KNIT PREFORM SHAPING

Design of Textile Preform and Edge-shaping mechanism for curved composite panel formation

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Abstract. This paper documents the development of our proposed fabrication strategy to manufacture doubly-curved Glass Fibre Reinforced Polymer (GFRP) cladding panels for facade components or internal walls. It uses a customised glass fibre knitted textile preform which is edge-shaped and sprayed with polyester resin to become a solidified composite panel. In this instance, we investigate the design of the textile preform and the development of an adjustable edge-shaping mechanism employed in this curved composite panel fabrication. We then test the shaping mechanism through the fabrication of several doubly-curved GFRP panels and compare their geometries to their respective digital models.

Keywords. Textile Hybrid Systems; Knitted Textiles; Glass Fibre Preforms.

1. Introduction

Textile hybrid systems with knitted membranes present a material-efficient strategy to create curved anticlastic geometries. These rely on the reciprocal interaction between its two main components - a tension-active knitted membrane stretched by bending-active members along its boundaries, which in turn get restrained in place by the textile (Lienhard, Knippers, et al., 2013). This configuration capitalises upon the inherent elasticity of the knit to accommodate to non-developable surfaces with large curvatures. At the same time, it benefits from the high flexural capacity of the bending-active members to produce significant curvatures using slender elements without yielding.

Our research adopts this principle to shape and manufacture curved glass fibre reinforced polymer (GFRP) panels for building applications. These composite panels can be used as internal walls or external building façade cladding elements to compose freeform envelope geometries.

First, we use custom-designed textiles machine-knitted from glass fibre yarns to function as flexible preforms for composite production. Next, we insert bending-active carbon fibre strips into sleeves integrated along the boundary edges of the textile. This setup undergoes a controlled flexing of its edge

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members to shape the initial planar textile into a curved surface. Once shaped, we apply polyester resin onto the textile preform to laminate it into a composite panel. Finally, we detach this solidified panel from the carbon-fibre strips for post-processing, so that the strips can be re-used for later shaping instances.

This workflow provides an alternative to existing mould-making and wet layup processes currently used in the industry to manufacture curved GFRP laminate panels. These methods employ significant amounts of expendable material through subtractive milling of the moulds, and labour from the simultaneous manual lamination to create these composite panels. In comparison, we posit that our method can remove the need for a hard mould backing and gradual build-up of the panel by using an elastic and inherently thick knitted preform. Such can stretch to a given geometry to become a stay-in-place preform for direct lamination. Thus, we believe that this can minimise resource consumption through our proposed strategy.

In this paper, we build upon our previous project (Tan & Lee, 2018) and investigate how to design and shape glass fibre machine-knitted preforms to achieve intended geometries. We discuss the developments of this research based on the following objectives:

- Testing the machine-knittability of glass fibre yarns into textiles and developing stitch patterns that are suitable for this fabrication method
- Developing a bending-active edge-shaping mechanism to create orthogonal curved geometries
- Evaluating the 3D-scanned physical prototypes against the digital geometries

2. Geometric Shaping using Textile Hybrid Systems

A review of existing literature shows that textile hybrid systems are emerging as a shaping strategy for subsequent composite formation. These have been used in:

(i) a direct manner, where flexing the bending-active members directly determines the geometry of the textile (Popescu et al., 2018); (ii) an indirect manner, where the bending-active forces are built-up within a pretensioned textile and these become the driver of the resultant form (Sharmin & Ahlquist, 2016).

Our scenario focuses on the former strategy where GFRP rods are threaded through sleeves that are knitted into the textile to directly flex it into an intended geometry. One prominent case study is Popescu et al. ’s KnitCrete bridge (Popescu
et al., 2018). Her work involved a flexible membrane knitted from aramid yarn and was shaped using bending-active GFRP rods and braided aramid ribbons. She positioned the rods and ribbons at alternating intervals within the textile to create a corrugated surface which acted as a stay-in-place formwork. Popescu sprayed a cement-paste coating onto the shaped textile to stiffen the surface for concrete lay-up. She then built up the thickness of the bridge using a subsequent layer of mortar and a final layer of structural concrete.

2.1. KINEMATIC AND TRANSFORMABLE SYSTEMS

Another body of work which we explored was kinematic textile hybrid systems. These moveable mechanisms fall under the category of direct bending systems and offer a good degree of control over the geometry of the bending-active members. In addition to the textile and GFRP rods, these systems consist of a series of wires or tension cables that restrain the bending-active members along specific positions to control the bending deformation of the rods (Anastasiadou et al., 2018; Lienhard & Gengnagel, 2018). Larger systems also include actuators to enhance the precision of the rods’ geometries (Körner et al., 2018).

An example of an adjustable bending-active mechanism would be Puystiens and her team’s kinematic form-active mechanism (Puystiens et al., 2019). Her setup consisted of two GFRP rods that were bent into a circular ring with a polyurethane-coated polyester membrane restrained within by adjustable belts. She included an internal GFRP beam element which spanned across the membrane. Subsequently, she affixed the boundary GFRP rod at two support points directly opposite one another and added a contraction cable at two other points. She then shortened the cable to simulate the kinematic deployment of the textile hybrid system. Thus, Puystiens used this setup to validate the strains developed within the membrane against her simulated data.

Puystiens highlighted that the bending of the rods was meant to maintain tension within the textile (Puystiens et al., 2015). This could be a concern as flexing the rods might cause too much or too little tension to develop within the textile. Both cases are detrimental because lack of tension might result in wrinkling of the surface, while excessive tension places significant strain on the bending-active members and cause them to experience torsion or material failure. Thus, the overall dimensions and tensioning of the textile during shaping need to be considered in addition to the stiffness of the rods.

3. Designing Glass Fibre Knitted Preforms

The first step of this research experiments on glass fibre knitted preforms, with regards to its machine-knittability as well as the development and selection of stitch patterns for the shaping procedure.

Knitted textiles offer a high extent of elasticity due to their intermeshed loop structure consisting of singular or multiple yarn(s). Additionally, we have observed that glass fibre yarns exhibit viscoelastic behaviour - a property that causes the yarns to undergo strain linearly under stress and shrink back to its original length fully when released (Somasekhar et al., 2012). Thus, we aim
to couple both properties to create preforms that are (i) inherently thick and (ii) possess good elasticity.

We believe that thicker preforms can minimise the need for further stacking of fibre glass sheets to build up the required nominal depth of the final composite. This is akin to spacer fabrics or certain non-woven textiles where the preform itself has adequate thickness to be directly laminated into a composite (Abounaim & Cherif, 2012; Kulas, 2015). Therefore, we referenced existing stitch patterns and developed new variants that utilise two needle beds as this allows us to create thicker textiles (Emirhanova & Kavusturan, 2008).

Customising the stitch pattern also confers different extents of elasticity and enables the textile to conform to curvatures of a given geometry. However, when dealing with glass fibre yarns, we need to rely on basic knit stitches because these yarns generally have a lower breaking extension (4.8%) than yarn materials typically used in fashion (eg. nylon, polyester with breaking extensions ranging from 12.0 - 28.0%) (Chattopadhya R, 2010). This means that the glass fibre yarns are prone to tearing when subjected to actions that cause significant elongation of the material, such as racking of the needle beds or constant transferring of the loops. Thus, we opt for front/back knits or tucks in the creation of the stitch patterns.

We employ CNC-knitting technology to develop several stitch patterns using glass fibre yarns to achieve the above characteristics (Shima Seiki, 2018). This enables us to design knits by specifying needle movement and yarn carrier positions using a specialised design software. The machine then reads these instructions to knit the textile by actuating the individual needles, yarn carriers and carriage. In this experiment, we knit 0.35mm diameter electrical (E)-glass fibre yarns with 224 tex linear density using the Shima Seiki MACH2XS (15G) at half gauge (ie. using every alternate needle). From our tests, the following patterns were selected:

![Double Jersey](image1)
![Milano Interlock](image2)
![Cardigan Milano](image3)

Figure 2. Closeup Photographs of Stitch Patterns (top) with their respective Knit Notation (bottom).
**Double Jersey** - This existing interlocking pattern creates a thick reinforcing knit which is suitable for composite applications. This pattern stretches almost equally in both wale-wise (longitudinal) and course-wise (transverse) directions.

**Full Milano Interlock** - This diamond lattice knit structure is the thickest out of these three patterns. After being knitted, the viscoelastic nature of the glass fibre yarn causes the textile to shrink wale-wise upon itself, resulting in a ‘puffy’ textile. It is elastic in the wale-wise but much less elastic in the course-wise direction.

**Full Cardigan Milano** - This porous knit is thicker than the Full Cardigan pattern but thinner than the Milano Interlock. The alternate tucking of loops combined with the tubular knit makes the textile more elastic in the wale-wise but less in the course-wise direction.

Subsequently, we characterise these patterns based on their bi-axial stretch capacity using a self-constructed tensioning jig fitted with bending-active carbon fibre strips. This simulates the loading behaviour of the textile during the geometric shaping procedure, where the wale-wise direction is stretched to its maximum first followed by the course-wise direction. The cutoff condition for maximum strain allowable is when the strips begins to flex during tensioning of the textile. This signifies that the textile has imposed too much force upon the edges, which would be detrimental to the shaping process. We also measure the thickness of the knitted preforms at their uncompressed (rest) state using a micrometer and benchmark this data against the thickness of a basic Single Jersey stitch pattern (1.6 mm) knitted with the same glass fibre yarn.

![Figure 3. Characterisation of Selected Stitch Patterns.](image)

### 4. Geometric Bending-Active Shaping

Next, we develop a shaping mechanism using carbon fibre bending-active strips to flex the edges of textiles to achieve an input geometry. This stage of the research tests the shaping of glass fibre textile preforms to achieve a series of singly and doubly curved orthogonal geometries.

Carbon fibre bending-active strips possess high flexural modulus, enabling them to achieve large curvatures using members of small cross-sectional profiles without yielding (Lienhard et al., 2013). This material behaviour resembles the...
physical representation of curves translated from digital space, where control points can be added along the strips to set the intended curvature. We envision these control points to be in the form of custom-made fixtures to fix the position and orientation angle along specific locations of the strips.

![Figure 4. Controlled Flexing of Carbon Fibre Strips.](image)

However, bending multiple strips of material in unison presents a challenge. This is further complicated by the non-trivial force-form relationship between both the bending-active members and the textile. As such, we need to bear in mind the following considerations:

- All strips need to be aligned and locked in place at the same time;
- Fixtures should isolate the bending of each individual strip to prevent adjacent strips from affecting the curvature of their neighbours;
- Tension of stretched textile should be adequate to prevent dislodging or breaking of the strips from their supports.

After various iterations, we arrived at a shaping system comprising an assembled network of extruded aluminum rail profiles with laser-cut 6.0 mm thick MDF fixtures to mount and lock rectangular cross-section (6.0 x 1.0 mm) carbon fibre strips in place. This allows us to make precise adjustments of the position and/or rotation of fixtures along the aluminum rails. Moreover, we included temporary spacers laser-cut from MDF boards to set and verify the distance between the fixtures.

We also developed a Grasshopper script (see Fig. 5) which reads the input digital geometry to output the necessary parameters of:

- Placement of control points/fixtures;
- Size of textile (factoring in pretension);
- Distance between aluminum profiles (x-, y-directions respectively);
- Height of joint from base of aluminum profile;
- Joint design (for laser cutting).

For this case, the textile preform uses the Double Jersey stitch pattern (stitch value of 70) which provides a similar bi-axial stretch percentage in both wale-wise and course-wise directions. We design it such that the textile requires 125% strain in both wale-wise and course-wise directions when tensioned to fit within an area of 250 x 250 mm. This allows for tolerance to adjust the textile when mounting it upon the shaping mechanism, while maintaining enough pretension for a non-wrinkled surface.

Furthermore, we incorporate channels along the perimeter edges of the textile for the carbon fibre strips to be inserted. The channels use the tubular jersey stitch pattern, with glass fibre yarn on the front needle bed and 30/2 x 2ends cotton yarn
on the back needle bed. The purpose of using cotton on one side is to detach the carbon fibre strips easily from the sleeves if resin accidentally solidifies on the edges.

4.1. PHYSICAL-TO-DIGITAL GEOMETRIC EVALUATION

To test the validity of our mechanism, we designed a grid of 2x2 panels with curved orthogonal geometries - Geo-1 being singly curved and Geo-2, -3 and -4 being doubly curved (Fig. 6). Each geometry consists of four boundary edges of lengths ranging between 250 - 280 mm. We record and use the physical curvatures produced by strips when bent individually to ensure accuracy in the later comparison of physical and digital geometries.

![Figure 5. Shaping Mechanism with Output Instructions.](image)

![Figure 6. Designed Geometries for Textile Shaping.](image)
Additionally, we simulated the behaviour of the textile’s geometry using particle springs with the Kangaroo plugin (Piker, 2017). This is under the assumption that the fixed edges are rigid edge supports. Other parameters include a 0.7 load value in the negative Z-axis, a mesh length factor of 0.7 and strength of 1.0.

After undergoing shaping, we apply a thin coating of thermosetting isophthalic polyester resin (R-280) (75ml) activated by 2% MEKP catalyst upon the surface. We leave this to dry for at least 12 hours to solidify the geometry. Additionally, we add a layer of 300 gsm chopped fibre glass strand mat on the surface and laminate it with the same polyester resin (75ml) to provide additional stiffness to the panel. After another 12 hours of curing, we demount the composite panels from the shaping jig and remove the carbon fibre strips to be reused for the next textile. We then verified the accuracy of the edges by aligning the panels next to one another.

![Figure 7. Resin Lamination (left); Demounting of Hardened Composite Panels (middle); Alignment of Composite Panels (right).](image)

We used an Artec Eva scanner to scan the demounted panels. However, we had to spray-paint the panels with a matte-grey colour before the opaque surface could be detected. Once recorded, we performed Global Registration, Fast Fusion and Mesh simplification algorithms on the scanned surface geometry in the Artec Studio Professional software before exporting the mesh.

Comparison between the scanned physical geometry and the digital model reveals an average deviation of 2.9 - 3.8 mm across the four geometries (Fig. 7). We observed that the highest deviations generally concentrated in a cluster which were closest to either a corner or an edge of the panel. These regions were where the panel’s geometry dipped lower than what was simulated in the particle springs.

We speculate that this could be due to the weight of the applied resin which flows and accumulates in ‘valleys’ of the curved textile. This imposes a load upon a specific region of the textile, making the preform stretch more than intended. Another reason could be that the textile lacks adequate tension in these regions and could benefit from a stiffer stitch pattern closer to the sleeves.
5. Conclusions and Future Work

In summary, our paper demonstrates the following:

- Machine-knitted textiles of glass fibre yarns can create preforms that are inherently thick (up to 5.0mm, 313% increment from a basic Single Jersey knit) with good elasticity (approximately 135% bi-axial stretch);
- Our bending-active shaping mechanism, comprising of laser-cut MDF joints mounted on aluminum profiles, can create 250 x 250 mm sized singly- and doubly-curved geometries with edge curvatures up to 9.5E-4. Comparison with the input model shows an average deviation of 3.2 mm across our four prototypes.

Thus, our method demonstrates the capability to manufacture singly- and doubly-curved panels with large surface curvatures while maintaining good geometric accuracy. We also can perform this economically with negligible expendable material and can be managed by a single person. On a larger context, this reduces fabrication constraints as there is less of a need to segment freeform building geometries into flat or singly curved panels for fabrication.

For our next step, we aim to broaden this approach to create non-orthogonal curved geometries. This will entail the reverse engineering of an input geometry to design a graded textile by mapping different stitch patterns onto specific patches of the textile. Such is intended to improve the geometric accuracy of the resultant prototype and accommodate larger curvatures of the edges. Other plans also include integration of actuators into the shaping mechanism and up-scaling of the system to shape larger geometries.

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