Designing with Deformation - Sketching material and aggregate behaviour of actively deforming structures

Anders Holden Deleuran, Martin Tamke and Mette Ramsgard Thomsen

CITA - Center for Information Technology and Architecture,
Royal Danish Academy of Fine Arts, School of Architecture
Philip de Langes Allé 10, 1435 Copenhagen, Denmark
andersholden.deleuran@karch.dk, martin.tamke@karch.dk, mette.thomsen@karch.dk

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Abstract

The recent development of material performance as a key driver of architectural design is currently challenging the role of representation and prototyping. This paper shares findings from a research project exploring the potential of a digital-material prototype capable of addressing this challenge. The project examines the possibility of incorporating material properties into digital models using respectively an analytical and a dynamics-based approach. The paper will present three design experiments with different material properties all attempting to deliberately embrace deformation as a key principle of design. This exploration of actively deforming structures is carried out using light weight dynamics simulation producing flexible and intuitive models for sketching material behaviour in the early design stages.

1. INTRODUCTION

Architectural constructions are traditionally conceived as rigid structures that are static in their behaviour. When considering the material performance of a brick wall or a concrete slab we imagine these as inherently fixed in time and space. However, as the project passes from design to production the parallel knowledge field of structural engineering is focused on the calculation and control of the dynamic qualities of these materials. Here, the performative role the built environment is foregrounded aiming to optimise for maximum stiffness with least deformation and to limit the bending, buckling or twisting of materials. Traditionally these two knowledge fields have been clearly separated, one succeeding the other, but as the tools of architectural design change new opportunities for designing for and with material behaviour appear.

The introduction of complex 3D modelling allows architects to engage with material simulation. Traditional architectural tools such as CAD based drafting support the static perception of our surroundings. Architectural drawing prioritises the geometry of the building proposal, delineating extension while giving little significance to the structural tensions and material behaviours of torsion and bending that take place within the structure. With the introduction of computation, 3D modelling and the ability to program models parametrically the direct simulation of material behaviour becomes possible. Working deliberately with material deformation, architects are able to investigate material performance as an integrated part of design.

This paper reports on three projects undertaken as part of a research focus on integrating material performance in architectural design. The projects examine a range of different materials moving from the mono-material to the composite. Our aim with the work presented in this paper is to investigate how material simulation can be used to explore material behaviour within the early design phase both as an analytical tool as well as a design tool. Exploring “light weight” tools for dynamic simulation and their interfacing with architectural design tools our objective has been to understand how simulation can lead to the design of new material structures.

2. RESEARCH INQUIRY

The architectural design space is traditionally defined by the hand drafting and modelling of non-associative geometry. The integration of parametric tools has advanced this by enabling data-driven “smart” geometry generated through a process of defining relationships in an algorithmic manner (Kolarevic and Malkawi 2005). Although being highly flexible these new tools still prioritise the perception of structures as being materially static and rigid. In this
design space deformation is therefore typically considered as a passive parameter. Geometric description and structural constraints are therefore in general manageable. This is not the case with actively deforming structures. These rely on a more complex set of spatial logics which fundamentally challenge the design space. When embracing active deformation the physical constraints which govern material reality need to be applied throughout the design process and therefore geometry may no longer be idealized as rigid.

As a consequence of this design involving actively deforming structures in an architectural context has very little precedent. Research within this field is therefore often informed by other fields such as garment making (McQuaid 2005), biology (Lienhard et al. 2010) and ship building (Lindsey 2001). In contemporary architectural research this field is rapidly maturing through an increased focus on the relationship between material strategy, digital representation and digital fabrication techniques. A recent example of this can be seen in the ICD/ITKE pavilion developed by a team directed by Achim Menges at the University of Stuttgart (Menges 2010). It convincingly displays how computational design, material simulation and robotic production processes can result in a novel bending-active structure made entirely of elastically bent plywood strips (Kaltenbach 2010). Other contemporary examples of this thinking can be seen in the work and literature of Michael Hensel (Hensel and Menges 2006), Mark and Jane Burry (Burry and Burry 2010) and Gramazio and Kohler (Gramazio and Kohler 2008)

Although such projects are proving highly innovative most work is generally still being carried out through the making of physical prototypes. Often the problem in projects that aim to integrate material behaviour such as bending or stretching is that the digital representations are limited in their scope for abstracting or simulating such behaviour. In these projects physical prototyping becomes a way of empirically testing concepts without directly employing digital representation (Tamke et al. 2009). The material prototype as a mode of design therefore engages deformation through the mode of physical representation i.e. scale models and full size mock-ups. This approach suffers several drawbacks being costly and time-consuming, lacking sufficient scalability and being very limited in their adjustability. The described shortcomings suggests that a medium is needed which bridges the gap between representation and reality more efficiently in order to better engage the domain of actively deforming structures.

3. THE DIGITAL-MATERIAL PROTOTYPE

The following describes our initial efforts to define and elaborate such a medium through the concept of a digital-material prototype. This prototype concept embeds material behaviour into the digital model and may potentially overcome the drawbacks of physical modelling. In this work the initial research is focused on conceptual modelling, looking at simulation as an early design tool and not only a tool for validation and analysis. Our primary goal is to develop a framework capable of producing flexible and intuitive models which may be employed in a process of sketching material behaviour in complex deforming structures. This goal necessitates the possibility of generating models capable of simulating various different materials in an interactive and intuitive manner, so as to quickly iterate ideas and concepts. In the following we will present and discuss two distinct approaches we have developed for digital-material prototyping. In the first approach we use empirical data as a basis for informing a parametric model simulating bending deformation. In the second approach we address the use of dynamics based physics solvers for simulating a more broad range of material behaviours, this approach is exemplified through three specific design experiments.

3.1. An Analytical Approach

Abstracting and embedding material properties is inherently problematic. We have conducted experiments aimed at informing digital models by analysing the behaviour of different materials and plotting the resulting data into the model using parametric software such as Grasshopper and Generative Components. An applied case of this approach is the installation Thaw. Thaw investigates the use of textile concepts for tectonic structures of an architectural scale. It is designed by CITA’s Mette Ramsgard Thomsen and Karin Bech for the “Digital Material” exhibition at the ROM gallery in Oslo. Thaw is a five meter tall woven wall membrane constructed of ash slats braced by steel joints. As a material structure it explores active deformation through the elastic bending and twisting of its wooden members as well as the friction based interlocking of the weave. For the design and construction of Thaw a geometrically relational parametric model was built. Following this the bending deformation of varying member lengths were analysed under a range of load conditions (figure 1. right). Subsequently the produced data set was abstracted into formulas which could simulate the “bend” of members using a law curve in the parametric
model (figure 1. left). This gave us a general idea of how the wood would deform in the structure, generating sufficiently accurate geometric data to use for the fabrication of a “geometry dependent” skin system attached to the wooden slats. The design model also supported real-time feedback which was valuable in quickly iterating proposals and making design decisions.

Figure 1. Left: The analytical bend simulation. Right: Plotting the bending deformation which produces the data set driving the law curve.

From this experimentation we learned that this analytical and empirical approach provides highly valuable data in understanding the material behaviour. The direct translation of this data into a function-based simulation has however exposed several drawbacks in representing material structures beyond that of the singular member. A model based on the isolated deformation of a single member does not account for the collective physical interdependency in the overall structure. The load-conditions applied in the process of analysing the singular component will furthermore not correspond to the actual distributed load condition for any given member in the structure. By comparing the analytical bend simulation of Thaw to the behaviour of the actual built structure (figure 3. right) these drawbacks are clearly seen.

This approach of embedding material behaviour thus result in models where the part-to-whole relationship does not include the distributed material behaviour and deformation of the system as a whole, what we refer to as the aggregate behaviour of a material structure. Due to the intrinsic nature of the analytical model it furthermore lacks the ability to incorporate external forces acting upon the structure such as gravity, wind or impact. This ability is crucial in order to meaningfully embed a property such as mass, which is essential, as the compound mass comprising the deadload of a structure greatly influences its aggregate behaviour. When working with active deformation and employing highly deformable materials this holds especially true as these display less resistance towards deforming forces than their rigid counterparts.

From these findings it can be concluded that a more holistic, exhaustive and flexible method is required in order to qualify as an apt digital-material prototype. The shortcomings of the analytical approach suggest that a decentralized approach - directly embedding material properties and physics based constraints into digital matter and the environment which it inhabits - might prove better suited. In the following this assumption is explored and elaborated upon.

3.2. A Dynamics-Based Approach

The dynamics-based approach explores the potential of integrating physics simulation in our digital models. This involves implementing a physics solver which can provide an approximate simulation by explicitly defining material properties. This provides a decentralized approach with full collective physical interdependency and the possibility of integrating participating external forces. In current explorations on simulation for generative design this approach is supported by research at Autodesk which suggest that “...physics-based generative design represents a paradigm shift from the traditional primacy of object to an exploratory approach of investigating interacting elements, interdependencies and systems. The integration of simulation opens up the possibilities for a more dynamic framework in the early stages of design” (Attar et al. 2009). Consequently such systems provide better support for the needed requirements of flexibility, scalability and distributed behaviour. The following presents an investigation into the involved factors of identifying specific simulation tools and techniques applicable to this agenda.

4. IDENTIFYING A DYNAMIC DESIGN SPACE

The description of material behaviour is an extensive subject of study with many distinct sub-fields ranging from elastic to plastic deformation characteristics, to damage and fracture mechanics, to fluid dynamics of gaseous and liquid media. As a consequence numerous specific approaches for
simulating material behaviour exist within many fields. These can be divided into four overall fields of employment: gaming, film/animation, engineering and natural science.

Film and animation is concerned with the simulation of physical phenomena with the main issues being stability, robustness and speed. Gaming has similar goals but with an increased focus on real-time performance and interaction. These fields are in contrast to engineering and the natural sciences which operate at a wider scope of simulation where the main focus is on accuracy, extendibility and reliability (Müller et al. 2006). Generally speaking this means that the described spectrum of applications can be perceived as going from light weight to heavy weight in terms of computational overhead and ease of use. The sum of these applications furthermore spans a vast amount of specialized tools as well as more flexible and sophisticated multi-physics solutions. This makes the subject extensive and more or less inaccessible for designers and architects. Determining an appropriate dynamics solver may therefore be problematic without specified requirements combined with sufficient research on the subject.

4.1. Light Weight Dynamics Simulation

Our goals for the use of simulation as a digital-material prototype disqualifies computationally intensive and less intuitive applications commonly used for engineering purposes and analysis such as Ansys, Sofistik or Comsol. Such applications do furthermore not interface particularly smoothly with 3D modellers commonly used in the early design stages by designers and architects such as Rhino 3D, 3ds Max, SketchUp or Maya. These factors point towards the branch of dynamics simulation related to computer graphics and the gaming industry. Researchers within these fields have historically developed dynamics simulation solvers for structured deformable objects aimed at interactive frame rates (Desbrun et al 1999, Terzopoulos 1987). Many of these integrated into 3D packages already familiar to designers and architects. Consequently we have focused on exploring the potential and applicability of such solvers which may generally be described as light weight dynamics simulation.

Precedent in the field shows that architects and designers have previously explored this subject in the pursuit of more intuitive models for structural and environmental analysis as well as the aforementioned generative design processes (Zarzycki 2010). This exploration has been driven by dynamics solvers utilized “as is” in commercial 3D animation packages or by writing bespoke software. Common to these dynamics solvers is the approach to model objects as a system of point masses (particles) connected by elastic springs or constraints (Ahlquist and Menges 2010). This method provides a relatively simple method for simulating deformable objects exhibiting realistic physics at interactive frame rates on personal computers.

Although lacking accuracy and being geared towards visual results “…particle systems are related to computer-based structural analysis methods used in the design of buildings, where the springs of the particle system correspond to finite elements used to model structural members” (Martini 2001). Despite this promising parallel the implementation of light weight dynamics simulation should not yet be adopted as a substitute for accurate finite element analysis. Instead it should be used as a complementary method for initial conceptualization, shortcutting the process by embedding similar tools in the design phase where the simulated structure can respond to the designers input in real time. This enables intuitive and immediate changes to the system, thereby increasing both structural understanding and the ability to iterate design concepts.

4.2. A Unified Design Space

Our design development of new material structures is based on experimentation with a diverse and often interacting range of distinct materials. The usability of our digital-material prototypes is consequently dependent on the implementation of dynamics solvers capable of simulating multiple interacting materials simultaneously in a unified manor. Traditionally light weight dynamics solvers have been designed to simulate particular types of objects such as rigid bodies, cloth or hair, thereby making combinations of such effects problematic due the transference of data from one solver to the other (Stam 2009). To resolve this and advance the flexibility of physics simulation promising developments towards unified and extendable solvers are currently being pursued. Based on unified generalizations of matter and forces, these solvers are capable of computing multiple physical phenomena interacting simultaneously, thereby supporting the identified requirements for a digital-material prototype.

Within computer graphics and animation these include the Nucleus solver, implemented in Autodesk Maya since
version 8.5, and the Lagoa Multi-Physics solver, released for Autodesk Softimage 2011. Interestingly, similar physics solvers are being developed for both parametric CAD modellers and text-based programming environments, including the Kangaroo Physics plug-in, available for Grasshopper in Rhino and Generative Components, and the Traer Physics Library, available for the open source programming environment Processing. Due to familiarity with Maya and the relative maturity and production proven nature of the Nucleus solver we have so far employed these as the initial toolset for design experimentation and elaboration of the proposed framework. This experimentation will now be exemplified through distinct applications of the proposed approach in the context of three concrete projects.

5. DESIGN EXPERIMENTS

5.1. Thaw: Weave and friction based tectonics

The first experiment presents a revisit to the installation Thaw. In order to confirm the assumption that the dynamics-based approach can provide a more accurate simulation of the actual behaviour than the analytical we built a new digital model using Maya/Nucleus. To inform this model we set up a calibration rig. This consisted of ten slats of varying lengths locked in one end deforming under their own weight due to gravity. By measuring and correlating this deformation with corresponding nMeshes (a polygon mesh with embedded material properties in the digital model) we tuned the parameters of the system and mesh resolution to a level where a relatively approximate behaviour was simulated (Figure 2).

From here the existing relational Grasshopper model was modified to generate meshes corresponding to the slats used in the construction while simultaneously adhering to the established mesh resolution. These were exported to Maya and converted to nMeshes. To create the meshes for the steel joints a MEL (Maya Embedded Language) script was written which can generate a joint based on selecting the two opposing faces of the slats to join and the angle at which they meet.

With the nMeshes in place the question was how to bend, twist and attach the pieces together. The first step here was to lock the end conditions at the top and bottom part of installation. Following this a considerable number of “attraction” constraints, linking one mesh vertex to another, were created and key-framed to pull the slats and joints together over time. To weave the slats in the correct manner each joint was loosely constrained to its world position thereby forcing the slats to attract outwards. By key-framing this order of events the process of weaving could be managed very precisely. In this key-framed timeline the slats and joints are connected in three primary stages, mirroring the real process, before finally reaching a stage of equilibrium in the final step shown here (Figure 4). By comparing the results of the dynamic model with the actual built structure (figure 3) it is seen that the dynamic model successfully manages to approximate the complex aggregate behaviour of the built structure very closely.

From the experiment we learned that the specific order of physical events in time is a highly important factor when simulating a complex structure such as Thaw. Due to the non-parameterized nature of polygon meshes the constraint creation could not be automated. The process was therefore remarkably similar to the tedious task of manually doing it by hand in real life. Beyond the problematic nature of setting up the constraints we also encountered issues with
making the slats stiff enough without having to use settings that seriously affected the frame rate. The behaviour of the model is therefore less rigid than the real installation.

Figure 4. Screenshots from the dynamic model over time. The process of weaving the slats and connecting them to the joints.

5.2. Reef: Minimal surfaces as a method of actuation

The second experiment explores the simulation of smart composite materials. In the responsive ceiling installation Reef CITA’s Aurélie Mossé and physicist Dr. Guggi Kofod are collaborating on the use of “electro-mechanically active polymers” to create self-organizing responsive components with embedded actuation. As a material structure these components are essentially minimal surfaces bounded by an elastically deformable frame. A pre-stretched elastomer sheet is attached to a thin laser cut plastic frame resulting in complex out-of-plane composite structures. The shape change occurs due to the elastomer attempting to minimize its surface, thereby pulling the frame and forcing it to bend out of plane. The elastomer has the ability to reverse this by running an electrical current through it. This enables the shape change to go from one state to the other based on sensor input. The component can thereby become responsive.

A primary challenge in this work is how to anticipate the self-organized shape of the component and thereby the design. A secondary challenge is how the overall performance of distributed components in the Reef may behave as a responsive environment. Through simulation we have developed a workflow which can anticipate behaviour in both these challenges.

Figure 5. Top: Mock-up of a component for the Reef ceiling installation. Bottom: A corresponding dynamics-based model with the elastomer undergoing surface minimization.

To simulate the material behaviour we inform the model using a similar approach of calibration as with Thaw. From here a CAD-file describing the planar shape of the frame is translated into a polygonal mesh. To ensure good mesh topology this is done using conventional poly-modelling (figure 6). The mesh is then duplicated and modified so that one mesh represents the frame and the other the elastomer. After converting to nMeshes the two are aligned and a constraint is applied which essentially “glues” the two together at their nearest vertices. The model is now in the planar state where the elastomer is active. To turn it off an attribute controlling the “rest length scale” of the mesh is used. By sliding this below its initial value the elastomer will begin to contract thereby simulating the behaviour of surface minimization and changing the overall shape of the component (figure 5. bottom).

Despite the rather liberal mesh interpretation of the frame shape it can be concluded that the dynamic model can anticipate the self-organized shape of the real component to a satisfactory degree. This has been further confirmed by simulating the behaviour of other components with dissimilar frame shapes. As with Thaw we have encountered problems with making the plastic frame stiff enough at an
acceptable frame rate. Due to the complex shapes used the biggest hurdle in the workflow has however been the translation from CAD-file to polygon mesh.

![Figure 6](image_url)

**Figure 6.** Left: CAD-file of laser-cut shape. Right: The translated polygon mesh divided into the frame (white) and the elastomer (grey).

To simulate the behaviour of the installation as a responsive environment we have distributed components into a “Reef”. From here the individual component actuation and resulting collective behaviour can be simulated using various parametric animation techniques such as “driven keys” and “expressions” using parameters such as proximity or wind direction as input to which the installation responds. This has proven a valuable sketching tool in the design process of the installation.

5.3. Project Distortion: Dynamics as a design tool

The final experiment explores the use of dynamics as a form finding tool in the design of a pavilion for the 2010 Distortion street festival in Copenhagen. It is the result of collaboration between CITA’s Martin Tamke and Brady Peters, students and supervisors from the Royal Academy of Fine Arts School of Architecture in Copenhagen and the Rensselaer Polytechnic Institute in New York. The pavilion is a configuration of connected equilateral cones constructed from acoustic foam and plywood joined using cable ties. Experiments with physical scale models revealed that the surface of connected equilateral cones acted like hinged triangles. This resulted in an overall textile behaviour where the surface is pliable, finding its form through pleating and wrinkling. Where these scale models helped to figure out a design we needed a more precise model to provide the data needed for the fabrication of the pavilion on CNC machinery. At this point we turned to dynamics-based simulation as a potential solution.

The input for the dynamic model was an array of cones generated through a Grasshopper definition which can propagate eight types of cones into an array based on parameters such as aperture, height, colour and the outline of the array. This array is converted to polygons and exported to Maya (figure 8). Here it is split in two and aligned to face each other. Since this form finding method is a geometric exercise informed solely by mass, gravity and collision the cones can in this case be idealized as rigid. To attach the cones to each other a constraint locking the overlapping vertices of the meshes is created. Two adjustable guide rails defining the desired footprint of the pavilion are created using inverse kinematic chains. To pull the array back together and simultaneously attract the base cones to targets on the guide rails a number of constraints using the same “attraction” technique as with Thaw is created. Finally the gravity on the solver is key-framed. While the geometry is being pulled into place gravity is set to zero. As the cones connect gravity is put in reverse for a further form finding process following the Gaudi inspired paradigm of inverted catenary chains. Once the system reaches equilibrium the form finding process is complete with a structure that inherits mainly compressive forces.

![Figure 7](image_url)

**Figure 7.** Distortion Pavilion. Top: Render of final form found configuration. Bottom: Photo of the built structure.

In the built structure the aggregation of cones ultimately becomes structural through bespoke steel braces fixing the cones in a staggered hexagon pattern across the arch of the pavilion. Therefore the form found geometry was imported back into Rhino where a second Grasshopper definition computes the angles between the cones and drives the fabrication of the braces. The purpose of the model thus becomes twofold: part form finding and part fabrication data. As figure 7 demonstrates this experimental design and fabrication method was successfully confirmed.
Figure 8. The array of cones from the Grasshopper definition translated to a dynamic Maya model and the process of form finding.

6. CONCLUSION:

We have established that the design of material structures based on active deformation may benefit from new design tools capable of embedded material behaviour. Through the concept of the digital-material prototype we have identified **unified light weight dynamics solvers** interfacing with existing CAD tools as a potential design space for achieving this goal. Finally we have validated this assumption through three successful design experiments using dynamics-based simulation.

The presented work has mainly focused on predicting the behaviour of a material system before it is built. In this process it has been the design intent which has informed the tool. The Distortion project conversely hints at a parallel application for dynamics-based simulation in which it is the tool that informs the design in a process of generative form finding. It can be imagined that combining these two levels of information by feeding them into each other might result in novel self-designing systems. In our future work we aim to explore this aspect more extensively.

The design experiments also exposed specific problems with physics-based simulation. The computational overhead can quickly result in the loss of interactivity and the polygon based workflow requires high-quality meshes and lacks sufficient parametric control. It can therefore be concluded that neither the analytical nor the dynamics-based approach can fully satisfy the requirements for a digital-material prototype as defined in this paper. In our further research we therefore aim to experiment with the development of new tools and workflows which can combine the advantages of both.

References


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