A Digital Model for Fabric Formwork Panels

Using physical data to train the digital model

Elena Prousalidou
University College London, United Kingdom.
eprous@gmail.com.

Abstract. In the context of a wider inquiry on the integration of material properties and construction processes in computational models, this paper proposes a digital model for fabric formwork panels. Plaster cast in different types of fabric can produce a significant variation of resulting forms. The aim is to investigate whether data retrieved from physical models with 3D scanning techniques can improve the accuracy and efficiency of a simulation based on geometric principles, and better predict the behaviour of cast material in relation to the type of fabric. Setting up the computational model and choosing its parameters and constraints is based on the physical construction process, highlighting the relationship between material and form. As part of the cyclical exchange, evaluation of the digital model with physical testing demonstrates that the simulation can actually be trained by reducing the physical/digital discrepancies.

Keywords. Fabric formwork; simulation; dynamic relaxation; 3d scanning; kinect.

INTRODUCTION

Current tendencies in design, and particularly a fascination with complex geometries generated by algorithmic logic, tend to disengage form from construction processes, fabrication concerns and material properties. The use of computational tools expanded the gap between design and construction. However, a shift in designers’ mentality is slowly emerging, due to advancements in digital fabrication that create a range of new possibilities for experimentation with material and construction processes. The turn to making sparks a renewed interest in materials and material simulation. Achim Menges (2011) describes the new field as ‘material oriented computational design’.

Projects such as the ICD/ITKE temporary research pavilion (Menges 2011) or the Persistent Model (Ayres 2011) reveal the advantages of blending digital and physical information. The first demonstrates how computational generation of form can be driven by physical behaviour and material characteristics, while the latter revolves around the procedure of free-form metal inflation and its digital representation, aiming to achieve a feedback loop between the physical and the digital model. The responsive relation between a digital model and a physical artefact, with concerns about the construction process, material behaviour and material properties, has inspired the system proposed in this paper. Based on the idea that combined use of physical and digital models allows for material and manufacturing considerations to be involved from the early stages of design, thus enhancing the performance, the aim is to explore a possible interaction between the computational and the physical model when developed as parallel processes.
**FABRIC FORMWORK**

The term ‘fabric formwork’ may refer to any technique that produces concrete elements by pouring concrete on a tensile membrane, rather than a rigid frame. The method is still at an experimental stage but certain features assert its potential in terms of sustainable performance, cost-effectiveness and aesthetic appeal. It can produce a variety of fluid forms, geometries and textures which allow the true nature of concrete as a casting material to find its expression. As Alan Chandler (2007) remarks, “casting is no longer a process of replication; rather it becomes, with the use of textile, a field of possible outcomes within a fixed set of parameters.”

P. Wall by Matsys [1], Grompies [2] and Fatty Shell [3] explore the architectural possibilities of structures produced with material cast in fabric, involving computational and digital fabrication applications. They computational models applied are restricted to a two-dimensional surface. Two-dimensional patterns are produced by an algorithmic procedure, in the last project also cut by a robotic arm, but after that traditional crafting takes over. The deformations in the third dimension come into play only after the material is poured. There seem to be no intention of connecting the physical products with the digital models that produced them.

Diederick Veenendaal (2008) developed a program that simulates and analyses concrete beams produced with fabric formwork. Fabric Former integrates manufacturing constraints, computational optimization and structural analysis. As the author notes, the results of FabricFormer, although not far from being translated in actual formwork, needs to be subjected to physical tests and still “remains inside the realm of the computer.”

Robert P. Schmitz (2006) proposed a program for fabric formwork concrete panels which uses analytical modelling and structural analysis to predict the deflected shape of concrete panels cast in formwork. Although promising, the procedure is derived from FEA analysis of rigid elements and adapted to the particular construction process. It can be argued that the top-down approach results in simulated panels which fail to express the fluidity of actual fabric formwork elements.

As an attempt to address the demand for computational tools of this innovative building method, this paper introduces a digital model for fabric formwork concrete panels. The system implements a simple dynamic relaxation model to simulate the fabric’s flexibility and is then informed by physical data retrieved by 3D scanning.

**DEVELOPMENT OF THE METHOD**

The method was developed simultaneously in two directions. A series of initial trials with plaster cast in different types of fabric revealed that the textile’s properties have a significant effect on the casts’ form. The plaster models were digitized with a 3D scanning system set up based on a Kinect sensor. At the same time, a computational model of fabric, plaster and constraints was developed in order to simulate the construction process. An interface associates the physical model with the simulation and calculates the discrepancies between the two. The simulation can then be ‘trained’ through repeated comparison with the physical data so that the discrepancies are minimized. All programs were written in Processing [4]. The steps of the process are presented next in more detail.

**Plaster models**

The production of plaster models followed the process for fabric formwork concrete panels developed at CAST, as described by Mark West [5]. It requires three frames placed on top of each other: a base frame with the supports inside, a second frame with the mildly tensioned fabric and the third frame on top where the plaster is poured.

The trials comprised of single and double rectangular support configurations testing four types of fabric. Cotton and lycra were selected for the final experiment as they have quite diverse material properties in terms of thickness, stiffness and permeability. When plaster is poured in cotton, the fabric applies restrictions to the form resulting in a more uniform distribution of the plaster and the cre-
ation of subtle volumes. When lycra is used as formwork, the relationship between boundaries and supports plays the primary role and the material weight produces concentrated bulks.

3D scanning with the Kinect sensor
A fast and easily accessible 3D scanning device was required to convert the plaster models into digital format. Scanning from one direction can obtain the depth map of the plaster model’s surface. High accuracy and high resolution do not play an important role for the purposes of this project.

The Xbox Kinect sensor by Microsoft, a motion sensing input device for the Xbox 360 video game console, was used and converted to a desktop 3D scanner. The code used a library that enables the communication of the Kinect sensor with Processing platform. *dLibs Freenect library* created by Thomas Diewald [6] is based on the libfreenect-software by OpenKinect [7]. It reads the Kinect 3D data, performs a simple colour mapping and draws a point cloud. After a suitable set up is established (Figure 2), the static surface of the plaster model can be 3D scanned providing a consistent point cloud data set. The method has the advantages of being low-cost, easily accessible, and relatively simple to control.

Computational model
The forms produced by fabric formwork pointed to conventional simulation form-finding algorithms of cable and membrane structures, such as dynamic relaxation. Those models consist of a grid of nodes connected by links. Internal forces on the direction of the links force the system to an equilibrium position. External forces on one direction, such as gravity or other loads are also commonly used. In other words, the geometry is represented by the mass distributed on the nodes and lines of force acting between them. The movement of each node is calculated as the average position of its four neigh-

Figure 1
Plaster models produced with fabric as formwork and a 30x30mm support. Cotton-left and lycra-right.

Figure 2
3D scanning setup based on a kinect sensor allows the simulation to be informed by digitised physical data.
bour nodes and is iteratively updated, affecting the interconnected links/forces and therefore the structure's geometry. The same repeats for all other points until the structure reaches the equilibrium position.

The simulation was based on the construction process used for the plaster casts. The fabric is simulated by a regular grid of linked nodes, on which the mass is distributed. The plaster is represented as a uniform load applied to the nodes and a series of box constraints indicate the supports beneath the fabric.

**Physical/digital interface**

The simulation and the data retrieved from the physical models are superimposed in an interface that connects all separate elements into a unified whole. The program displays the ‘relaxed’ fabric surface as a series of links with one or more supports underneath (Figure 3) and the digitised data as a point cloud (Figure 4).

The point cloud is mapped to the grid so that a single point is assigned to each node. The difference between a node and its equivalent mapped point from the point cloud set is calculated and a line is drawn between the two. Red lines indicate that the physical point is lower than the predicted point and blue lines that it is higher. In this way a clear representation of the differences, or discrepancies, is instantly acquired (Figure 5).

Additionally, three indices are calculated to facilitate the comparison and quantitative analysis of the results. $D_{\text{mean}}$ indicates the average difference, or discrepancy, between the position of a node as predicted by the simulation and its corresponding mapped point from the point cloud data set. The smallest this value is, the more accurately the simulation works. Ideally the simulation would predict exactly the same positions as the point cloud data and $D_{\text{mean}}$ would be equal to zero. $D_{\text{max}}$ is the maximum node/point cloud difference. It shows how far the simulation can go from the actual values and serves to point out the ‘sensitive’ areas of larger discrepancies. $N_{\text{overmean}}$ is the percentage of nodes having a difference value greater than $D_{\text{mean}}$.

![Figure 3](image)
*Display of relaxed form with links representing the fabric and a support underneath.*

![Figure 4](image)
*Point cloud display.*
RESULTS AND OBSERVATIONS

The experiment
In order to test the digital model, four plaster models were produced using two types of fabric and two sizes of supports. The mixture used for each panel was approximately 2kgs of fine casting plaster with 2.6kgs of water. The dimensions of the plaster panels produced were 280x380 mm with each cast weighing on average 3kgs when dried. The models are labeled CottonA, Lycra A, Cotton B and Lycra B.

- Cotton A: cotton formwork with 64x64mm support.
- Cotton B: cotton formwork with 30x30mm support.
- Lycra A: lycra formwork with 64x64mm support.
- Lycra B: lycra formwork with 30x30mm support.

The plaster models were scanned and their point clouds were imported in the Processing interface. The simulation was initially tested for a grid of 38x28 nodes, to match the physical models, and the uniform load distributed on the nodes set to 0.5. The internal parameters of the model were: mass at each node = 10, spring constant k = 0.9, rest length = 5, damping factor = 0.9999.

The program ran multiple times testing the effect of altering all of the above values. Change of the mass, spring constant and damping factor values didn’t have any effect on the results. Various values were tested for the load proved to have a dramatic effect. Increasing the grid’s density to 76x56 (4256 nodes) also had a significant effect. Indicative results are presented in the following tables.

As explained above, the lowest \(D_{\text{mean}}\) value implies smaller overall discrepancies and is associated to the most accurate result, referred to as ‘best’ result. The simulation converged to a ‘best’ load after 10 iterations. It was observed that best results for the two materials are produced for a different load. For a grid of 1064 nodes, this load is 0.05 for cotton and 0.1 for lycra. For a grid of 4256 nodes, the load is 0.02 for cotton and 0.025 for lycra.

\(D_{\text{max}}\) served as an indicator of the load value chosen for the next iteration, keeping the results within a close range. If it gets too high, the simulation is obviously far from accurate. \(N_{\text{over mean}}\) values ranged from 65 to 80 meaning that more than half of all nodes have discrepancies greater than the average. Discrepancies are not equally distributed on all nodes.

Contrary of what was expected, an increase in the grid’s density results in a reduction of the overall

<table>
<thead>
<tr>
<th>Load</th>
<th>(D_{\text{mean}})</th>
<th>(D_{\text{max}})</th>
<th>(N_{\text{over mean}})</th>
<th>(D_{\text{mean}})</th>
<th>(D_{\text{max}})</th>
<th>(N_{\text{over mean}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.025</td>
<td>1.01</td>
<td>5.82</td>
<td>70.2</td>
<td>2.62</td>
<td>13.43</td>
<td>67.5</td>
</tr>
<tr>
<td>0.05</td>
<td>0.72</td>
<td>4.84</td>
<td>73.02</td>
<td>1.917</td>
<td>10.37</td>
<td>66.9</td>
</tr>
<tr>
<td>0.075</td>
<td>1.07</td>
<td>7.46</td>
<td>67.6</td>
<td>1.313</td>
<td>7.51</td>
<td>70.3</td>
</tr>
<tr>
<td>0.1</td>
<td>1.82</td>
<td>10.38</td>
<td>73.1</td>
<td>0.904</td>
<td>5.17</td>
<td>71.6</td>
</tr>
<tr>
<td>0.125</td>
<td>2.62</td>
<td>13.22</td>
<td>76.6</td>
<td>0.955</td>
<td>6.46</td>
<td>64.7</td>
</tr>
<tr>
<td>0.15</td>
<td>3.44</td>
<td>16.33</td>
<td>80.5</td>
<td>1.603</td>
<td>7.75</td>
<td>75.5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Load</th>
<th>(D_{\text{mean}})</th>
<th>(D_{\text{max}})</th>
<th>(N_{\text{over mean}})</th>
<th>(D_{\text{mean}})</th>
<th>(D_{\text{max}})</th>
<th>(N_{\text{over mean}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.025</td>
<td>0.85</td>
<td>5.23</td>
<td>72.8</td>
<td>2.27</td>
<td>12.91</td>
<td>62.8</td>
</tr>
<tr>
<td>0.02</td>
<td>0.82</td>
<td>6.31</td>
<td>69.4</td>
<td>1.49</td>
<td>9.73</td>
<td>67.1</td>
</tr>
<tr>
<td>0.05</td>
<td>1.14</td>
<td>7.89</td>
<td>65.9</td>
<td>1.19</td>
<td>8.25</td>
<td>69.3</td>
</tr>
<tr>
<td>0.1</td>
<td>3.59</td>
<td>16.24</td>
<td>79.8</td>
<td>1.87</td>
<td>9.74</td>
<td>75.1</td>
</tr>
<tr>
<td>0.1</td>
<td>8.62</td>
<td>35.01</td>
<td>79.6</td>
<td>6.77</td>
<td>24.35</td>
<td>80.3</td>
</tr>
</tbody>
</table>
accuracy, with highest $D_{\text{mean}}$ values. A less dense grid gave results closer to the actual values. This could be possibly due to the accumulation of small mistakes in the dense grid that increase exponentially the average value.

Another round of simulations ran for the plaster models with the 30x30mm constraint. The results are presented in the Table 3.

As before the simulation performed better for load values of 0.05 for cotton and 0.1 for lycra. For both A and B constraints, lycra showed higher differences, maintaining a consistency between load and material.

### Training the model

The patterns observed in the plaster casts are easily detected in the graphical representation of the discrepancies, with red areas showing where the actual model is deeper than the simulation and blue areas where it is higher.

To adjust the simulation to materials with different elasticity, a different load pattern was considered necessary; one that takes into account material specificities. ‘Training’ the simulation aims at minimizing the discrepancies and took the form of searching for the best possible load pattern to counterbalance the physical/digital difference. This should be transferred to the 1064 grid nodes. The technique devised to achieve the weighted load dis-

<table>
<thead>
<tr>
<th>Load</th>
<th>$D_{\text{mean}}$</th>
<th>$D_{\text{max}}$</th>
<th>$N_{\text{over mean}}$</th>
<th>$D_{\text{mean}}$</th>
<th>$D_{\text{max}}$</th>
<th>$N_{\text{over mean}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.025</td>
<td>1.01</td>
<td>5.82</td>
<td>70.2</td>
<td>2.67</td>
<td>14.03</td>
<td>67.01</td>
</tr>
<tr>
<td>0.05</td>
<td>0.72</td>
<td>4.84</td>
<td>73.02</td>
<td>1.78</td>
<td>10.14</td>
<td>66.8</td>
</tr>
<tr>
<td>0.075</td>
<td>1.06</td>
<td>7.46</td>
<td>67.6</td>
<td>1.20</td>
<td>8.21</td>
<td>67.71</td>
</tr>
<tr>
<td>0.1</td>
<td>1.82</td>
<td>10.38</td>
<td>73.1</td>
<td>1.12</td>
<td>10.96</td>
<td>58.5</td>
</tr>
<tr>
<td>0.125</td>
<td>2.61</td>
<td>13.22</td>
<td>76.6</td>
<td>2.01</td>
<td>13.73</td>
<td>75.8</td>
</tr>
<tr>
<td>0.15</td>
<td>3.44</td>
<td>16.33</td>
<td>80.5</td>
<td>3.13</td>
<td>16.64</td>
<td>82.2</td>
</tr>
</tbody>
</table>

Table 3
Cotton B and Lycra B results for various load values– grid of 1064 nodes.
ttribution was to divide the frame into eight parts in x and y directions, resulting in a 7x7 matrix of load values. The simulation run multiple times with the patterns adjusted each time so as to optimise the values. The diagrams in Figure 7 present the load matrices which produced improved results. The size of the red dots indicates weights of 0.5, 1.0 and 2.0.

After 10 iterations, the lowest $D_{\text{mean}}$ value for cotton was 0.656 (0.723 for uniform load) and the lowest $D_{\text{mean}}$ value for lycra was 0.806 (0.904 for uniform load). The 10% improvement of the predicted values for both fabrics confirms that a non-uniform loading pattern can improve the simulation, adjusting it to a more or less elastic material.

DISCUSSION

General characteristics of the digital model

The digital model brings together a physical model in its digitized form and a computational model. In addition, it provides a clear graphic representation of the difference between the two which is used to further improve the accuracy of the predicted cast forms.

Each part of the process was developed with very simple means. The computational model employs a grid of nodes linked by spring elements with a rectangular constraint underneath—simulating fabric tensioned on a frame with a support underneath. Loading acting on the grid represents the plaster cast in the fabric. It is interesting to observe how close this simple system is to physical data. 3D scanning with the Kinect sensor is used as a fast, convenient and inexpensive way to digitise physical data. In this case, plaster casts are used to inform the simulation and allow for the fabric's elastic properties to be taken into account.

The benefits of the method can be expressed in both quantitative and qualitative terms. On one hand the results obtained when testing the system proved that, only with a few manually adjusted non-uniform load trials, the physical/digital discrepancies were reduced by 10%. It becomes apparent that a cyclical exchange allows room for further improvements in the accuracy of the simulation.

In effect, the digital model can link a textile type to a 7x7 non-uniform load matrix, for a given configuration of supports. It can be used as a tool that integrates form and material. The designer can choose from a palette of fabric types, adjust the number, size and location of supports and instantly acquire information about the resulting cast form. He can interact with the model, experiment with the values, create multiple virtual instances, and finally arrive at an informed decision.

Moreover, a tool that relates physical and digital data offers additional insight into the construction process. As observed during the development of the system, the production of physical and digital models in parallel nurtured an intuitive feeling, increased confidence and awareness of the system and proved to be very useful when important decisions about
the simulation setup had to be made. This is part of a design process closely linked to fabrication. It contributes to a shift of design focused on form to the trinity of material, form and the process of making (Beukers and van Hinte 2005).

Lastly, the expression of the fabric’s material properties through the use of the plaster’s weight acting as a load, can be seen as a direct reference to the unique properties of the fabric formwork technique, where fabric and concrete form a closely linked system in a constant exchange and flow.

Further work
Since the purpose of the project was to investigate whether a reduction of discrepancies is possible or not, the search for an optimised load pattern was performed manually. A 10% reduction was considered satisfactory to end the search. The application of an optimisation algorithm in the program is expected to reduce the discrepancies. Further reduction could be achieved using a professional 3D scanning device or testing a large number of physical samples. The next step would be to increase the scale of the models and set up experiments with building materials, concrete and technical textiles.

Although the digital model was tested for a single rectangular support, the program allows for any configuration of multiple rectangular and cylindrical supports. With a series of physical testing and calibration, it can evolve into a parametric tool which accepts values for the type of fabric, the weight of the cast material and the shape and size and number of supports as input and generates a virtual cast.

CONCLUSIONS
This paper introduces a digital model for fabric formwork panels, aiming to explore how the integration of physical and computational models into a single tool can enhance the design process.

Rather than using tools designed for rigid frame structures whose production follows a different logic, a closer look at the physical construction method and the intricate relationship of fabric and concrete hinted to possible directions. The simulation of fabric formwork panels was developed in parallel with the production of plaster casts.

The performance and efficiency of the system was evaluated based on physical testing. Adjustments of the simulation based on the digitised point clouds were made by introducing a non-uniform load pattern adapted to the type of fabric. This led to a reduction of the discrepancies, demonstrating that the digital model was informed by physical data.

The digital model successfully represents the construction method of fabric formwork panels. It integrates both geometric and material parameters and creates an interface where the digital and physical data can be combined and manipulated. It can be used as a design tool and parts of it can be modified for other materials and construction techniques.

It should be emphasized that computational and physical models as well as the 3D scanning technique with the Kinect sensor all contributed equally to the system. Superimposing physical and digital models brings material on the same level with computation and opens a range of opportunities for interaction on equal terms.

ACKNOWLEDGMENTS
The work presented is part of the author’s MRes Adaptive Architecture and Computation dissertation at UCL. The author would like to thank Ruairi Glynn for his invaluable input while supervising the thesis, and Sean Hanna for his insightful comments. A special thanks to Processing and OpenKinect open communities for sharing and inspiring.

REFERENCES


