ITERATIVE DESIGN PROCESS BETWEEN PHYSICAL MODELLING AND COMPUTATIONAL SIMULATION FOR PRE-TENSIONED GRID SHELL STRUCTURE

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Abstract. Grid shell structures are widely used in many types of buildings. In this paper the author proposes a new grid shell structure, which is pre-tensioned by stretchable membrane. Through iterative process between physical modelling and computational simulation, one pavilion is finally presented as a demonstration of the architectural performance of this structure.

Keywords. Material computation; form finding; pavilion; grid shell; active bending.

1. Introduction

With the development of computational tools, many natural phenomena can be simulated. In architectural design, it also helps to simulate material behaviour, especially elastic or flexible material, even though these kinds of bending materials were used empirically, even in primitive architecture. This paper shows a new type of grid shell structure, which is created by using the equilibrium of two elastic materials. The grid structure is made out of a bendable material (wire), its deformation made possible by attaching a stretchable fabric smaller than the size of the grid structure. Usually the shape of this grid shell structure is formed by one single material, such as bent wood, and the membrane just covers the shape. But in this case, by controlling local deformations (which comes from the equilibrium of two elastic materials), one can create 3D geometry. Therefore, by changing the 2D grid pattern, the various geometries of a grid shell structure can be generated. In addition, it does not require any supporting formwork for making complex curved geometries, since the system is completely created from a 2D pattern.
In the research of “form finding” by Frei Otto, the German engineer and architect, the form of architecture is developed by way of a series of physical modelling (Otto, 1995). Although it is mainly for structurally optimized forms for tensile structures, the geometries Otto created are so varied and organic, that it is hard to design by a more man-made, top-down idea. This means that the interaction of material and humans still has the primary power as the design driver. Although the main purpose of form finding by Frei Otto is the minimisation of material in construction, this research is focusing on the possibility of form finding as new design tool. Of course, now computational tools can help this process with regard to design speed and quantity of the studies.

Thus, this design process started with finding materials, and with successive, iterative physical modelling using these materials. This physical modelling is always starts with a small model, which can be easily made by one person. Then, after several physical and the computational tests, the model can be scaled up to larger pavilion-scaled structures.

Although these computational tools are widespread in contemporary architectural design practices, the result of the process is only architecturally meaningful if it can be translated into real, physical construction. In reality however, some digitally designed proposals completely lack material performance, and therefore cannot be realised. As opposed to this, the design system proposed in this paper focuses on rational construction, emphasising the material behaviour both for smaller models and larger architecture.

2. Iterative design process between physical modelling and computational simulation

The difficulty of this system is that it is hard to precisely control the material behaviour, since both the grid and the membrane are flexible and relatively soft. It therefore needs an iterative design process using both physical modelling and computational simulation.

The computational simulation is done by way of a particle-springs system used in 3D modelling software. By simplifying the material behaviour into the movement of particle and spring, one can simulate the geometry easily and rapidly. It is very helpful to know an appropriate grid pattern for the target geometry. Of course, whenever the used material is changed, the parameter of the simulation settings needs to be changed by comparing the result of the physical modelling and the computational simulation. For example, the simulation with the piano wire for small model and the one with carbon fibre for a mock-up are different. As a result, it is important to have a feedback loop between the physical and the computational. After several mock-ups,
computational simulation, and structural analysis, a pavilion with a 5m by 5m footprint has been built.

![Figure 1. Iterative design system.](image)

3. Physical modelling from shrink film to stretchable membrane

3.1. SHRINK FILM

In the beginning of the research, the physical modelling was tested with shrink film and piano wire. Shrink film is a very thin film made out of PVC (polyvinyl chloride) and usually used for wrapping material, shrunk by applying heat. In addition, piano wire is also thin and has elastic behaviour, with very flexible bending properties. By combining these two material characteristics, the specific geometry can be generated. (Kuma, 2014) Piano wires are attached to the flat shrink film by transparent tape in a grid pattern. After applying heat by dryer, the film shrinks, and this tandem system deforms into a three-dimensional, wavy surface. The direction of the bent wire is automatically defined, because it follows the deformation of the surface. However, since the shrink film has limited scalability, a stretchable fabric with more tensile capacity is adopted as alternative material.

![Figure 2. Model photos of shrink film and stretchable membrane.](image)
3.2. STRETCHABLE MEMBRANE

Stretchable fabric is usually used for clothing such as swimwear or sports-wear. It is composed of 88% polyester and 12% polyurethane. By stretching, it can expand to more than double its original area. For the model, the same piano wire is used as with the shrink film. As an initial setup, the stretchable fabric needs to be pulled and held into place by a wooden frame. Then, the piano is directly stitched to the stretchable fabric, rather than with the previous tape. Once all the piano wires are attached in a grid pattern, the resulting surface is released from the frame. As a result, it becomes a 3D wavy surface from 2D. However, if each of the grid spaces is small, it does not create local deformations. On the other hand, when one creates a 2D gradational pattern that has larger spacing in the periphery, and smaller spacing toward the centre, it creates a global dome shape with a wavy surface. This is the result of large local deformations at the periphery, and the much smaller deformations at the centre.

For a larger scale model, the piano wire is too thin, and therefore it is replaced by carbon fibre strand rod, which is light and has high tensile capacity. The mock-up with carbon fibre rod is tested again and again. For example, the several types of joints of the fibre rod and the membrane are tested for structural capacity in this mock-up process. This data also translated into the computational simulation, which is discussed in the following chapter.

4. Computational simulation

For the computational simulation, 3D modelling software with a physics engine approximates a system of particles and springs. (Piker, 2013) The wire is composed of particles and springs in this simulation. It is converted into a polyline, which is the continuous line described by the connecting each of the particles. The membrane is composed of a network of simulated springs, in turn connected to the particles on the polyline. Two features of the wire are represented abstractly. One is the restoring force. The wire tends to become straight by inner stress. The second one is the limitation of bending.

Figure 3. Patterns for local deformation and global deformation.
There is a limitation to the curvature of the fibre rod, defined by its material. The first feature, the restoring force, can be simulated in particle and spring system, by a bend function, which controls the angle between three particles. In this situation, the function is set to make those angles to be 180 degrees. Thus, this can be used to simulate the inner stress. With the second feature (limitation of bending), by measuring the curvature of each wire, it is possible to detect any curvature over a determined limit.

The images below show how the 2D grid pattern deforms by changing the shrinkage of the membrane. In the third picture, the shrinkage is 37.5%, which is as same as the setting of the physical modelling. The colour of the wire shows the minimum curvature of the carbon fibre strand rod. Red indicates the limitation of the curvature. If it is smaller than that, the fibre rod can become broken. By comparing with the result of the physical model, the setup of computational simulation is adjusted: the feedback of the computational simulation allows any newly generated pattern to be tested in a physical version, and vice versa. This workflow makes the simulation more accurate.

In addition, for the simulation of pavilion scale prototype, gravity needs to be considered. This is because in reality, the system is too heavy to become a 3D shape from a 2D pattern only by the shrinking force of the membrane. Thus, some anchor points in the periphery are moved to target locations for enabling the tendency to create a 3D shape, in addition to the shrinkage of the membrane.

\[\text{Figure 4. Computational simulation for local deformation.}\]

5. Structural analysis

The contribution of the membrane is not only for making a deformed grid, but also for reinforcing the global structure by adding pre-tension. In that sense, this structure has a new type of integration between tension and compression forces. In this project, the structural analysis is done by FEM analysis software developed by Prof. Jun Sato from University of Tokyo. It calculates stress and visualizes the safety factor distribution of the model generated from computational simulation mentioned in previous chapters. In that computational simulation, the material property is not considered, but
this structure analysis is based on the structural properties of carbon fibre rod and stretchable membrane. Colour variation represents the safety factor, which is defined as a ratio of calculated stress to allowable stress in each member. For example, blue (less than 0.5) means high safety margin, red (more than 1.0) is over the allowable stress. The structural performance of each model can be compared by the colour distribution. Basically, the new computational models are continually tested in this FEM analysis by changing the form until it attains structural safety as indicated by good colour distribution.

This analysis shows that the structure with a wavy surface is structurally more rigid than one with a smooth surface. The image below shows the comparison between the model without membrane (left) and one with membrane (right). The one with membrane is actually the model of the final prototype. This analysis shows that the one without membrane has red appearing around the bottom. This means that it may not be even self-supporting. The one with membrane has just a few areas of red, and most of the parts are blue, so that it can be self-supporting. In other words, by combining the membrane with the grid wire, the amount of the wire can be minimized. This is because the membrane itself is reinforcing the structure instead of adding the wires.

Figure 5. Structural analysis for the model without membrane and one with membrane.
6. Prototype

To make a pavilion-scale prototype, the stretchable membrane is doubled. Thousands of zip-ties connect the carbon fibre rod to the fabric. First, the carbon fibre rods, cut in specific lengths, are laid down on the ground. Second, connecting the intersection points makes the grid structure. Third, the stretchable membrane is attached to the fibre grid from the centre by zip-ties, while pulling the membrane taut. Fourth, after the attachment of the fibre and the membrane, the stainless pipe for the base is installed. Finally, by moving the fibre and the membrane, some of the fibre edges are fixed into the stainless pipe. This is the procedure of construction of the prototypical pavilion. Following this, by making a 3D scan of this geometry from the series of the photos of the pavilion, the actual model and the computational model are compared, to know if the simulation works precisely.

![Figure 6. Construction process of prototype.](image)

Although the local wavy surface of the pavilion is not exactly same as the simulation, the global geometry is reasonably close, nearly matching the location of highest point, the size of the entrance, and so on. This pavilion stood for one week in the open air, at the University of Tokyo. It accommodates more than ten people inside.
7. Conclusion

As the prototypical pavilion shows in the chapter before, the combination of two elastic materials can create new architecture in terms of visual effect and spatial quality. In particular, this architecture exhibits lightness without any air-pressure or rigid-structure. This is because the material performances are maximized in terms of structure and design.

In addition, this design process is very adaptive to various types and sizes, since this shows the relationship between 2D patterns and 3D form. It is similar to how origami works with regard to form generation from 2D pattern. But instead of having any folding lines (which are always problematic at a larger scale), this system has a graduation of local deformations in order to create effects on the global structure. Compared to traditional form-finding research, this system has more flexibility in the resulting form. This is because the form is generated by a 2D grid pattern. It means that there are potentials for adapting to given spatial requirements.

Furthermore, the computational process could contribute not only to making faster design studies, but also to integrating multiple factors of architecture, such as the structure analysis in this paper. In analyzing this kind of complex double curved form, the 3D model is necessitates FEM analysis. Potentially other types of analysis can be performed, such as wind load response, or several kinds of environmental analyses.
8. Outlook

Although computational tools are used through the entire process, and the geometry of the resulting pavilion is close enough to the simulated target surface, the accuracy is not so high yet. Therefore, in order to get satisfactory results, the iterative process between the physical and the computational models take a long time because of this inaccuracy. Now, the simulated material’s behavior is abstracted into a system of particles and springs. This simulation system can be updated by the integration of FEM. In this, the material properties—such as the exact material size, its generated modules, or other structural information—can be included into the calculation, resulting in more accurate results, as well as the full integration of morphological simulation and structural analysis.

Moreover, a future goal is to scale up this pavilion by using the same system. At the moment, the materials of the pavilion—the membrane and the carbon fiber—are not rigid enough for a more permanent structure, and not durable in the outside environment. But by combining a suitable stretchable membrane for architecture and a more rigid bending material, it can be enlarged to the next scale. This is because this system does not require specific material. It uses just the relatively simple two material behaviors: stretching elasticity and bending ability.

Additionally, the system for construction has more room for further development. For example, if at the full scale the membrane is already in ten-
sion and stretched by a rigid frame, people do not need to pull the membrane for the attachment to the wire. By releasing the membrane and the wire after the attachment, it automatically pops up from 2D to 3D in a real scale, much like the smaller physical model. This could improve the speed of the construction process.

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**References**


