MATERIAL PERFORMANCE BASED DESIGN COMPUTATION

An Inquiry into Digital Simulation of Material Properties as Design Generators

NERI OXMAN AND JESSE L. ROSENBERG
MIT, Department of Architecture and the Department of Mathematics, USA
neri@mit.edu, jessel@mit.edu

Abstract. The paper unfolds the association between geometry and material behaviour, specifically the elastic properties of resin impregnated latex membranes, by means of homogenizing protocols which translate physical properties into geometrical functions. Resin-impregnation patterns are applied to 2D pre-stretched form-active tension systems to induce 3D curvature upon release. This method enables form-finding based on material properties, organization and behaviour. A digital tool developed in the *Processing* environment demonstrates the simulation of material behaviour and its prediction under specific environmental conditions. Finally, conclusions are drawn from the physical and digital explorations which redefine generative material-based design computation, supporting a synergetic approach to design integrating form, material and environment.

1. Introduction

1.2. BACKGROUND

“What does a brick want to be?” In his philosophical explorations the architect Louis Kahn proposed that buildings were not inert configurations of form but “living organic entities” (McCarter, 2005). Let us replace the word “brick” with the notion of “material”, and the concept of “task”, or “function”, with that of “performance”. Now let us speculate on how does a material perform? Moreover, is there a way in which we could *predict* material behaviour and organization within a given context? Pursuing further this strand of logic, the notion of *form-finding* attributed to Frei Otto (1995) follows Kahn’s conviction of a predetermined search for material form, but produces perhaps the synergetic relationship between performance and material integrity. Our research seeks to build upon design work based on physical form-finding and to extend this to the inquiry into what the implications of such experiments may be *when translated from the physical to the digital realm*. How, and indeed when, does *digital matter* transcend its representational value and acquire ontological, operative and, even, generative validity for the designer in his creative search for formal, structural and material integrity.

1.2. PROBLEM DEFINITION

Current CAD applications, including associative modelling software packages, appear frequently to promote generative approaches to design (Shea, 2003). Rather then treating the computational media merely as an "output station" prior to production, the designer is now able to establish parametric relationships between features, methods and/or functions in a way which supports design processes of an exploratory nature. However, this liberation which seems to be manifesting itself across the board throughout the continuous phases of the design process is currently mainly driven by geometrical constraints. Generative performative modelling approaches have been introduced which engage principles of engineering with from-finding (Burry, 2005). And yet, even when integrating performance factors and tools that are significant in determining architectural form, material organization and behaviour are already pre-determined design constraints; predetermined factors. Form finding, in the digital realm, is thus restricted to the relationship between structure and geometry (and/or fabrication); it does not generally incorporate, and/or support, the expression of material properties, organization and behaviour.

1.3. AIMS AND OBJECTIVES

This work seeks to establish a *synergetic* approach to design whereby material organization and behaviour, as they may appear in the physical world, may be integrated into digital tools for design exploration. The approach is based on the premise that *material, structure, and form* can become inseparable entities of the design process which relate to *matter, performance and geometry* respectfully. Beyond this theoretical significance, the goal of the experiments presented here is to effectively link the simulation/computational techniques across adjacent scales of physical behaviour so that microscopic level physics and mechanisms are incorporated into the description of properties and behaviour at the mesoscopic (micro-structural) level, and beyond that, in order to suggest descriptive attributes even at macro scale. The paper thus presents some first steps in the creation of a digital simulation tool developed in *Processing* (JAVA environment) which is informed by material behaviour and targeted towards material-based design generation.

2. Introductory Work: Physical Experiments

As the research seeks to unfold the relationship between "curviness" and "stretchiness", strategic decisions were made with regards to material selection. The physical experiments were executed in three groups, each exploring different aspects of the same phenomenon and growing in complexity. Elastic membranes made of rubber latex were selected as a working material.

The initial experiment (Figure 1) demonstrates the behaviour of an elastic membrane when upon pre-stretching, local resin impregnation is introduced to promote non-homogenous material distribution within the membrane (once released). This phenomenon is in some ways analogous to that of a funicular shape which is one similar to that taken by a suspended chain or string subjected to a particular loading. The impregnated resin is equivalent to “lines of constraint or hardness” which force the membrane to remain at its initial (pre-stretched) length when released, and as a result induce curvature upon release.

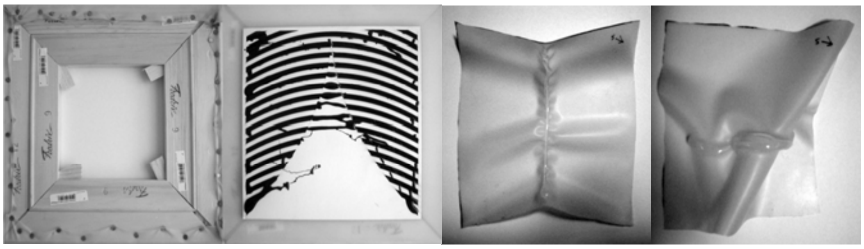

Figure 1: Resin impregnated latex-membrane experiments. Left: Rapid moulds designed for pre-stretching and impregnation. Right: Impregnation applied parallel and perpendicular to stretch to stretch.

In this experiment, the latex membrane is stretched in one direction and the resin (“line of force”) is introduced, once parallel to the stretch, and again, perpendicular to the direction of the stretch. Figure 1 illustrates the basic experiment: in the left-hand image, impregnation is applied **perpendicular** to stretch direction and results in local folds along impregnation after release. In the right image impregnation is applied **parallel** to stretch direction and results in global curvature of the fabric after release.

The next series of experiments demonstrate the relationship between the resin impregnated patterns applied to the pre-stretched membrane and the resulting curvature produced upon release.

In this experiment (Figure 1), the latex membrane is homogeneously stretched on a wooden frame (left and middle images illustrate bottom and top configurations of frame); laser-cut chipboard with impregnation pattern is attached to the membrane and resin is applied into the “negative cutting” pattern. Once the resin has dried, the chipboard is removed and the latex membrane is released from the frame.

Establishing such relations between the impregnation pattern, the direction of stretch, and the resulting geometry would assist in predicting the induced three-dimensional form based on the two-dimensional pattern.

Two models were experimented with which illustrate such relations. The first employed an elliptical pattern and the second, a hyperbolic pattern, both of which proved to be diagnostic of essentially two different forms of global curvatures: synclastic and anticlastic curvatures respectfully. In other words, the impregnated pattern, by forming a composite material (resin impregnated latex), promoted a non-homogeneous behaviour within this material system.

Figure 2 illustrates the result of such an experiment: the non-homogeneous resin pattern was applied to a homogeneously pre-tensioned latex membrane. Once the stress is released, the membrane deforms completely, based on the 2D impregnation pattern, to form a 3D structure with global synclastic curvature.

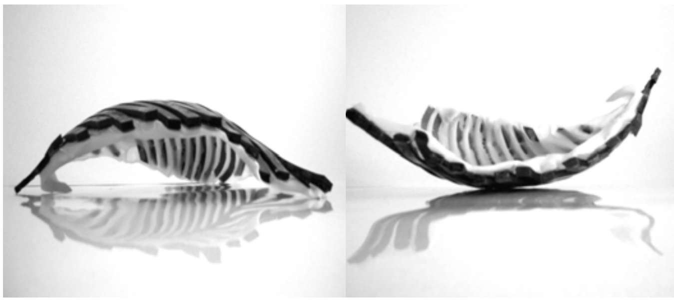

Figure 2: Resin impregnated latex-membrane physical experiment (left and right - frontal and dorsal elevation views) demonstrating curvature induced by pre-stretching.

3. Simulation System Description and Implementation

The experiments illustrated here were developed as parallel investigations in the physical and digital realms. Physical experiments were executed which defined the criteria for simulation and further generation of form, based on material behaviour under extrinsic loads as determined in the material experiments. The computational tools were developed in the *Processing* environment, an open source programming language developed by Ben Fry (Broad Institute) and Casey Reas (UCLA Design, Media Arts), which enables ,among other things, particle system animation.

In this demonstration the aim was to compute material behaviour in two modes: the “top-down” mode promoted the creation of a constraint space emulating the physical system explored. This so-called “space” is defined by limited degrees of freedom (DOF) defined as geometrical constraints driven by physical material attributes. The “bottom-up” mode promoted the application of local, and at certain cases, incremental constraints which were systematically introduced to the “constraint space” to fit specific physical manipulations; more on this later. Before introducing the computational model let us discuss some basic principles of the system at hand.

3.1 DIGITAL IMPLEMENTATION AND TOOL DEVELOPMENT

In the process of converting the physical findings to digital representations, which may potentially become tools for material behaviour simulation and prediction, it is essential to determine the way in which ‘material behaviour’ is coded as geometrical features, methods and functions (Hübsch, 2003). Both typical cases introduced in the previous section include the perpendicular-to-stretch application of resin impregnation (which resulted in pleating-like cresses formed in the direction of the stretch in the process of compensating for the shortening of the membrane after release with local folds/curves) and parallel to the stretch (which results in a general synclastic and/or monoclastic curviness of the surface as a result of the resin which forces the membrane to fold upon itself upon shrinkage and stress release).

In computational terms this phenomenon of shrinkage vs. stretching must be accommodated by highly articulated “material solvers” that are capable of mimicking material behaviour and translating physical properties into geometrical attributes. The computational tool developed for material emulation and material-based form-generation is based on the creation of a *particle-spring engine* built in Java. The fabric is modelled as a set of interconnected particles connected by springs (particles are represented as points, and springs are represented as lines connecting between those points).

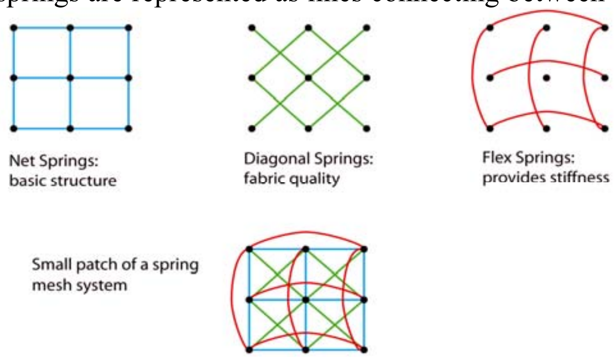

Figure 3: Composite image illustrating the stretch fabric simulation logic. Three underlying computational structures were modelled as the initial mesh: (a) net springs provide for the basic structure (stretch); (b) diagonal springs mimic fabric behaviour (shear); (c) flex springs provide for additional stiffness (bend).

3.2. DEFORMING THE MESH: EXTRINSIC VS. INTRINSIC DEFORMATION:

Mesh deformation is carried out either by introducing extrinsic deformation (adding accumulative amounts of springs to the mesh locally) or by introducing intrinsic deformation (modifying the characteristics of the springs themselves across the surface). As the membrane strongly resists stretching motions while being comparatively permissive in allowing bending or shearing, the simulation had to account for the intrinsic forces as much as the extrinsic ones.

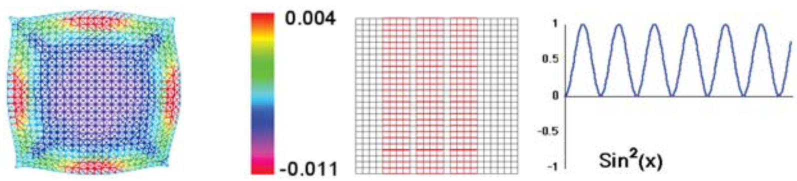

Figure 4: Left: Gaussian curvature representation indicating areas of positive and negative curvature in the mesh. Right: Increasing the length of red regions driven by a Sin^2(x) curve introduces intrinsic deformation to the mesh.

Figure 4 illustrates a sin function which informs the way in which the mesh deforms. The degree of change may potentially be modified by applying varied mathematical formulas.

Controlling the degree of mesh deformation by modifying the Gaussian curvature of the mesh:

The Gaussian curvature of a surface at a point is the product of the principal curvatures at that point. The tangent plane of any point with positive Gaussian curvature touches the surface at a single point, whereas the tangent plane of any point with negative Gaussian curvature cuts the surface. Any point with zero mean curvature has negative or zero Gaussian curvature.

Figure 4 illustrates the colour-coded Gaussian curvature in a generic mesh model: Any points on the surface with curvature values between the values specified by the user will be displayed using the corresponding colour. For example, points with a curvature value half way between the specified values will be green. Points on the surface that have curvature values beyond the red end of the range will be red and points with curvature values beyond the blue end of the range will be blue. A positive Gaussian curvature value means the surface is bowl-like (synclastic or positive curvature). A negative value means the surface is saddle-like (anticlastic or negative curvature).

4. Tool Demonstration

The mesh variables include the Spring Constant (K) indicating the strength of the fabric, the gravity force (G) within the modelling environment, the time step (T) for each increment, and the damping factor (D).

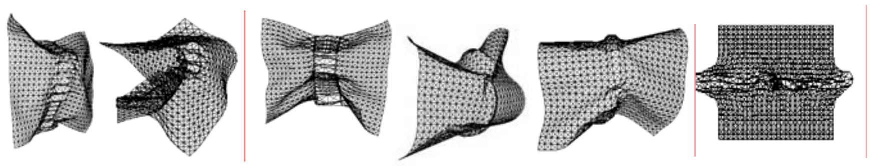

Figure 5: Digital simulation of resin impregnation which is applied perpendicular (left) and parallel (right) to stretch

The above two experiments demonstrate the digital simulation of the initial physical experiments. The top images illustrate the digital output of a stretch simulation which is applied to a resin-impregnated mesh where (right) the resin is applied **perpendicular** to the stretch direction and results in local folds along impregnation after release. Left: impregnation is applied **parallel** to stretch direction and results in global curvature of the fabric after release. Compare with Figure 1 illustrating the physical equivalent.

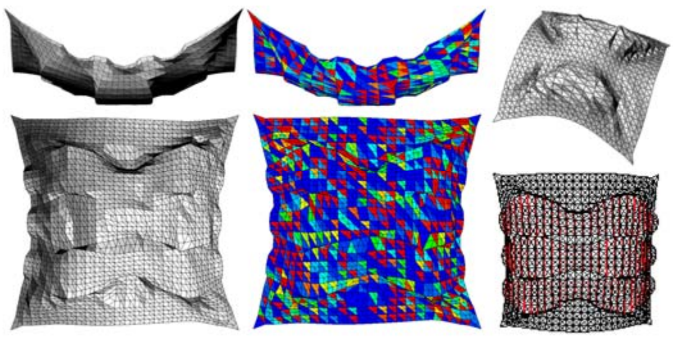

Figure 6: Digital Simulation of Intrinsic Forces in Mesh

5. Summary and Conclusions

The tool presented here is one of many potential applications in design computation which promotes the integration of material properties and behaviour alongside associative modelling environments which allow for structural optimization. In doing so, it seeks to define a synergetic approach to generative design processes by linking the material world to that of geometry and promoting design explorations of an iterative nature bridging physical and digital modelling.

5.1 FINDING-FROM BY CONTROLLING ANISOTROPIC MATERIAL ORGANISATION

Isotropic materials are materials which exhibit properties with the same values when measured along axes in all directions. Anisotropic materials are those which exhibit properties with different values when measured in different directions. The level or degree of "property differentiation" may be determined across different scales of investigation. When examined both in the local (molecular material composition) scale and the global scale (defined herein as building scale), the rubber-latex membranes exhibit homogeneous properties of behaviour in all directions. The act of applying resin strips over the surface, given a specific pattern arrangement, creates a material composite (resin impregnated rubber-latex) which acts in a heterogeneous manner when stretched and released.

5.2 THE HOMOGENIZATION PROCESS: INTEGRATING PHYSICAL DATA IN DIGITAL PROTOCOLS

The process of translating physical material behaviour into digital particle-system-based entities requires matching mathematical and geometrical equivalents to physical phenomenon such as stress, strain, gravity etc. This is where a structural, or rather organizational, hierarchy is needed for the simulation. The notion of "homogenizing" physical parameters which are not of the same order of magnitude and/or do not register, or measure, with the exact same unit conventions, promotes an approach for "calibrating" these orders such that they are comparable to one another.

5.3 COMPUTATIONAL STRATEGIES FOR EMULATING PHYSICAL BEHAVIOUR OF GLOBALLY MODULATED SYSTEMS

The experiments illustrated in this paper demonstrate a system of materials (resin-impregnated rubber-latex composite) which is globally modulated across its entire surface area (by pre-stretch, impregnation and release) to promote both global and local curvature. Two strategies in general were instrumentalized to simulate the material behaviour across both local and global scales. The first strategy was to differentiate the forces of stretch within the mesh based on a given mathematical formula which was integrated into the script; the second strategy was to locally add springs as needed to simulate different degrees of stretch once force is applied in a non-uniform manner.

These two strategies promote two very different approaches to the computation of material properties. The first strategy appropriates the mesh in its entirety and seeks to treat it as a *continuous* geometrical entity modulated by a global formula; the second promotes *discreteness* of material elements, which do not necessarily go hand in hand with the way in which the material itself is described physically. It is probably worthwhile emphasizing that the closer the computational strategy is to the material logic, the more inherent - and thus better - it becomes. Membrane structures seek continuous solutions whereas component-based systems would promote a more discrete strategy with regards to computation of material properties.

Acknowledgements

This work has been carried out by the authors' collaboration in the framework of an MIT course directed by Dr. Dennis Shelden, Chief Technology Officer of Gehry Technologies. The authors also wish to thank Yanni Loukissas, teaching assistant, Dr. Axel Kilian and Alexandros Tsamis for their invaluable input. The Java programming for the tool was executed in *Processing*, a 3D programming environment developed for the design community by Benjamin Fry and Casey Reas at the MIT Media Lab, Cambridge, USA.

References

Barraf, D. and Witkin, A.: 1998, *Large Steps in Cloth Simulation*, In *SIGGRAPH* Computer graphics Proceedings, Annual Conference Series, pp. 43-54.

Burry, J., Felicetti P., Tang, J., Burry, M, and Xie, M.: 2005, *Dynamical structural modeling: a collaborative design exploration* International Journal of Architectural Computing 3(1), pp. 27-42.

Burry, J; Felicetti P.; Tang, J.; Burry, M, and Xie, M.: 2005, *Dynamical structural modeling: a collaborative design exploration* International Journal of Architectural Computing 3(1), pp. 27-42.

Hübsch, P. F.; Middletona, A. J.; Knoxb, J.: 2003, *Computation of the elastic properties of a resin impregnated wire mesh by the means of a homogenisation procedure* in Medical Engineering & Physics, Elsevier Science Ltd 22(7), 2000, pp. 521-524.

McCarter, R.: 2005, *Luis I. Kahn*, Phaidon press, New York

Otto, Frei: 1995, *Finding Form*, Edition Axel Menges, Berlin.

Shea, K., Aish, R. and Gourtovaia, M.: 2003, *Towards Integrated Performance-Based Generative Design Tools,* Digital Design 21st *eCAADe* Conference Proceedings, pp. 553-560.