**. In order to meet the complexities analyzed in **Figure 5** aim this latter, we are currently exploring different possibilities for improving the behavior of our algorithms to achieve a better approximation of the aesthetical ornament, and a better performance of the overall structure.

The major case study discussed here **(Figure 7)** experiences major curvature variations with an impact on the overall structure. In **Figure 6**, the left surface (Srf00) is based on a positive double curved design whilst the right surface (Srf01) is based on a negative double curved design. Here, our algorithm uses a major feature where the output ornament may be variable in form. In doing so, our explorations become relevant in terms of structural and aesthetical meaning. With the current approach, we intend to create a digital feedback that loops towards getting one of the best performances that embrace the whole network of components working as a single self-support system. Thus, by inferring in the ornament in the first place, one may get both the approximation of the desired design and the control of the aesthetics of the pattern.

4.1   FEM FEEDBACKS FOR DESIGNING AN ORNAMENTAL TOPOLOGY STRUCTURE

In order to negotiate the aesthetics of the ornamental design on a self-supported structure, we know that FEM feedbacks (*section 7*) constrain our designs in a two-fold way. The first is that the flat panels on a surface should communicate tension forces through the whole surface and over a single direction without breaking the path **(Figure 8,** P0 and P1 lines**)**. As we will explain in section 8 this will also lead to the population of components and the aesthetics of the overall joint system. The second issue, consequently, is that the very first design should be similar to a transitional surface. In other words, the two border lines **(Figure 8,** BLa0-BLa1 and BLb0-BLb1**)** forming a surface should remain similar in dimensions. At the end of section 6 we are providing some early results of the structural tension tests in order to keep the overall aesthetics by using one single material (CLT).

In the following sections, we explain in more detail how the CLT structures, the assembling techniques and the joints explored in our project, are generated in order to create an integrated algorithmic design.

5   Freeform CLT Structures

Freeform CLT structures are not very common especially the ones with exposed structural detail; usually the structural details are not visible, hidden under an external envelope and/or interior layer. One of the rare

built examples is the Chapel for the Deaconesses of St-Loup, built in 2008 by Localarchitecture + Danilo Mondada **(Figure 9)**. The structural engineering was performed by Hani Buri and Yves Weinand from IBOIS, Lausanne; based on a former research project by Buri named *Origami – Folded Plate Structures* in which he investigated the performance of regular Origami folded plate structures (Buri 2010).

Another example that explored exposed structures is the Serpentine Gallery Pavilion (2005) by Álvaro Siza and Eduardo Souto de Moura in collaboration with Cecil Balmond of the AGU-Arup, where the latter investigated a universal connection detail in a grid roof structure that was entirely built of timber. The construction works well in detail, but it deforms the homogeneous pattern along the surface. For example at the intersection points we observe an irregular displacement of the structural pattern from one intersection point to the next one **(Figure 9)**. Joints have significant influence on the structure's characteristics, therefore the consistency of an architectural structural detail over the structure, as a whole is crucial for the appearance of a building with an exposed structure. In the following section we will discuss how to control the pattern of a joint detail of a self supported CLT -freeform structure, in order to preserve the aesthetic of the initial design, both in terms of the form and the architectural detailing.

6   The Beauty of Architectural Structural Details

"Joints are the key to harmonious structures. The challenge for the designer is to produce joints which early communicate their function - the job they are actually doing - and to do this in an efficient and elegant way" (Addis 1994). Andrew W. Charleson identifies ten characteristics of contemporary detailing: refinement, slenderness, expression of materiality, innovation, complexity, sculptural quality, relationship of building form, sensitivity to human proximity, relationship to building function and expression of structural action (Charleson 1994). We consider five of these characteristics of fundamental importance for our investigation: refinement, innovation, sculptural quality, and relationship to building form, function and expression of structural action.

In the following section, we discuss how structural detailing can contribute to the aesthetic of an exposed timber structure. Naturally, structural engineers and architects have different objectives when evaluating the performance of an architectural detail. However, the aim is to find a compromise between the engineer's criteria, providing enough structural performance of the joint detail, and the architect's urgent need for the aesthetics of structural detailing. In other words, we integrate a FEM stress analysis of a non-homogeneous plane structure into the design decisions at an early design stage. We consider how much influence does the architect have concerning the joint design? With associative and parametric software, we compare different discretized pattern variations on a desired design, on which we apply different patterns in order to compare the resulting joint pattern. As a result of this work, we expect to deepen the collaboration between architects and engineers.

As described by Andrew Charleson, the joint system dramatically contributes to the appearance of the exposed structure (Charleson 1994). In order to meet the designated requirements of the joints (i.e. aesthetically pleasing higher performance load transmission capacity and easy assembly) in our project, we had to invent a new joint system - the so-called "sewed" joint **(Figures 10, 11)** (Schimek et al. 2010). At the moment no such joints for CLT- space structures exist (Schickhofer et al. 2010).

Since such space structures are made of cross laminated timber panels or CLT, which carry all loads without any additional structure, the joints of the single panels have to transfer both, positive and negative axial forces, lateral forces and bending moments.

Simultaneously, the joints must be as efficient as possible due to aesthetic and economic reasons. Hence, the load-bearing capacity of the joints should not be much lower than the panel's one. Thus, for instance, areas with low stresses get a smaller number of connectors.

Caused by the anisotropic material behavior of timber, deviations between the grain direction of the outer layer of the CLT-panels and the cleats have to be avoided as far as possible. Tensile stresses perpendicular to the grain in the panels should be as small as possible **(Figure 12)**.

With a CNC-machine, slots are cut into the panels in order to glue parallel laminated veneer (cleats made of KERTO-S, which is an engineered timber material with high mechanical load capacity). According to the stresses, the interval of the cleats can be modified.

We are currently working on a parametric controlled connector system in order to connect the panels of a freeform building using processed standard elements like CLT-panels (Schimek et al. 2010).
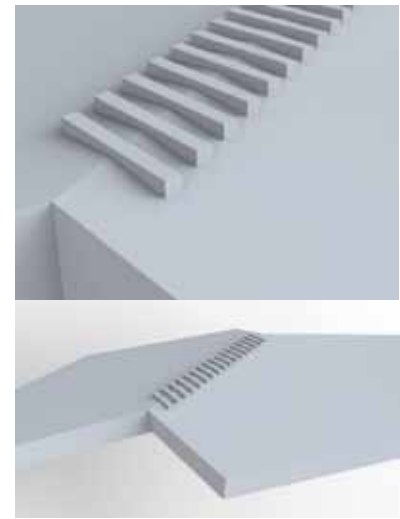
Fig. 11

Fig. 12

Figure 11. *Top: 3D-model of inserted KERTO-S cleats (close-up) - Bottom: Sewed joint between CLT panels*

Figure 12. *Joint assembly in real scale at the tension load test - KERTO-S connector and panel are sliced for the test - CLT grain direction and connector aligned*
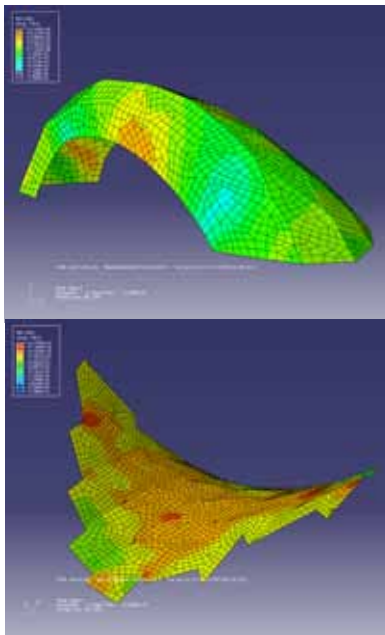
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Fig. 13

Fig. 14

7   Pattern of Joints

Five criteria define and respectively constrain the aesthetical appearance of our innovative joints: size, geometry, position, orientation and quantity of connectors. Two of the criteria, size and geometry, are determined by the structural engineers specifications. This is based on their experience, their empirical observation of load tests with mock-ups and FEM analysis. Hence finding room for an architectural inference is very challenging and leaves us with the question at hand to what extent will the remaining three criteria (position, orientation and quantity) be flexible for an aesthetical intervention?

The engineers deliver the FEM stress analysis of the shape designed by the architect. The model used in this analysis is an ideal model, in other words the orthotropic characteristics of the timber material is not taken into account; mechanical parameters of the material are being estimated. Two calculation algorithms are performed in the FEM software ABAQUS:

- Orientation of stress components give a hint for the required grain direction of the relevant member – required data for joint orientation and position

- Range of section moments give a hint for the number of connectors to be inserted

We consider this early stage FEM stress analysis a "calculated estimation" that conducts the design interventions concerning the connector position, distribution and orientation. We use this method to investigate different patterns on the same shape and compare the joint patterns that are dependent on ABAQUS' pre-calculation. **Figure 13** shows the visualization of the section moments field output of the FEM analysis that provides the data for the design interventions on the desired surface. According to the retrieved data, we adjust the parameters of the shape's discretized pattern in the parametric model. After visualizing the connector pattern, the loop goes back to the FEM again. In case of an unsatisfying result, we repeat this process until we reach an aesthetical satisfying solution. The connector´s angle depends on the shape of the surface and, more importantly, on the selected ornament. **Figure 14** shows that it is crucial to use an ornament, which allows a preferred (grain) direction between the panels over the entire structure. The consequence is a limitation of the variations of possible patterns but also challenges the potential of our algorithm.

8   Modulation

The alteration of the pattern flattens the angles of the neighboring members leading to a preferred grain direction of the members, which is to be favored since a minimal deviation between grain direction of the outer layers of the panels and connector orientation is crucial to optimize the load transmission ratio **(Figure 15)**.

Another issue, which arises from the manipulation of the pattern, is the length of the connecting edges. We need to keep a minimum length of the connecting edges in order to place enough connectors that meet the required static performance of the joint, which has been calculated in the structural analysis – the longer the edge the more connectors can be set **(Figure 16)**. With this optimization process, we are able to influence the appearance of the joint pattern significantly.

9   Conclusions and Further Discussion

We have discussed a novel computational design strategy for integrating digital design freeforms with the building construction constraints. Our present approach is, to solve major computational geometry issues that are constrained by the material and the construction features. The fundamental desired outcome of our approach comes from the logics hidden on the algorithmic calculations that combine both the aesthetical organization of the cells forming a topological structure and the aesthetical population of the structural loadings, which tend to turn the overall computational design meaning into physical self-support systems.

There are very few, either engineering or architectural, contemporary strategies that are trying to deal with these kinds of complexities in order to meet a given design. However, most of them do it after the design has been defined, and, this is a fundamental issue that we believe needs to be solved in the very first place, i.e. when the design is being conceived. Certainly, this is not a straightforward task since, in order to do so, one may need to integrate major fundamental features from different design and engineering backgrounds.

To this end, we are currently developing a software-tool, which would be able to crack the complexities hidden in computational geometry and mathematical form finding into more manageable processes, in order to make them more suitable and intuitive for designers. We expect to deepen

Figure 13. *Visualization/Comparison of Srf00 (Top) and Srf01 (Bottom) in Abaqus showing section moments (SM) at integration points (colored mesh)*

Figure 14. *Visualization and comparison of connector pattern of two different shapes. Laser cut cardboard models; Top: Srf00, Bottom: Srf01*

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the collaboration between architects and engineers. For testing this, we are currently working on a major structure that is intended to integrate the digital desired form on a physical building. This structure will demonstrate the possibilities inherent in the software-tool that can be used for other major buildings in the present and in the very near future.

Acknowledgements

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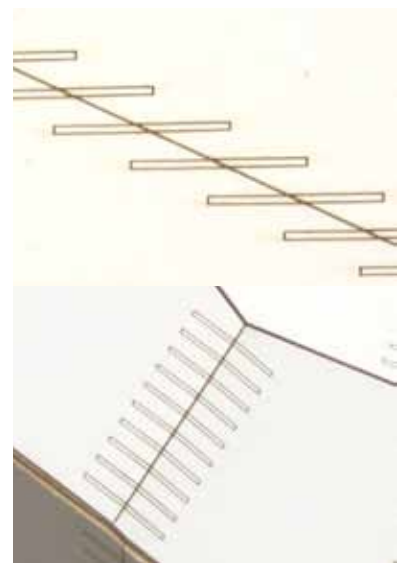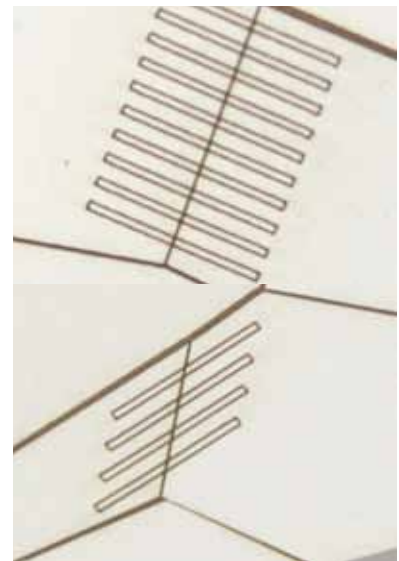
Fig. 15

Fig. 16

Figure 15. *Physical models comparing the connector angles*

Figure 16. *Physical models comparing the length of connecting edges*

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