

The Synergy between Structure and Ornament

A reflection on the practice of tectonic in the digital and physical worlds

Mania Aghaei Meibodi¹, Hamia Aghaiemeybodi².

¹Lulea University of Technology, Sweden, ²KTH Royal Institute of Technology, Sweden.

¹<http://www.ltu.se>, ²<http://www.kth.se>

¹mania.meibodi@ltu.se, ²hamia@kth.se.

Abstract. *The use of digital design and fabrication technologies in architecture has followed a paradigm shift, which has seen the topology, form and structure of architecture pushed to incorporate areas such as climate, construction, acoustic etc. While these digital technologies are intended to enhance the processes and performance, a discussion of aesthetics has been ignored. Surmising that the use of digital technology enhances the performability and efficiency aspects of architecture as well as the aesthetics, this research questions what the new relationships and arrangements for structure and ornament are. What are the challenges when structure uses a process-based logic and is sensitive to materiality whereas the aesthetics has a representation-based logic and is not sensitive to materiality? The authors of this paper contribute to this debate by using the notion of tectonic as a platform for gaining and creating knowledge about this issue and examining the issues through the design and prototyping of a Multi-functional Pavilion.*

Keywords. *Processes; ornament; digital technology; tectonic; architectural expression.*

INTRODUCTION

In architecture, computer technology has created the opportunity of working more closely with topology along with the “ability to control fabrication digitally, to drive cutting, bending and assembling, to simulate and optimize material performance, to control geometry with precision” (Penn, 2011). This has led to the emergence of new techniques and a paradigm shift: “...others believe that we are witnessing a “topological turn” amounting to a digital paradigm shift in architecture history...” (Markussen, 2008).

In this paradigm shift, much of the contemporary research has focused on the processes and the use of digital tools for enhancing the efficiency of the architecture in its intended role. Often, the material, the structure and the form need to fulfil a spe-

cific role, in areas such as acoustics, climate change and construction processes. Examples of such projects can be found in “Performative Architecture: Beyond Instrumentality”, edited by Kolarevic and Malkawi (2005). What is interesting in these projects is the attention given to aspects of efficiency and process coupled with the lack of attention that the aesthetic received. The discussion of aesthetic, ornament and decoration in architecture has become somewhat taboo.

In particular trajectory of digital design and fabrication, many projects whose purpose was to accomplish a task (such as material and structural performance) share a similar aesthetic and artistic expression through the way constituent parts of the

artefact are interrelated or arranged (topology). If we surmise that the use of digital technology enhances performability and efficiency aspects of architecture as well as the aesthetic, then what potential do these tools offer for previously separate constituent parts of architecture? How are the constituent parts of architecture interrelated or arranged? In particular, what is the potential for the relationship between the previously distinct categories of “structure” and “ornament” in architecture? What are the challenges in managing this relationship when the process of creation is carried out in both a material and non-material world? Does the forging of this relationship take place only in a digital world? How does this relationship offered by technology actually become manifest in the produced artefacts? What is the potential for developing architectural features, language and expression, in regard to structural and ornamental aspects, when using digital technology in the design process? What is the relationship between the physical representation of an artefact and the digital processes that created it?

This paper contributes to this debate by examining an experimental design as a case study. An experimental design was studied on the basis that it is not possible to understand the impact of a tool used to create something unless it is examined whilst actually being used.

TECTONIC PRACTICE AS A CREATION PROCESS

One cannot avoid the topic of tectonics when the study of an artefact is developed on the one hand due to its application and on the other hand due to its conformity to notion of art. This is especially true if the study draws attention due to the technological changes involved. The term “tectonic” refers to objects, without distinguishing between the fields of art and technology or the processes used to create these objects (Schmidt, 2007). The word originates from the Greek word *tekton*, meaning “carpenter and builder”, that derives from the root *tek-*, meaning, “to make”. Later, as the role of “tektone” was given to a master builder, or “arkitekton”, the term

evolved to refer to an aesthetic rather than technical aspects of their work. In this paper tectonic means, “to make” and is understood to be a way of gaining or producing knowledge. With the introduction of digital technology, Leach (2004) and many other authors touched upon this topic and introduced a combination of the two, termed “digital tectonic”, in which tectonics is practiced digitally. Schmidt (2007) and others view digital tools as merely transforming the way tectonics is practiced. In this case, tectonic practise deals only with physical material whilst Leach’s perspective is that digital information forms the material for digital tectonics. This is a matter of how one views the word tectonic. From our point of view, tectonics is not bound to material, because the origin of the word tectonic itself does not link to material. From this point of view, it is important which medium the practice of tectonics (“making”) is taking place through and for what purpose. If the aim of “making” through a digital medium is the production of a physical artefact (which is the case in this paper) then it is important to understand how this “making” (tectonic) in the digital world is synchronized with the “making” (tectonic) in the physical world. It is also important to understand whether the techniques used in the digital world are in anyway constrained by the techniques used in the physical world. How does the combination of the physical and digital worlds improve the process of “making”?

Digital technology and ornament

In his conversation with Leach on “The Structure of Ornament”, Lynn viewed ornament from two different perspectives, either as an applied decoration or “fused interacting processes” (Lynn and Leach, 2004). His interest in ornament comes primarily from the method of crafting surfaces using CNC technology [Figure 1]. *“I try to exploit the tooling artefacts that the CNC machines leave on formwork and objects. This gives a highly decorative effect”,* Lynn said. He further noted that *“The process of converting a spline mesh surface into a tool path can generate a corrugated or corduroy-like pattern of tooling artefacts*

on surfaces...the decoration emerges from both the design of spline surfaces" digitally and the "conversion into a continuous tool path" for the physical world. In this case, Lynn stated that ornament "is not applied but intrinsic to the shape and mathematics of the surface, and in this way the ornament accentuates the formal qualities of the surface". Further he claims if ornament is seen as "fused interacting processes (if it is though intricately)" it can accentuate structural form. Leach expanded this topic by surmising that if ornament can accentuate structural form, structure itself can be seen to contribute to the ornamental. Lynn added that previously distinct categories of ornament and structure "would have to open themselves up with some lack or deficiency to then allow the other term to reorganize it internally. So it is not just the expansion of structure into the field of ornament or ornament becoming structural, but rather dependency on collaboration that transforms each category in some unforeseen and unprecedented way".

Ornament and structure

Throughout history, ornaments have had various relationships with structure and were introduced at different stages of construction. In the post and lintel principle of classical architecture, ornament was a separate entity and was an applied decorative. In the new structural principle of the gothic architecture to achieve light, ornament was a visual part of the structural system and was introduced as part of the construction process. In the modern era, the industrial revolution neglected ornament [FIGURE 2]. In the history of western architecture, the closest relationship between structure and ornament relating to expression in architecture can be seen in the vault and ribs of a gothic church.

Robert Willis described the gothic ribbed vault thus: "the ribs are the principle features, and the surface of the vault subordinate" (Willis, 1910). For many years, it was generally accepted that gothic ribs played a predominantly structural role. However,

Figure 1

A temporary installation for the Cologne furniture firm (Lynn and Leach, 2004) in which the foam are formed by a 5 axis router with a large diameter cutting tool (right). Illustration of cutting tools (left).

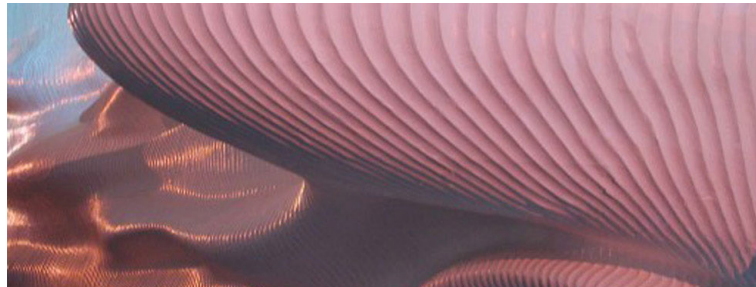
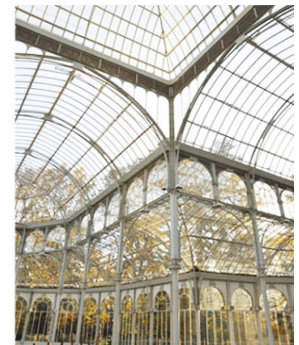
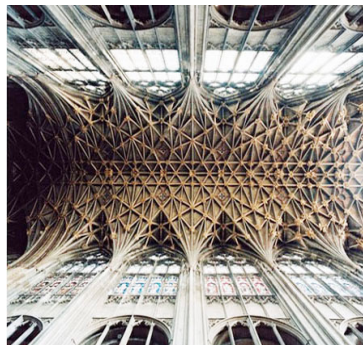


Figure 2

Examples of classic and gothic architecture alongside industrial building.



disagreements between structural theorists regarding the constructional and structural role of these ribs led to further studies. Through these studies, the ribs have been shown to lack structural function within the complete vault system. The rib was originally assumed to strengthen the vaulting, but, by 1300, its non-structural nature was well understood (Alexander, Mark, and Abel, 1977). However, the constructional and aesthetic aspects of the ribs take on a greater importance than their structural function (Alexander et al., 1977). The ribs in the gothic vaults have contributed to the process of “making”, the construction and the geometrical orientation of those vaults. When the last stone of the vault is placed and the centring is taken away, the role of the ribs are shown to be just ornament and the vaults play the principle role of carrying the weight.

Minding the gaps

In the digital approach discussed by Lynn, the ornament, as seen from the perspective of fused interacting processes, is, however, extracted from the mathematics defining the surface in the digital environment and does not play a role in the digital or physical construction of the artefact. The form is defined and the ornament is extracted from it; thus the ornament could also be seen as an applied ornamentation or a customisable by-product. In the example of gothic ribs and vaults, the ornament (ribs) determines the form and shape of the vault by being involved in the physical construction process. In other words, ornament is part of the decision-making in the making process (tectonic). An important

part of this making is the construction and the way of putting the constituent parts together. How does the making of ornament and structure take place in the digital world where physical laws (such as gravity) and materiality are absent? To what extent do the tools that are used to synchronize the digital world with the physical world play a role in determining this relationship? What challenges arise as a result of the synchronization between the digital design and the physical construction?

Experimental case study: the multi-functional pavilion

The examination of the relationships between ornament (aesthetic), structure (performance), tectonic (processes and methods) and tools (techniques and technology) has been carried out through the design and production of a Multi-functional pavilion. Based on the questions we had in mind, the nature of the site (in Lulea city, North Sweden) and user behaviour across the seasons, we listed the qualities that the pavilion must have: 1 - the pavilion should be expressive of the technology of its time; 2 - the ornamental, structural and constructional aspects must have an intricate relationship with its form; 3 - it should explore singular structural and ornamentation principles; 4 - it should be made economically, with available material and using only one type of fabrication technique with CNC technology; 5 - its width, length and height should not exceed 4.0 x 10.0 x 3.0 metres respectively and not be smaller than 1.0 x 6.0 x 2.6 metres; 6 - it should be a place to sit or lie, usable throughout all the seasons; 7 -

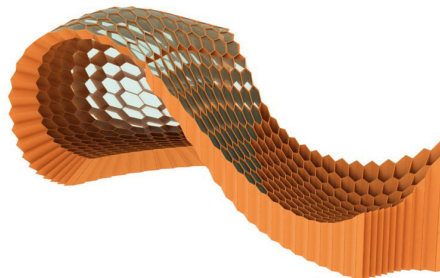
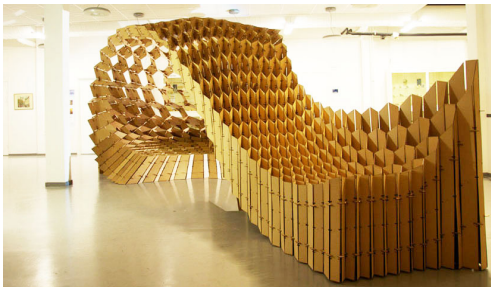


Figure 3
Prototype of the pavilion.

Figure 4
Digital model of the pavilion.

in all seasons, it must allow penetration of sunlight through its skin; it must not be totally enclosed and allow circulation of fresh air; 8 - it should protect the user from the wind and snow.

The result was a full-scale prototype of the intended pavilion with a width, length and height of 3.0 x 7.0 x 2.6 metres respectively [Figure 3]. The budget meant that the prototype was not built with the glass panels, which are shown in the digital model [Figure 4]. These glass panels were designed to prevent wind flow through the pavilion. Their location was based on results from wind simulation. The pavilion is built out of 2976 geometrically different plates and joints using 3.2 mm Masonite; these elements are nested in the form of a hexagonal structure, forming a snail shell. One end of the structure gently turns inwards, touching the ground, to create an enclosed space and seating area. The other end merges with the landscape and site topology to create an area to lie on.

Network of connections

A network of connections between design intention (diagrams), geometric realisation, structural analyses, cost and fabrication layout was created digitally. Based on prototyping and machining, an empirical matrix was created to collect data about material behaviour, constraints of fabrication, machining and construction. Since this empirical matrix was based on observation and experience, the empirical data were interpreted by the design group and then translated into a diagram that showed the geometric realisation. These empirical data were also used to estimate inputs for the structural analyses. The network consisted of the following models:

- A geometric model that was determined by sets of algorithms (Grasshopper-Rhino).
- A diagrammatic model, fed by design intention and empirical data collected in the physical world (modelled in Grasshopper-Rhino).
- A financial model defined by sets of algorithms connected to the geometric and fabrication models (modelled in Grasshopper-Rhino).
- A digital fabrication model, driven by sets of al-

gorithms and linked to the geometric and the diagrammatic models.

- A structure analytical model linked to the geometric model (Abaqus FEM analysis software).
- A computation fluid dynamic (CFD) model linked to the geometric model (ANSYS-CFD)
- An empirical matrix of material behaviour created experimentally and linked to the structural analyses model and diagrammatic models (Excel).

Detailed descriptions of the interaction between these models are beyond the scope of this paper and can be found in the complementary paper written by (Aghaei Meibodi and Aghaiemeybodi, 2012).

Ornamental representation and machining technology

Using a two-axis (CNC) cutter led to a particular method of realising the digital geometric design. The CNC laser cutter is based on digital technology. The two-axis machine only enables perpendicular cutting of material sheets. Knowing this, contouring, tessellating and sectioning/egg crate were considered as techniques to use in constructing the digital geometry. The product of each technique had different potential to reveal the relationship between structure and ornament. Distribution and convergence of structural loads through each of these techniques led to a particular ornamental representation in the product [Figure 5]. Since we only wanted to use one type of fabrication technique and CNC technology, techniques such as moulding with a CNC cutter and thermoforming were not options. Modelling with cardboard was helpful to manifest the ornamental and structural relationship offered by the CNC cutter in the product. However modelling with cardboard proved unhelpful when scaling up the project. The scale prototyping and understanding of the material behaviour was crucial, as it would be revealing what is actually possible, economical and feasible to create.

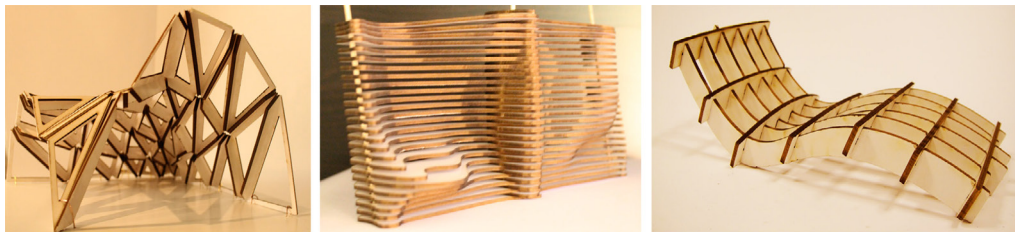


Figure 5
From left tessellating, contouring and sectioning/egg crate techniques. Cardboard models by students: Segerstein, Haraldsson and Lundgren.

Material complexity, technology and technique

Due to the limitations of the CNC cutter, the budget and the short time frame, 3.2 mm thick Masonite was chosen as a suitable material [Figure 6]. Masonite is produced in sheets of a certain size and with different thicknesses. It is a type of hardboard made of steam-cooked and pressure-moulded wood fibres. Being a composite wood panel, Masonite has very poor compression and shear properties when compared to timber. Needless to say, when compared to other composite wood panel material, Masonite has a high bending strength, tensile strength, density and stability due to the use of long fibres in its production.

Masonite plates were judged too weak to span a large distance like a beam; therefore, they had to be either laid over each other in pieces creating a massive structure, attached together as a long span beam using lamination or cut in pieces and nested using triangular or hexagonal patterns. Layering, lamination and triangular pattern methods were costly due to the amount of material needed. Therefore, after some digital geometric construction and costing, they were omitted.

The hexagonal pattern was chosen because the circumference of a hexagon uses the least amount of material to tile a surface. This arrangement had to be used in a way that satisfied the structural and ornamental aspects of the intended artefact. By comparing the design with those found in nature, it was discovered that a honeycomb shape is the best match for the material constraints of this project. A honeycombed structure in nature provides a structure with minimal density and achieves relatively high out-of-plane compression and shear properties. This would strengthen the tension and compression properties of the overall structure. Structures that have honeycomb geometry minimize the amount of material used thus achieving minimal weight and minimal material cost. Based on the machine technology and material properties, flat plates and flat joints were used in our geometrical realisation.

Digital realisation

Based on the programmatic framework, an elementary ("sketchy") surface was developed within the digital environment, as a diagram of form. The inherent UV grid of the digital surface of the pavilion was further augmented with the inner tessellation of the hexagon, which can be seen as a cell system.

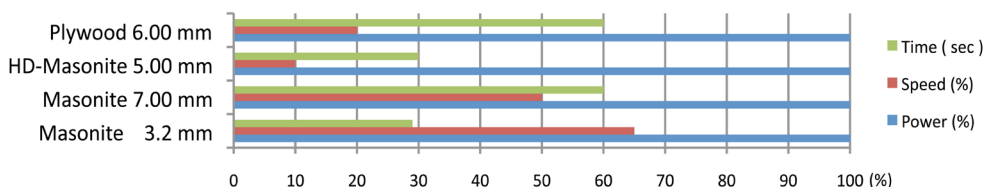


Figure 6
A chart presenting the time used to cut each material via two-axis CNC-laser cutter.

The smaller the cells, the greater the tessellation and thus, the greater the ornamentation effect on the surface. The tessellation aims to manifest infinite visual pattern configurations of the surface. This mathematical tessellation approach to texture creates tactility in the surfaces.

Prototyping and aspects of representation

Once the design abstract (brief) was decided on, alternating between the digital design and the prototype was essential. An important example of this was the jointing, which was at first to have curved sides but through prototyping found to be too weak to support the whole weight of the structure, especially when more than 20 plates were nested [Figure 7]. So the edges were straightened in the digital model to allow a tight fit. In parallel, experiments with different joining methods were carried out to find a stable solution. Eventually, it was discovered that putting joints at each corner gave the structure a lot of stiffness and reduced sag [Figure 8]. The physical limitations of the material and equipment had the biggest effect on design decisions.

Figure 7
Prototyping of joints.

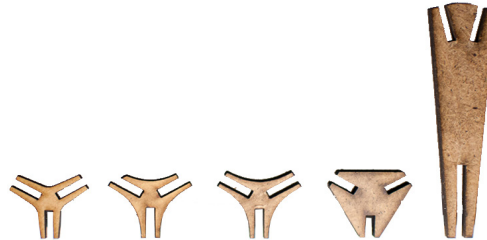
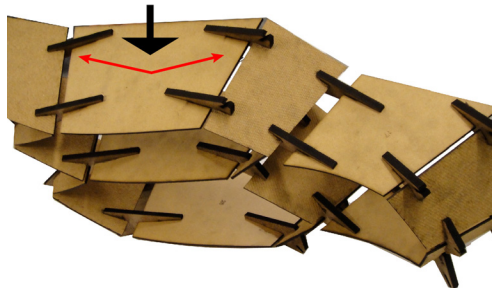


Figure 8
Arrangement of joints and plates.



Structural, constructional and ornamental aspects

The “sketchy” surface that was developed in the digital environment, as a diagram of form, was further realised based on the process logic of structuration and ornamentation. The componential system of joints and plates could be nested in a hexagonal pattern on the UV of the digital surface, creating a physical textured surface. This gave tactile quality to the surface and mimicked a woven fabric. To enhance the structural aspects, the arrangement and packing density of the components were adjusted. In order to achieve a physical equilibrium, the nested components were adjusted and adapted to transfer and bear loads thus enabling sitting and lying on the structure. To improve the balance of the structure, the digital tessellation at the two ends of the object was thickened. To support the whole weight, particular areas were thickened, extruded, or made shallower. The structural strength of the geometry was repeatedly simulated using FEM engineering software [Figure 9]. However, this feedback was only a rough estimation of the structural behaviour in the physical world since many parameters were missing from the digital environment.

Particular areas of the texturing were identified and thickened to maintain the balance of the pavilion and act as the main load bearing areas. These sets of zones, whose margins formed an essential line of the structure, are neatly camouflaged with the ornamental and textural quality of the surface [Figure 10]. There are no beams or columns in a conventional sense, no wall and no roof. “In” is “out” and “out” is “in”.

To aid construction on-site, the Masonite plates were joined together and assembled in zones [Figure 11]. These areas were identified, using an algorithm, based on the tension and compression of each area in relation to the whole. Another algorithm was written to place the necessary scaffolding. It was surprising to find how difficult assembling the structure was with a lack of the bigger components or a secondary structure that could embrace each cluster of components.

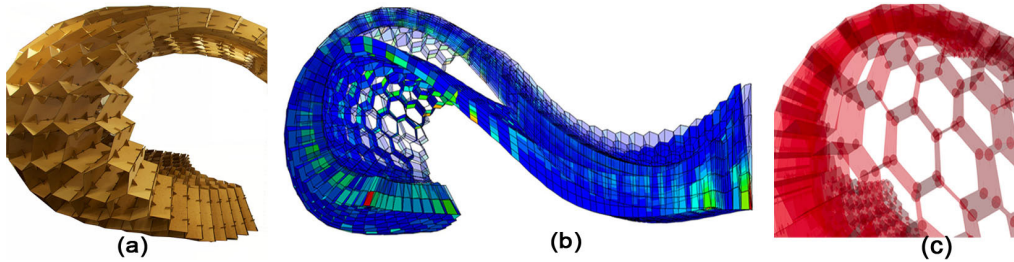


Figure 9
Sitting areas were thickened while the hanging part is made shallower (a), FEM structure analyses (b), and digital articulation (c).

PHYSICAL AND DIGITAL TECTONICS

The tectonic approaches in the digital and physical world were rather different. The digital ornamental and structuration activities on the pavilion included the mathematics of the surface (based on UV), consideration of orders and series, creating plates without thickness, marking of the joints and nesting of the plates on a digital NURBS surface. Some of these digital elements were never meant to be actually built, but were constructed digitally to aid the digital tectonics. The double curved surface, for example, was only used to help with the digital construction of the hexagons. Thus, this surface did not exist in the physical world but supported the physical tectonic. The physical tectonic required the use of secondary structures that embraced the hexagonal components in clusters and helped with the construction. However, this was not done in this project and made assembly harder than necessary. The domain of information such as the mathematics of the surface is not important in the physical construction but is the main working area for the digital tectonic (digital data). These digital data are treated differently depending on the type of fabrication technology. Using a CNC cutter, as was the case with the pavilion, led to specific approaches and techniques of testing the digital data relating to the surface. The two-axis CNC cutter is fed with data that represent the X and Y axes on a plane surface. Knowing this, we treated the digital surface by extracting UV data from it to enable the construction of the hexagonal pattern. If we were to use a CNC router, or a 3D printer instead of the CNC cutter, the way of treating the surface and the type of physical material would

be different too. This shows that the techniques and methods of digital mathematical construction are very dependent on the physical material and methods of fabrication in relation to the fabrication tools. The tectonic, as a making process in the digital world was totally different from the physical one. But the tectonic of the digital world was influenced by the techniques determined by the type of digital fabrication tool (synchronizer).

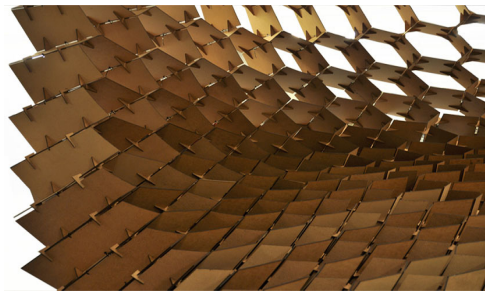


Figure 10
Image illustrating the textual quality of the surface.



Figure 11
Components are assembled in zones.

Structure and ornament fused into one body

Just as Lynn observed, in this experiment the ornament accentuates the formal qualities of the digital surface. By just looking, one can say how it was digitally constructed, as the pattern follows the way the rows are defined on the UV surface [Figure 3]. The surface of the artefact is intricately responding to the structure of its form. Its structural and ornamental features are seamless. This results from a fused interaction of ornament and structure in the process of creation. The depth of such fusion is not only dependent on technological development, but also on the methods and techniques used to realise the digital construction, economic factors and material behaviours.

DISCUSSION

New technology makes it easier and more possible to fuse performative and aesthetic aspects into one physical body. If one does not have a predefined definition of ornament as an applied decoration then the process of structuration can be the process of ornamentation too. Digital technology, perhaps, enables production of ornaments that are understood to be not a separate entity from structure but an inherent part of it. In other words, the representation corresponds to the performative aspects of the structure and vice versa. This is not a new phenomenon, but as digital technologies improve it becomes easier for this fusion to occur. This interactive relationship between aesthetic and performative aspects of a structure, developed with digital technology, in a way, can reduce the typology of constituent parts of architecture.

With regard to aesthetic aspects, architecture can benefit from digital tools by changing the concept of plastic, continuous architecture to ornamental continuous architecture, whilst being economic. However, if designers do not achieve the control over the digital tool, use of digital tools in this direction can lead to production of over-decorative and monotone architecture. With regard to the architec-

tural features, perhaps the terms wall, column, ceiling and floor could be rethought of as components rather than elements. Since digital technologies enable ornamentation to be incorporated into the early design and production processes, it enables the ornamental features to be part of the decision-making. This early incorporation helps the fusion of ornamentation with the process of structuration.

This case study challenges the profession, questioning the traditional notion of tectonic when it is not carried out in the material world but is intended for physical production. It touches upon the effect that digital tools have on the interrelation, formation and arrangement of the constituent parts of architecture (the performative and aesthetic ones). This might trigger the possibility in the development of a new culture of aesthetic. Because there are fewer constraints on the digital world than the physical one, the process of making is less interrupted. However, if it is to be realised physically then the methods of creating the design in the digital tectonic should be greatly determined by the techniques afforded by the synchronizers (digital fabrication tools).

One very important part of making (tectonic practice) is the way information or material is constructed and connected. Currently, the tectonic practice intending to create a physical artefact, cannot fully take place in the digital world because the principle of tectonic in a digital environment via current design tools does not fully correspond to the one in the physical world. Perhaps it can never fully correspond, but the tectonic process in the digital world should be carried out with full awareness of the medium and the synchronizers. Architecture consistency has always relied on the tectonic and constructive principles; however, there are new ways to explore through the synergies produced by computer aided architectural design and manufacture. This brings opportunities for new forms of ornamentation, with an interaction between it and the performability of the structure.

ACKNOWLEDGMENTS

The Pavilion is a product of the architecture studio, Design & Making, taught by authors. We are particularly grateful for the amount of work and effort put into this project by the students *Jonas Haraldsson, Lars Pettersson, Susanne Segerstein, Ante Lundgren, Karin Eknor, Emma Berggren, Oliver Sjöberg and Carl-Johan Carlsson*.

REFERENCES

- Aghaei Meibodi, M and Aghaiemeybodi, H 2012. Synergies between Computational Design, Computational Engineering and Prototyping, *draft*.
- Alexander, KD and Mark, R and Abel, JF 1977. The structural behavior of medieval ribbed vaulting. *Journal of the Society of Architectural Historians*, 36(4), 241-251.
- Kolarevic, B and Malkawi, A 2005. *Performative Architecture: beyond instrumentality*: Routledge.
- Leach, N and Turnbull, D and Williams, CJK 2004. Introduction. In *Digital tectonics*.
- Lynn, G and Leach, N 2004. The Structure of Ornament. In N. Leach, D. Turnbull & C. J. K. Williams (Eds.), *Digital tectonics*, pp. 63-69.
- Markussen, T 2008. *Fact or Fuzzy? On the Topology of Space Perception in Digital Architecture*. Paper presented at the Proceedings of the Architectural Inquiries Conference, Gothenburg: Chalmers University of Technology.
- Penn, A 2011. Foreword. In R. G. a. B. Sheil (Ed.), *Fabricate: Making Digital Architecture* (pp. 12-13): Riverside Architectural Press.
- Schmidt, AMD 2007. *The Tectonic Practice: In the transition from the pre-digital to the digital era*. Ph.d. thesis, Aalborg University.
- Willis, R 1910. *On the Construction of the Vaults of the Middle Ages*: Royal Institute of British Architects.