The Challenge of the bespoke

Design, Simulation and Optimisation of a Computationally Designed Plywood Gridshell

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The Dermoid project, a series of three plywood grid shells, navigates at the interface between parametrically designed architectural spaces and the efficiency and resourcefulness of the simulations that are necessary in order to build them. It highlights the increasingly common challenges and conflicts which occur in building practice ranging from design to fabrication and highlights approaches that facilitate implementation in multiple scales of material, element and structure.

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THE RELATION OF PARAMETRIC DESIGN AND SIMULATION

Frederic Migrayou coined in 2003 the term "digital chain" (Migrayou 2003) for workflows that link the digital design space with the fabrication of architectural objects. Where this definition was related to the level of geometry, current research is venturing into workflows in design, which take material and structural behaviour into account (Schwinn 2013). Though different methods of simulation might be used, all provide a means to predict and evaluate the behaviour of a building structure in the design phase. Repeated feedback from simulation is used to improve the design. However the validity of this performance based approach towards design (Kolarevic 2003) depends greatly on the models, that are used for the simulation of the designs performance. Where simulations might be understood as tools that

Figure 1
The Dermoid III demonstrator in May 2013 in Melbourne

Figure 2
FE Simuation, Build Prototype, 3D Scan - A snapshot of the wide reaching spectrum of modeling in the Dermoid project

can be readily applied in design, they are often only providing reliable results in a quite narrow set of framing conditions. These are often directly depending on the datasets and assumptions, which form the base of the simulation model. In the case of simulating material behaviour, the underlying data for material properties is for instance found through repeated tests on standardised material samples. A precise simulation becomes a seemingly challenging task the more complex a structure becomes, the more individualised elements interact and finally the more a structure diverges from an existing well understood structural typology - all of which are recent tendencies in architectural research, even more complicated through the use of novel composite constructions and materials.

A further challenge emerges through size, as the simulation of large systems does not scale linearly and forces modellers to use more and more abstract underlying models. In consequence the results of simulation are becoming seemingly inappropriate and can hardly provide good quality feedback about the performance of a design. The question emerges how simulation can be effective and efficient in projects that want to make use of the innovations of the digital chain on material and construction level.

PROJECT

The three Dermoid demonstrators (Burry 2013, Tamke 2012; see e.g. figure 1) explore the potential of a novel interplay between structure, construction, production, assembly and material. The streamlined computational form-finding and production tools are here linked to structural analysis and in order to integrate material behavior in the design with the production of bespoke structural elements. The project provides hence a rich ground for the discussion of principal approaches in design, simulation and testing of bespoke material systems (Lafuente et al. 2012; also see figure 2).

MATERIAL SYSTEM

Where material is often seen as stiff and bound to a defined geometry, the Dermoid series nurtures an understanding of material as pliable and adaptive.

Using strategies of Active Bending, as described by Lienhard (Lienhard 2012), exclusively planar plywood elements of 4mm material thickness curved to form curved T-profiles. The flanges of the curved "S-beams" are elastically bent and locked in position by means of entirely reversible mortise joints. Two of these S-beams are then connected to one other through pinned tenon joints forming a bifurcating base element referred to as a wishbone (Fig.3).

Extensive experimentation led to refinement of the tolerances in sizing and spacing of teeth and perforation. Other parameters such as allowable bending curvatures for a given plywood thickness and zipper configurations were also explored in depth during early development (Fig.4). The prototyping led finally to a near annihilation of tolerances in the fabrication and construction system, which was reflected in the space of parameters in the design system.

Figure 3
Two s-curved plywood elements form the base for reciprocal beams that are collected in a hexagon pattern. Dermoid III had textile infills, that were knitted bespoke to the size of the size of the hexagons they were positioned in.

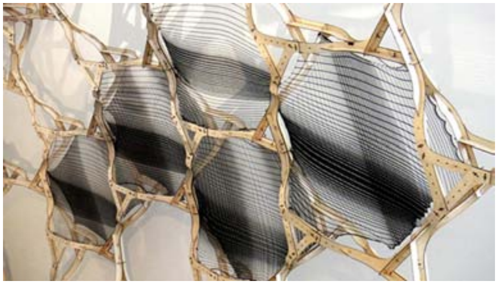
Figure 4
Zipped connection: Birch ply flange and web with matched perforations in the flange and teeth on the web for a dry friction joint

DESIGN: GENERATIVE APPROACH

The multitude of concurrent parameters that influence the form-finding process of the Dermoid design system prohibits a procedural computational approach (Tamke 2012). An investigation of the Dermoids system displays two types of parameters, those that have a high level of reciprocal relation, such as the amount of elements, the boundary conditions and the elements geometry, and parameters that are only depended on a single (higher level) parameters, such as the detailing or curvature of a beam. These parameters could usually be abstracted as min and max values. Following this categorisation the overall design system could be devised in a design system, where geometry with a high level of abstraction was generated, and a production system that took the data and created detailed fabrication information. A workflow was devised that integrates the parameters from construction and material with in a geometry oriented design environment. The intention was that a lightweight approach could embed the crucial material and construction parameters in the design stage, while it allowed for the exploration of the constructions potential to create complex surface topologies. The lightweight approach should as well enable an easy exchange with high end structural analysis, whose underlying Finite Element approach is not suitable for design interaction.

DESIGN SYSTEM

The third Dermoid provided an opportunity to redevelop the surface manifold formfinding and design workflow used in previous Dermoids, which consisted of a diverse chain of platforms, including Maya, Nucleus, Rhino, Grasshopper, MEL, VB and C. This led to an inflexible and slow design process with little opportunity for the intended design iteration or refinement (Davis et al. 2011). The current design tool is in contrast integrated within a single Grasshopper definition implementing Python, RhinoCommon and the Kangaroo physics engine (Fig. 5). On both a technical and design level this has led to a more robust, flexible and streamlined workflow.



Form-finding Input Geometry

The design intention for a surface manifold is captured using a technique inspired by patch modelling in industrial design and CGI. Here a network of curves representing surface topology and boundary curves is constructed. Through evaluating the surface topology a configuration of a hexagonal polylines is manually configured ("Cells"). During simulation the boundary curves act as rails constraining the naked perimeter of the Cells configuration ("RailsEndCurves"). To match the Cells and RailsEndCurves a second set of curves is constructed ("RailsStartCurves). This three layered configuration form the geometric input for the parametric and dynamic formfinding system.

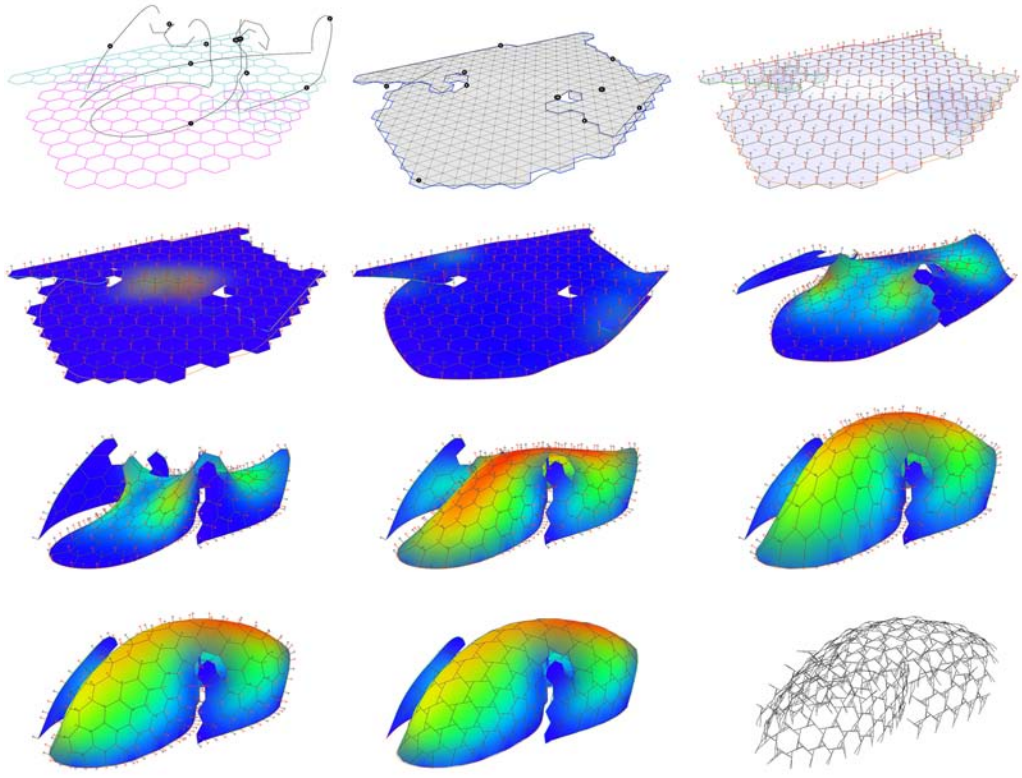


Figure 5
The formfinding input and process. From top left: 1) A Cells configuration and the RailEndCurves. 2) The derived mesh manifold and RailStartCurves. 3) Cells ID, vertex normals coloured by polarity and tweened RailCurves in their initial state. 4) The dynamic mesh prior to forces with curvature analysis on. 5) The perimeter vertices/particles are pulled to the RailCurves. 6) The RailCurves tween at 50%. 7) The RailCurves tween at 100%. 8) Shell forming forces applied at 50%. 9) Shell forming forces applied at 100%. 10) The mesh faces are adjusted to become more equilateral. 11) The derived reciprocal geometric network. 12) A simple two-layered S-curve beam design.

Mesh Manifold and Beam Graph Topology

The principal geometry type for the formfinding and reciprocal beam network process is a polygon mesh. These can describe topologically complex manifolds not possible using single NURBS surfaces and are suitable for particle-spring based simulation, with mesh vertices as particles and mesh edges as springs. Meshes furthermore carry along additional information used downstream such as vertex normals and colours. The initial manifold mesh is generated using the Cells polyline vertices with an additional vertex at the centre of each Cell polyline. A uniform triangulated mesh is thereby constructed which ensures predictable dynamic behaviour during simulation. For the downstream generation of the reciprocal beams a graph is generated which maps each unique Cell edge to its corresponding mesh vertices. This data structure is subsequently processed using an algorithm which flips the edge direction to achieve the Dermoid style negative/positive connectivity polarity.

Physics Based Lightweight Simulation

A primary goal in the Dermoid project is to explore bidirectional modelling techniques which enable explicit top down user control and self-organizing bottom up emergent processes within a unified design space. The integration of light weight dynamics simulation engines within CAD environments is a promising path for such design spaces (Deleuran, Tamke and Thomsen, 2011). In the current design tool the Kangaroo physics engine is linked with the input geometry in an interactive real-time formfinding system. Here the manifold mesh is discretized as particles and springs and a multi-layered system of dynamic constraints and forces is generated. The architectural design aim of the Dermoid manifold is to resolve spatial conditions through a self-supporting, topologically complex manifold with displays inherently smooth curvature and structurally mainly compressive forces. This directly dictates which forces to use and how to combine them. These may be grouped into four overall categories:

Surface Properties
Forces which determine the intrinsic and local behaviour of the mesh manifold. This includes the springs keeping the mesh together. These are defined be their stiffness and rest length. Additionally a force is applied which operates on the mesh triangles and attempts to keep these equilateral, in turn resulting in relatively equiangular hexagonal cells. This is not only desirable aesthetically but also ensures fairly consistent beam connection angles. Finally a Laplacian smoothing force is added on top of this, taking out any mesh extremes and ensuring an even mesh.

Geometric Constraints
Constraints defined by the simulation input geometry. The naked vertices/particles along the perimeter of the mesh are subjected to a force "pulling" them to their assigned RailsEndCurves. Additionally the rail curve endpoints are treated like anchors, meaning that any vertex/particle which is coincident with a curve endpoint will be completely fixed to this position in space while the remaining perimeter particles are free to move along the rail curves. During simulation the user may interpolate between the set of RailsStartCurves and RailsEndCurves, moving the mesh from its initial perimeter state to the perimeter defined by the RailsEndCurves.

Shell Forming Forces
Forces which induce curvature onto the mesh manifold. Here two forces are applied to the vertex particles. 1) A gravitational force applied along the Z-axis of the world space, simulating the catenary principle of the inverted hanging chain made famous by Antoni Gaudi. 2) An inflation force applied along the vertex normals of the mesh, simulating internal pressure analogous to the inflation of a balloon. The first force results in a mesh which tends to inherit mainly compressive forces while the second tend to result in more aesthetically pleasing curvature. During simulation the user is free to mix the two forces.

Attractors
Forces which operate using attraction or repulsion principles as a function of distance. A force is applied to the vertices/particles sitting on the naked mesh perimeter. Here a power law is applied which forces the particles to repel each other if they get within a certain distance. This results in an even distribution of beams along the manifold boundary.

Output and Reciprocal Beam Geometry
The user may activate several modes of visual and numerical analysis. This includes visualising the model topology (cells, normals, edge polarity and IDs) and evaluating the mesh manifold (curvature and local extremes causing irregularities). Similarly the user may activate the component which computes and visualises the reciprocal beam construction geometry. The reciprocity is achieved by placing a plane on the midpoint of each cell edge perpendicular to the mesh surface. By rotating each plane and intersecting it with its neighbours the reciprocal network emerges. Using the inherent geometrical data of the mesh and the described Beam Graph, this component allows the user to input an angle of beam rotation, a minimum number of beam neighbours and a maximum beam connection angle. Using this data the component computes a range of geometrical and auxiliary data which may be used downstream to design a plethora of reciprocal beam designs.

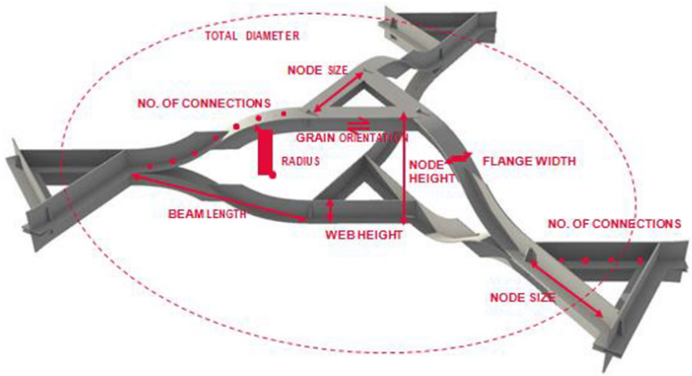


Figure 6
The Dermoid module has a high number of changing geometric parameters in the system. Attempts were made to maximise the number of slave and minimise the number of parent parameters.

STRUCTURAL ANALYSIS

The high geometric variation in the system coupled with unknown mechanical properties of the plywood, along with a tight schedule required a fast and effective way to simulate the complex structure while also making attempts to improve the structural design of the Dermoid.

Our work resulted in three parallel strategies that can serve as good practice at the interface of design development and analysis.

1) Controlling Variables

The large amount of geometric and mechanical variation in the Dermoid design is visualised in Fig.6. A conscious design choice was made to reduce the number of independent variables in the system and where possible to define all geometric properties as child of a set of very few parent variables.

2) Approximation of structural typology

Although structures such as the Dermoid do not adhere to established structural typologies, an approximation is still possible. In the case of the Dermoid, the structural definition of an elastic timber grid shell was used as a way of interpreting and improving its structural behaviour.

3) Computational and empirical modelling

The geometric variation in the system coupled with the unknown mechanical properties of the plywood complicated the ability to find a quick and effective method of simulating the structure. Using the finite element simulation package Sofistik, various modelling techniques were considered:

Simplified surface mesh (Fig. 7). Pros: Geometry transfer between grasshopper and Sofistik easier to script, High detail possible. **Cons**: Excessive computational demand, Millions of elements, Large effort for low accuracy.

Simplified beam mesh (Fig. 8). Pros: Reasonable geometry scripting, Computationally reasonable, Easy to apply loading. **Cons**: Errors in simplification hard to judge, Unknown composite action behavior.

Simplified equivalent spring model (Fig. 9). Pros: Simulate the behaviour not the thing, Computationally simple, Don't have to worry about complex interactions. **Cons**: Slightly more time needed for geometry definition, SW load definition, Simplifications may go too far.

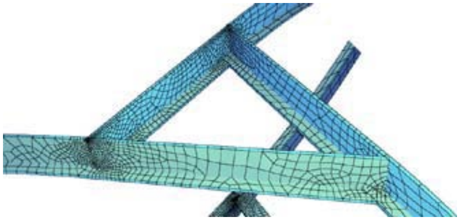


Figure 7
Simplified Surface Mesh

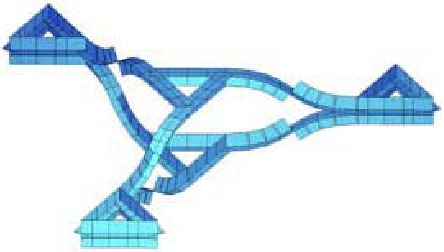


Figure 8
Simplified Beam Mesh

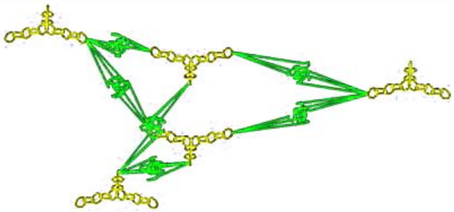


Figure 9
Simplified equivalent spring model

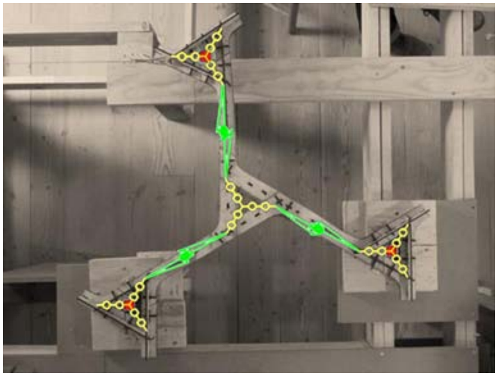


Figure 10
Image overlay of the equivalent FE spring simulation and the physical test specimen.

Final Simulation Model

The Dermoid III was finally simulated by means of an equivalent spring model in order to produce a simplified and a computationally undemanding representation of the tripod modules based on a few simple empirical tests (Fig. 10) instead of simulating in detail the complex material behaviour and all of the jointing interactions (friction, slippage, plastification, buckling etc.).

Results showed that in comparison both the beam FE model and the simplified spring model were highly accurate for in-plane deflections (Fig.11). For out of plane deflections however, both simulations were inaccurate with the spring model having the largest overall error (Fig.12).

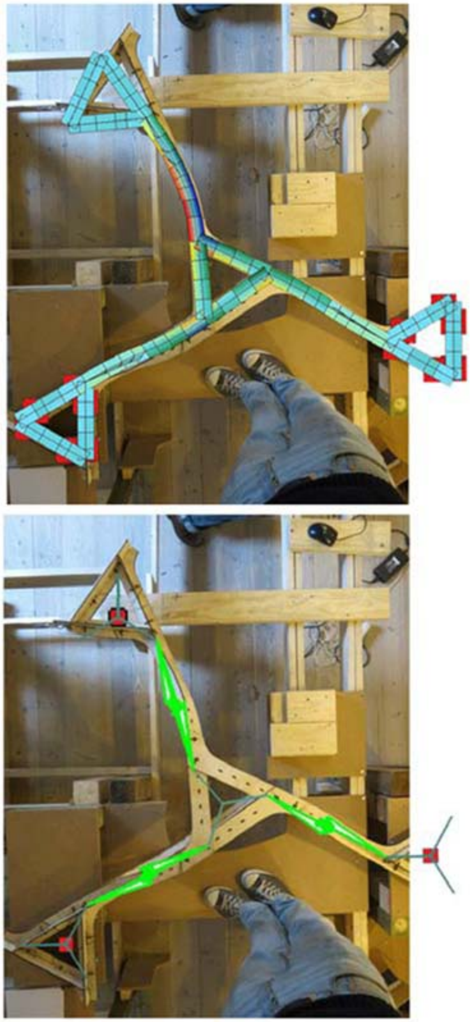
Attempts were made to modify the spring model in order to improve its accuracy for out-of-plane deflections. Additional rotational springs combined with complex restraints and releases were able to significantly improve the accuracy of the simulation (Fig.13).

FABRICATION

The two dimensional production data for laser cutting is directly derived from the data generated in the design system. Jointing details, offsets for material thickness and beam-beam intersections are computed on the fly during the generation of the production. The necessary knowledge and the adjustment of the interplay opf design and production system was developed through extensive prototyping on the fabrication machines (Tamke, Hernández, Deleuran, Gengnagel, Burry & Thomsen, 2011).

The fabrication data tool was creating a unified design and production tool within a single Grasshopper definition (Fig.5), thus being able to check and control the integrity and buildability of the individual beam production drawing in real time while designing the overall shape of the shell

The global accessibility of digital production machinery allowed the team to generate the fabrication data in Europe and cut the parts in Australia. The production was initiated through a calibration process in which the machine specific tolerances were determined, which informed the digital fabrication system. Here after the production in Sydney took place without flaws.



ASSEMBLY

While the production of several hundred bespoke plywood elements was fast the assembly of those took a longer period. This as previous Dermoid installations had assembly teams that constituted of persons involved in the design and programming of the piece and of novices. The assembly team in Australia constituted almost completely of the later. This required a substantial learning effort to comprehend the numbering system of elements, modules and subassemblies and their assembly and complicated the understanding of the implication of assembly process and structural behaviour. A better coordination of efforts between design and assembly team would have helped to ease the erection of the several hundred bespoke elements.

Figure 11
Comparison of beam and spring model in-plane. Both represent the physical tripod with accuracy.

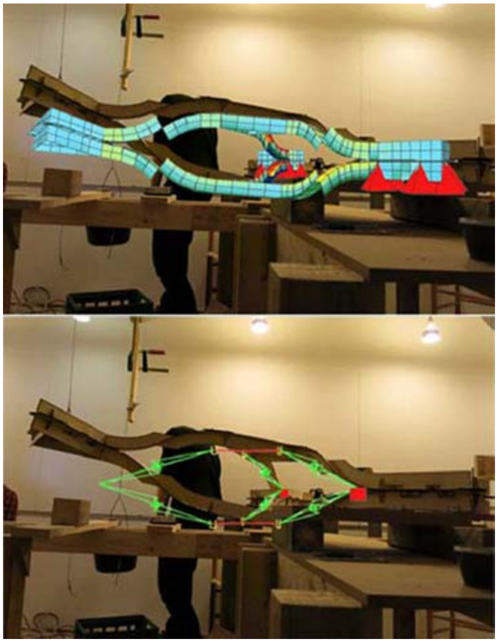


Figure 12
Comparison of beam and spring model out-of-plane. Both simulations are inaccurate with the spring model having the largest error.

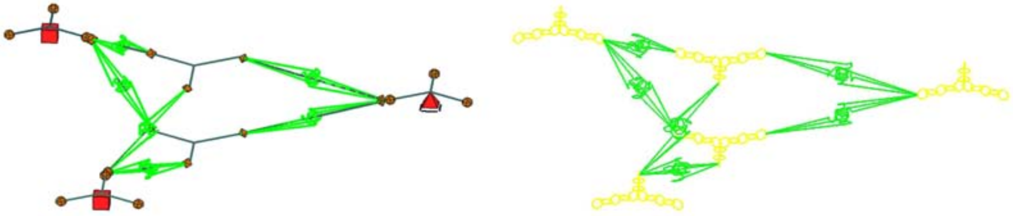


Figure 13
a) original simple spring model comprising of rigid links and linear springs only, b) modified spring model with improved accuracy but with additional rotational springs, restraints and releases.

EVALUATION

A paragraph that evaluates the overall behaviour of the structure in comparison to the simulated one (laser scan)

OUTLOOK

The results of this project should be understood as a contribution to the ongoing debate on design strategies with mass customised elements and offer a template for the resourceful and efficient generation and simulation of complex systems. While the digital design chain suggests a consistently high level of numeric precision the Dermoid project demonstrates that the complexity of a intended complete simulation in the design process places a disproportionately high demand on resources. This leads to a note of caution against the risks of over-parameterisation, the value of considered and insightful global design and development of details as the need to establish computational methods and approaches that work with tolerances.

The project points however at the benefits of softer structures for architectural application. While softer structures may not withstand the rigor of the existing building codes, it can be argued that it is right to question the level of redundancy and its implied waste in the structures that we build today.

ACKNOWLEDGEMENTS

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