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Shear-deforming textile reinforced concrete for the construction of double-curved structures

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Abstract

A composite textile reinforced concrete (TRC) material is developed to overcome the difficulties of constructing double-curved freeform structures. This is possible by shear-deformation of the woven reinforcement. It affects the direction of reinforcement and thickness, resulting in variable orthotropic properties over the surface. The research translated the properties of aerospace materials to the scale and limitations of building construction materials. To accomplish this, knowledge about TRC is combined with strength and geometric knowledge about the design of shear-deformation. This resulted in a new type of material and design method that links material properties, digital formfinding, and construction documents/process. This new material should primarily be used as formwork for concrete, a very laborious part of double-curved construction. To conclude the research, a case-study building was created to confirm the complete process from digital formfinding, though structural analysis, to construction documentation. The case-study building, a landmark double-curved concert hall, is used as a narrative to connect the various research realms.

Keywords: Shear-deformation, Textile Reinforced Concrete, Freeform Architecture, Double-Curvature.

1. Introduction

1.1. Freeform structures and double-curvature

Freeform structures are increasingly easier to design and analyze due to advances in software, however their construction remains complex or labor-intensive. Such structures have been traditionally built with extensive formwork and skilled labor or more recently with computer aided manufacturing (CAM). The difficulty of their construction is largely due to their double-curved geometry, which is unable to be built from flat, cuboid elements. Beyond aesthetic benefits double-curved freeform structures, if designed correctly using the logic of shells, however can be more structurally efficient than orthogonal constructions. This paper is the summary of a Master of Science thesis completed in 2014 titled "Shear deforming textile reinforced concrete for the construction of thin double-curved freeform structures" at the Technical University of Delft [6].

1.2. Narrative material development

With appropriate construction techniques, for example inflation/air-support, new composite materials could be developed to enable the construction of double-curved structures. This paper uses a narrative to outline the research and development of such a material through a case study building, representing a high-profile concert hall. This includes element dimensioning, detailing, formfinding, analysis, and construction logic.

2. Shear-deformation

While double-curvature can be created through extensional-deformation, it can be achieved by shear-deformation. In aerospace textile composites the yarns do not allow for much extensional deformation, therefore shear-deformation of the textile is used to achieve double-curved geometry. Here, the angle of between the yarns varies throughout the element based on the initial placement and orientation of the reinforcement. Greater shear angles allow for greater levels of double curvature. When filled with a matrix material (eg polymer resin) this shearing created a thickness increase, which is caused by a decreased void area between the yarns and a constant volume of matrix material. This change is illustrated in Figure 1 below.

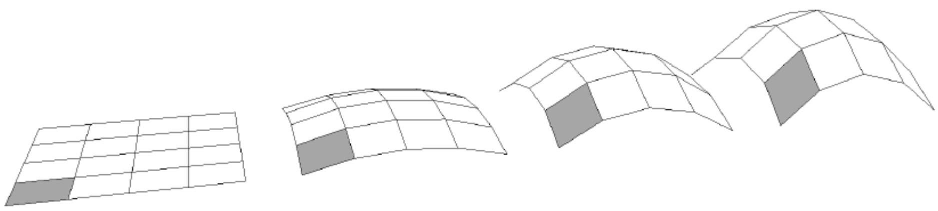

Figure 1: Example of shear-deformation transforming a square planar element into a hemispherical shape. (Image courtesy of P. Eigenraam [3].)

Geometrical software, such as Drape by Dr. Bergsma [1], can be used to determine the shear angles and associated thickness increase, for a given form to be created with textile reinforcement. While textile reinforced concrete has been applied to façades and even a commercial product called Concrete Canvas [2], it has not yet taken advantage of shear-deformation to enable the construction of double-curved geometries. In the present study, physical and analytical tests were conducted on a hemispherical form to determine an approximate maximum constructible shear-deformation angle of 40/140 degrees.

3. Studies

3.1. Textile reinforced concrete

Textile Reinforced Concrete (TRC) has been researched by Dr. Josef Hegger [4] and others. That research, with modifications, formed the basis of understanding in this research for the strength of textile reinforced concrete after shear-deformtion. From Hegger's experimental data on orthogonally oriented TRC, Hegger's Oblique-Loading Coefficient, was modified mathematically for the non-orthogonal, shear-deformed, reinforcement angles required in this research.

A graphical method was used to view and analyze these modified data. In Figure 2 below the dashed line represents a strength-factor for non-shear-deformed textile reinforced concrete relative to the angle of loading. The two peaks show were the material performed the best, when the loading angle acts in line with one of the yarn directions. The two valleys represent the worst performing orientation, when both yarns are at a 45-degree angle to the load. Correspondingly, the solid line represents a shear-deformed material with and angle of 40-degrees between the textile yarns. The two peaks represent the loading in line with a yarn in each direction and the valleys represent the worst loading case where both directions of yarns are oriented away. This shows that that shear-deformation causes increase performance in some loading directions and decreased performance in others.

This process is elaborated more fully in the thesis report [6].

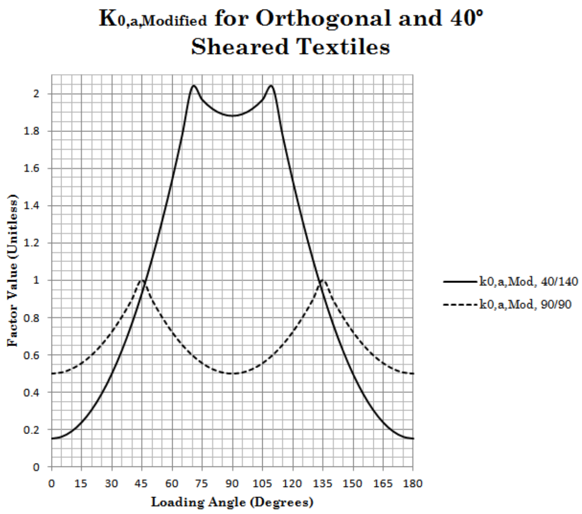

Figure 2: Modified oblique-loading coefficient for orthogonal and the maximum 40/140 degree shear-deformation cases.

3.2. Material composition

The composition of this new shear-deforming material must balance the requirements of construction (air- and water-tightness), constructability, and strength. Inspiration was taken from the product Concrete Canvas [2], which is constructed as a sandwich of a 3D textile reinforcement impregnated with unhydrated concrete, sandwiched between a layer of canvas and PVC. Once in position the Concrete Canvas is hydrated and left to cure. Similarly the material composition for this research consists of four layer types: water-permeable canvas, woven glass-fiber reinforcement, unhydrated concrete, and an air/water-tight elastic foil.

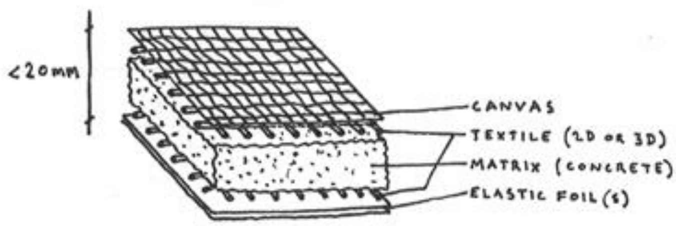

Figure 3: Material configuration.

3.3. Elastic foil shear-deformation

The air/water-tight layer is required for cement hydration and construction using inflation/air-support. It should behave similarly in shear to the reinforcement. This happens through extensional-deformation of the elastic foil, because it is resistant to shear. This layer must be stiff enough to insure consistent thickness and support during construction, but also elastic enough so that it does not wrinkle during deformation. Experiments were conducted on a variety of elastic foils.

Figure 4: Room temperature shear-deformation of a thin elastic film with burlap for comparison down to 40 degrees.

3.4. Dimensioning

The material is envisioned to act primarily as a formwork layer, especially for larger structures, and is therefore dimensioned to withstand forces during construction. Using Hegger's modified research and FEM analysis of a hemispherical test-shape, preliminary dimensions were created. This hemispherical test-shape was also used to examine the effect of variable stiffness/thickness due to shear-deformation and the possibilities of discontinuities/windows.

Figure 5: Photo of the physical prototype of the material showing reinforcement, concrete matrix, black elastic layer, and grey-black cloth layer, 20mm thick, 100mm wide, and 200mm long.

3.5. Detailing

The product Concrete Canvas [2] comes in up to 200-meter long, 1.1-meter-wide rolls, which are overlapped in-situ to form a continuous surface. This width, although relatively narrow, was used in this research as a manufacturability benchmark. Multiple methods of joining these long rolled strips of material were preliminarily detailed in such a way as not to inhibit shear-deformation, while allowing for force transfer, and air-tightness. Such details were required between the long and short edges of the material strips as well as foundation connections.

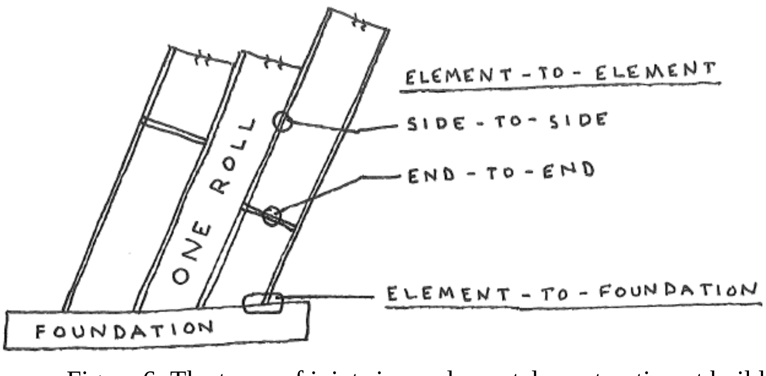

Figure 6: The types of joints in an elemental construction at building scale, side view.

4. Formfinding

The logic of construction, material properties, and architectural requirements were used as parameters for formfinding. These included inflation pressure, material weight, material slack, and footprint shape. The process began with the architectural footprint of the structure, to this an elasticized mesh controlled by material slack and weight was fitted, finally the inflation pressure was added and all parameters were varied until a suitable architectural height and form was achieved.

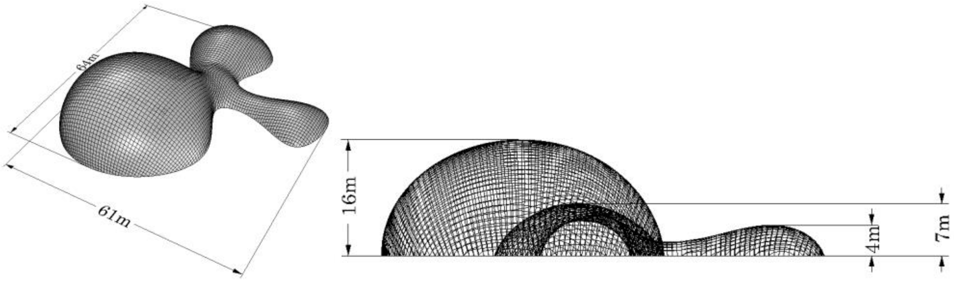

Figure 7: Geometry and dimensions of the formfound geometry.

5. Analysis

5.1. Structural bays

The software Drape [1] was used to split the geometry into structural bays, so that all areas could be constructed with shear-deformation less than the maximum of 40/140 degrees. This resulted in three bays that could be constructed from independent "blanks": large flat pieces composed of joined rolls of the material. Such breaks between structural bays could be appropriate for the placement of expansion joints. A preliminary structural analysis showed that three areas of structure would require more than one layer of the material to resist construction forces. These areas could be constructed from a thicker version of the material or from joined layers of the standard thickness.

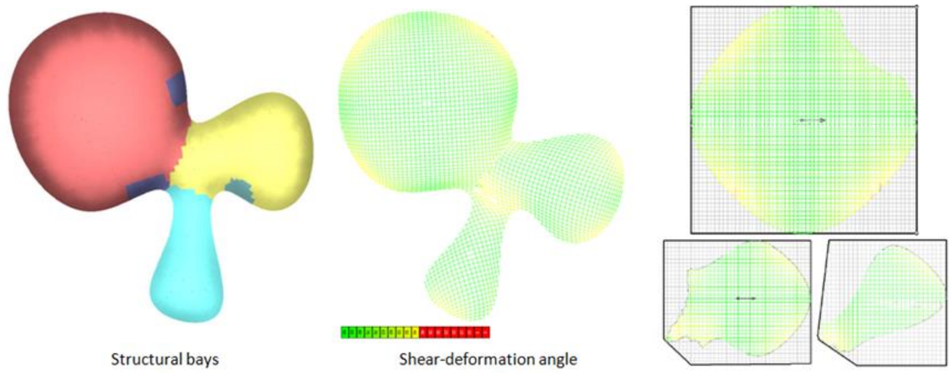

Figure 8: Formfinding with material layering (left), Shear-deformation study (middle), flat un-sheared material "blanks", one for each structural bay (right).

5.2. Reinforcement stress checks

Special attention must be given to the tensile capacity of the material as the reinforcement shears. Three critical points are evaluated as an example of the relationship between the principle stress angle and the angle of sheared reinforcement. Using the modified version of Hegger's coefficient, the tensile capacity at each point is computed and then compared to the principle stress at its effective angle. For each point the angle of deformation is determined, which can then be plotted to find its tensile capacity at various loading angles (Figure 9, bottom). Following this, the angle of the principle stress is determined and used to read the tensile stress capacity plot (red circles on Figure 9, bottom). This process is fully detailed in the thesis report [6].

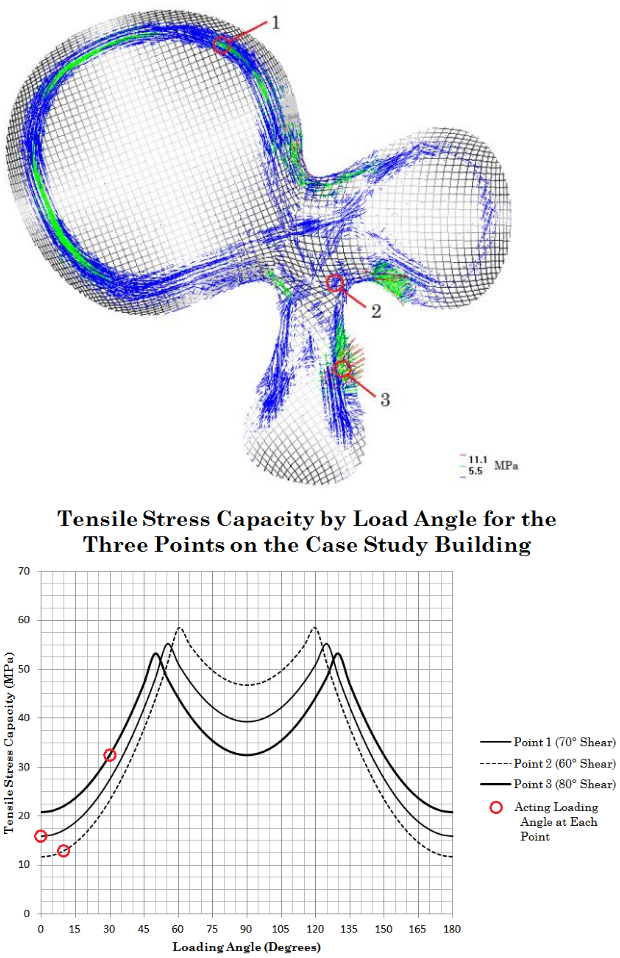

Figure 9: Plan view of the structure showing shear-deformation and tensile principle stresses (top), tensile stress capacity graph showing three points from the case study building (bottom).

6. Construction

A hypothetical construction would proceed as follows: the construction of the foundation, joining of the material strips on site into the prescribed flat "blanks", preparing for inflation by flexibly retraining the material edges, addition of temporary constructions at structural bay boundaries, inflation, connecting to the foundation, hydration of the concrete, curing, structural concrete topping, releasing the air pressure, cutting of windows/openings, and lastly finishing.

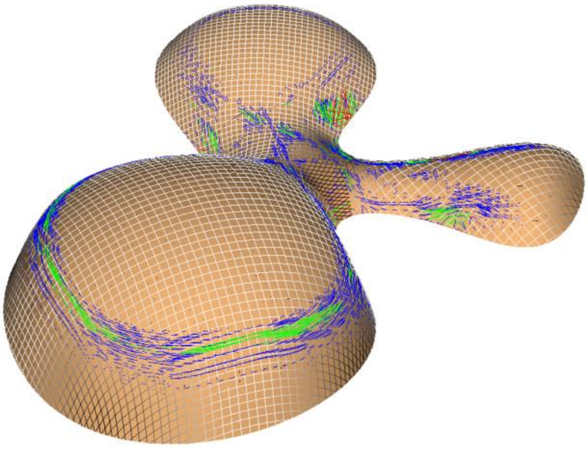

Figure 10: Completed form showing the width of the shear deformed material and tensile principle stress lines.

7. Conclusions

Double-curved geometry is possible with shear-deforming materials and could be used in the building industry. New materials such as this should be used in smart ways, not only to construct known geometries but also to enable new forms. Existing research and computation is already enabling the design, formfinding, and analysis of this type of material. Future research, both experimental and analytical, could be conducted in the areas of detailing and construction, as well as the integration of computer tools for design, structural analysis, and fabrication.

Acknowledgements

This research began from a Dutch patent from 2011, by Prof. Dr. Adriaan Beukers and Dr. Otto Bergsma [5], entitled "Sheet-like building material". The research was conducted as a Building Engineering Master's Thesis, at the Technical University of Delft in The Netherlands, under the guidance of Prof. Dr. Rob Nijsse, Dr. Otto Bergsma, Andrew Borgart, and H. Roel Schipper, completed in 2014.

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