

Integral Computational Design for Composite Spacer Fabric Structures

Integral Processes of Form Generation and Fabrication for Sandwich Structured Composites with 3D Warp-Knitted Textile Core

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Abstract: *Spacer fabrics are three dimensionally warp-knitted textiles that can be draped over complex double curved surfaces with no need for cut patterns or additional seams. This paper explains the development of an integral computational approach to the design and fabrication of sandwich composite structures with a spacer fabric core. Contrary to the common hierarchy of architectural design processes that prioritizes the definition of form over the inherent characteristics of materialization, this approach aims at an integral computational design process capable of unfolding a design from the constraints of making. The way the material capacity of spacer fabrics combined with the constraints of sandwich composite manufacturing directly informs the computational design process will be explained along the development of two prototype structures.*

Keywords: *Integral computational design; computational morphogenesis; computer aided manufacturing; digital fabrication; computational design methodology; composite structure; material system; spacer fabric, 3d warp-knitted textile; sandwich lay-up.*

Introduction

This paper is based on a two year long research project at the Department for Form Generation and Materialisation (Prof. A. Menges) at HfG Offenbach exploring integral computational design and computer controlled fabrication processes for composite sandwich structures with a 3D warp-knitted textile core. The progress of this research project followed a threefold aim, the explanation of which will provide the underlying structure of this paper.

First, the overarching objective of striving for integral processes of form generation and fabrication and the related developments in design methodology and computational techniques will be discussed. In this context 'integral' refers to the ability of the developed computational tools to integrate key material characteristics, manufacturing constraints and assembly logics through which a material-specific form can be derived. Contrary to the common hierarchy of architectural design processes that prioritizes the definition of form over its subsequent

rationalization for building, this enables the architect to unfold a design from the constraints of making.

The second important thread of the research to be discussed in this paper are the related processes of defining and parameterizing the relevant characteristics of a material system, which are an essential prerequisite for such an integral design approach. They will be investigated through the development of a sandwich composite system consisting of glass fiber skins with a 3D warp-knitted textile core and the associated CNC mold manufacturing and contact molding processes.

The interrelated development of the computational design tools and the material system was continuously tested and informed by full scale prototypes. Thus in the third part of the paper the design and fabrication of two such pilot applications, a single-surface furniture piece and a multi-component spatial enclosure will be explained in detail.

Integral form generation and materialisation

The project to be presented here aims at advancing the field of research that investigates the possible synthesis of computational design techniques and manufacturing technologies (Menges, 2008). In contrast to these integral development processes of material form, architecture as a material practice is still predominately based on design approaches that are characterised by a hierarchical relationship that prioritises the generation of form over its subsequent materialisation. Since the Renaissance the increasing division between processes of design and making, as proclaimed by Leon Battista Alberti (Carpo, 2008), has led to the age-long development and increasing dependence on representational tools intended for explicit, scalar geometric descriptions that at the same time serve as instructions for the translation from drawing to building. Inevitably, and with few exceptions such as Antoni Gaudi, Frei Otto, Heinz Isler and some others, architects have embraced design methods that epitomize the hierarchical separation

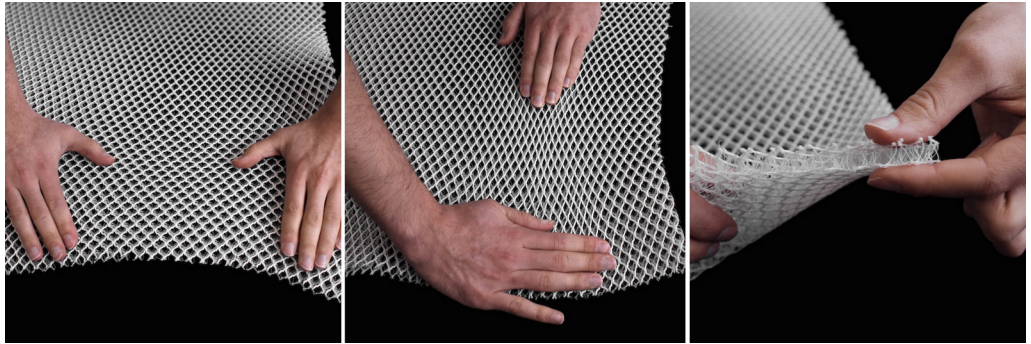
of form definition and subsequent materialisation. Even in today's practice digital tools are still mainly employed to create design schemes through a range of design criteria that leave the inherent morphological and performative capacities of the employed material systems largely unconsidered. Ways of materialisation, production and construction are only subsequently strategized and devised as top-down engineered, material solutions.

The research presented in this paper explores an alternative, morphogenetic approach to design that unfolds morphological complexity and performative capacity from material constituents without differentiating between formation and materialisation processes. This requires an understanding of form, material and structure not as separate elements, but rather as complex interrelations that are embedded in and explored through an integral computational design model (Menges, 2007). It is important to note that there is a crucial difference between established processes of material simulation and this designer-oriented approach: while material simulations require all variables of the system to be defined at the onset, the computational models developed in this research allow for exploring the design space given by the constraints of a material system. The definition and set-up of such a computational model and the related modes of integrating design techniques, production technologies and system performance requires a careful analysis of the material system's crucial characteristics.

Material systems: characteristics, constraints and affordances

The development of an integral design approach as explained above can never remain generic but needs to be material specific. Extending the concept of a material system by embedding its material characteristics, geometric behavior, manufacturing constraints and assembly logics allows for deriving and elaborating a design through the system's intrinsic performative capacities (Hensel and Menges,

Figure 1
3D warp-knitted spacer fabric



2006). In the case of this research project the critical processes of parametrizing the relevant characteristics, constraints and affordances of a material system was guided by the collaboration with four expert partners from the relevant industries: a leading manufacturer of warp knitting machines for the production of spacer fabrics, a supplier of industry standard composite products and a control engineer for programming five axis CNC milling machines for mold production. Together with these partners the project commenced with the development of a novel material system consisting of a spacer fabric sandwiched in a stressed glass fiber skin. For the second development stage initiated by the OCEAN network, the research project was joined by the Institute for Industrial Design at AHO Oslo and YNOR, a Norwegian boat builder with special expertise in producing one-off double layer composite hulls.

Material Characteristics: 3D warp-knitted textile core

Spacer fabrics (Figure 1) are produced on double-bar raschel machines. They are three dimensionally warp knitted textiles consisting of two textile layers connected by a pile. The manufacturing process allows using different fibres in the fabric and the spacing between upper and lower layer resulting from the pile can be varied between 1.5 millimeters to 60 millimeters. The three dimensional structure of the spacer textile and the use of strong filaments in the pile provides for high compressive strength while

the textile remains to be very lightweight (Knecht, 2006).

The spacer fabric used for this project was produced with a pile depth of 10mm. Relating to the research presented here the most important characteristic of this non- elastic material is its capacity to differentially stretch and contract through geometric deformation, which offers the possibility to drape the spacer fabric over complex double curved surfaces with no need for any seams or cut patterns (Figure 2). This suggested the possibility of using the spacer fabric as the core of a sandwich structured composite consisting of two very thin, translucent glass fiber skins that are laminated to the upper and lower layer of the spacer textile. Due to local and global maxima of possible drape there are still limits to the achievable surface geometry that can be seamlessly articulated with the spacer fabric. Thus the possible ranges of double curvature, which were established through elaborate physical tests, constitute one critical aspect of the material system.

Manufacturing constraints: contact molding of skins and sandwich assembly

The second category of the material system's critical aspects is given by the constraints inherent to manufacturing processes of sandwich structured composites, the production of which comprises of the following steps:

First, the outer surface constituting one of the sandwich skins is manufactured by hand layup. This

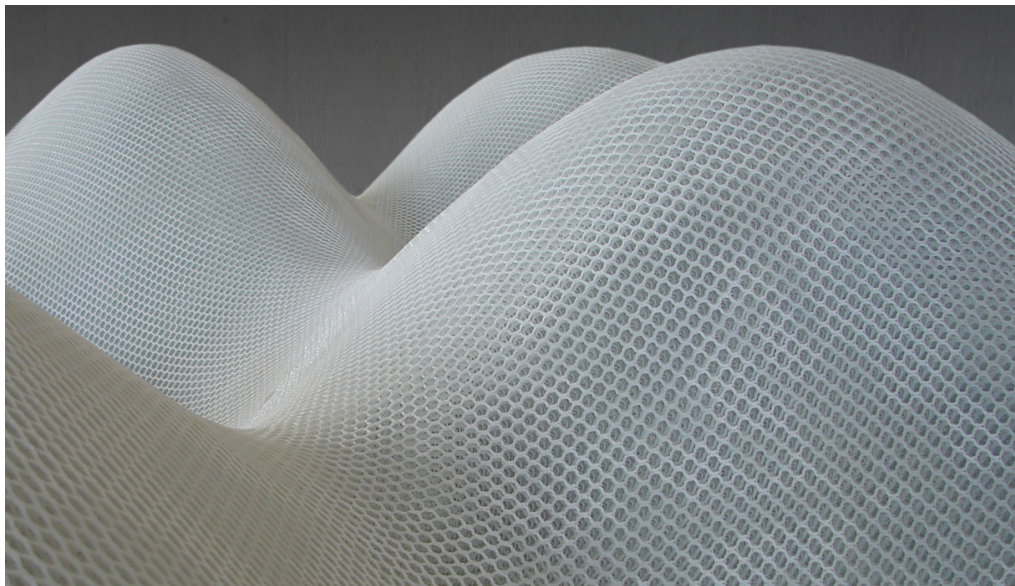


Figure 2
Spacer fabric draped over
double curved surface

entails applying a transparent gel coat, a resin applied to the mold and gelled prior to lay-up. The gel coat becomes an integral part of the finished skin laminate and defines the surface finish. After the gel coat is applied, plies of glass fiber mats consisting of chopped filaments are successively placed in the mold and subsequently impregnated with polyester resin to form a one millimeter thin GRP skin. The contact molding process imposes a number of constraints on the mold geometry, for example the maximum draft angles for demolding. Furthermore, the machine constraints of the five-axis CNC mill used for the mold production need to be considered (Figure 3). In the second step the spacer textile is bonded to the sandwich skin by applying resin to the surface and draping the spacer textile over it. Subsequently the second sandwich skin also consisting of thin glass fiber mats is laminated to the spacer textile surface. As this application of the core and the second sandwich skin entails vacuum bag molding, the size and shape constraints of this molding technique also need to be considered in the design process (Figure 4).

Computational integration

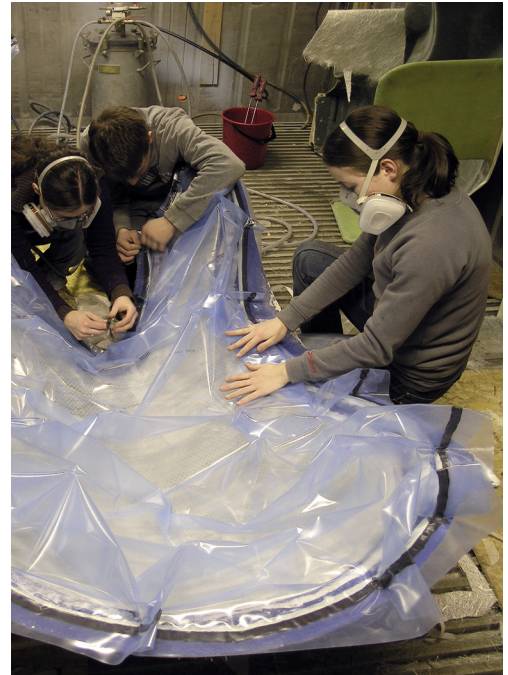
Both the characteristics of the material system and the constraints of the related manufacturing provided the base for developing a custom computational tool for the design process. First this entailed writing a tool for analyzing the differential stretch in the spacer textile resulting from the specific drape geometry (Figure 5). The calibration of the computational results and the findings of a large number of physical tests lead to the definition of the geometrical drape limits. This definition of possible surface articulation was further consolidated by including both the constraints of the mold manufacturing process given by the limits of the 5 axis CNC mill and the geometric constraints of contact molding and vacuum bag molding processes as explained above. The subsequent development aimed at finding ways of computationally defining the limits of possible surface articulation while at the same time enabling the designer to explore the design space within these limits.

A mathematical equation capturing the limits of the material's drape capacity and the manufacturing

Figure 3 (left)
Five axis CNC mill used for
mold production



Figure 4 (right)
Vacuum bag molding of
spacer textile sandwich



constraints was developed and implemented in a mathematical surface generator. In the case of the *Lounge Landscape* single-surface structure, which is explained in the next paragraph, this equation only defines the surface's oscillation in the Z direction. For the more complex geometry of the multi-component spatial enclosure of the Deichmanske Media Stations the equation is based on the mathematical definition of a stereographic sphere. The design space defined by the equation's variables was subsequently explored through multiple feedback loops integrating the most critical design criteria (Figure 6), as for example the surface ergonomics and aesthetics, the structural stability and, in the case of the Deichmanske Media Stations, the assembly logics and transport volume.

Prototypes: testing integral computational design strategies

The development of the integral computational design process for sandwich structured composites with warp-knitted textile core was constantly informed by and tested through the production of full scale prototypes. The most important prototypes, one investigating a single-surface structure, the other exploring a multi-component assembly, will be explained in the following paragraphs.

Lounge Landscape (Department of Form Generation and Materialisation, Prof. A. Menges, HfG Offenbach)

The production of a first prototype for testing and verifying the applicability of both design methodology and system was instigated by the commission to design and manufacture seating furniture (Figure

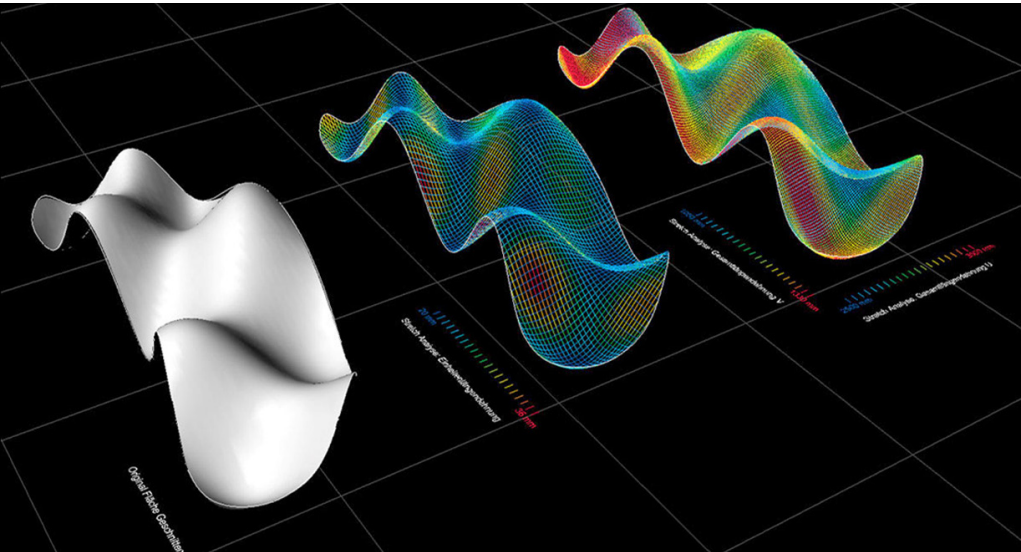


Figure 5
Custom written computational tool for analyzing the differential stretch within the spacer fabric

7) for an anniversary party reflecting the school's design and prototyping expertise. The set-up of an open computational model as described above enabled a morphological evolution of iteratively testing and evaluating parametric variants of the mathematical definition in relation to structural, ergonomic and aesthetic design criteria. The resulting form was CNC manufactured as a "mother mould" facilitating

the production of a multitude of individual, geometrically different furniture morphologies all remaining to be material specific. More importantly, this integral approach to form, material, structure and manufacturing also provides an inroad for rethinking surface articulation as a means of differentiating possible body-surface interaction. Each Lounge Landscape furniture piece provides for a multitude

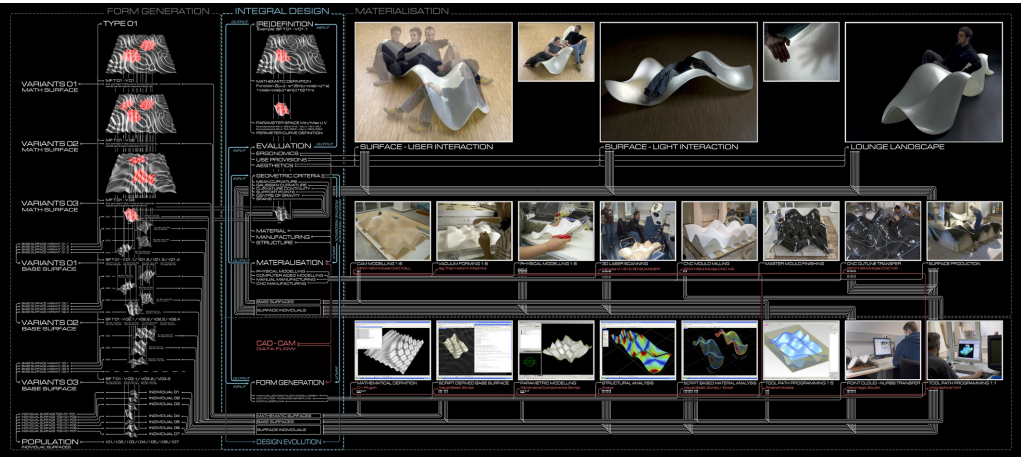


Figure 6
Diagram of the feedback based integral computational design process

Figure 7
*Different Lounge Landscape
furniture pieces all produced
from the same mother mould*



of anticipated as well as divergent activities by up to 7 people at a time while remaining to be extremely lightweight. The open-endedness of possible uses and loose-fit ergonomics, and the concurrent erosion of clearly demarcated functional zones of more conventional seating furniture, demands a conscious (re)positioning of the user within the landscape-like articulation and its micro social context prompting an intensified individual and collective experience.

Deichmanske Media Stations (Department of Form Generation and Materialization, Prof. A. Menges, HfG Offenbach; Institute for Industrial Design, Prof. B. Sevaldson, AHO Oslo; OCEAN design research network, M. Hensel)

The second prototype followed a commission by the Deichmanske Library in Oslo, the largest public library in Norway, to design and manufacture four media stations that, via touch screen, serve as access points for the library's extensive audio-visual archive. The challenge to progress from single-surface furnitures to a multi-shell spatial enclosure necessitated the further development of the computational design tool. The objective of assembling the media stations as an integral monocoque construction by bonding various separately manufactured shells requires a precise geometric articulation of

the overlapping joints. Thus the mathematical description of possible surface geometry of the spacer fabric sandwich lay-up developed for the lounge landscape project was expanded and elaborated as a parametric variant of two intersecting stereographic spheres. Possible derivative morphologies of this precise description of the surface geometry and flange alignments were explored through an evolutionary process of incrementally informing the computational model with additional structural, ergonomic and aesthetic criteria. From the resulting mathematical model the G-code for CNC milling was directly derived and used for producing the positive moulds, which were subsequently finished and prepared for the production of negative master plugs. These master plugs were used for the lamination process, during which the spacer fabric was shaped within a composite cloth through a vacuum bag molding technique. The individual parts are then bonded together to form a spatial enclosure (Figure 8). The resulting media station's overall shape, the structuring of the surfaces by the shadows of the overlapping joints, the gradient surface translucency and all other details (Figure 9) of the final articulation unfold from the intrinsic characteristics, specific manufacturing constraints and particular assembly logics of the material system (Figure 10).



Figure 8 (left)
Multi-component shell during
assembly

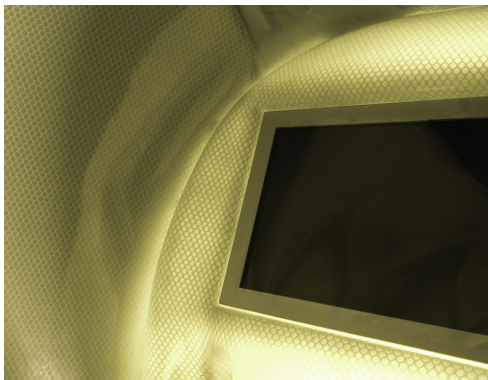


Figure 9 (right)
Detail of composite spacer
fabric structures

Conclusion

The above research demonstrates the potential inherent to an integral design approach and the related challenges for design methodological developments and advancing the required design tools. In terms of the developed material system further research will focus on more intricate local manipulations of the spacer textile. The two projects presented above

mainly exploit the inherent characteristics of the material system on the scale of the overall geometry. However the material also displays particularly interesting behavior resulting from local gathering. This provides an interesting inroad for further informing the developed design methods by integrating local surface undulations that add considerable structural capacity. While a high level of integration of material characteristics and manufacturing constraints



Figure 10
Deichmanske Media Stations

has already been achieved, the next step of development needs to further elaborate the integration of system external influences and forces; for example, the form generation process should be informed by more sophisticated structural analysis in order to calibrate the structural contribution of both the overall curvature and local undulations resulting from local textile gathering.

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