3D KNITTED FABRIC FORMWORK FOR CONCRETE CASTING

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Abstract. The paper presents a novel process of fabricating concrete columns using 3-dimensional (3D) knitted fabric in conjunction with an industrial robotic arm acting as scaffolding. The research explores the feasibility of using wool as a biomaterial for fabricating formwork, thereby reducing construction waste and weight compared to traditional steel, fibreglass, or timber techniques. By examining the knit architecture in conjunction with experiments in slump admixture and tensile testing of the fabric formwork, the research developed several full-scale prototypes. The outcomes were scanned and analysed to understand the geometric deviation as a result of repeat usage of the fabric as formwork. The research demonstrates the resilience of the knitted wool fabric as formwork for concrete casting.

Keywords. Fabric Formwork, 3D-Knit, Robotics, Concrete Casting.

1. Introduction

The construction industry contributed 11% of embodied carbon emissions from manufacturing building materials such as glass, steel and cement, with an estimated third of the world's waste from demolition and construction processes going into landfills. While significant research is invested in waste management, including recycling and up-cycling, the key issues lie in how a building is constructed, designed, and assembled. Design waste and waste minimisation at the source are two main aspects of waste management within the architects' remit and responsibility (Osmani 2011).

The research examines 3D-knitted fabric as formwork for casting concrete columns with variable shapes. Typically, such formwork utilises fibreglass, timber or steel, discarded as construction waste after a single use. The project uses natural biodegradable Australian wool as the primary material, which is less than 1% of the weight of traditional formwork. The research demonstrates that 3D-knitted fabric formwork is durable due to the lack of seams in the knit architecture, allowing the fabric to be reused several times to create repeatable casts. The computer numerically controlled (CNC) knit pattern is crucial in shaping the form of the column. The fabric

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is stretched into its desired form using an industrial robotic arm. The outcomes were digitised, and the data was used to understand the deviation caused by repeat usage of the fabric formwork. The research has potential industrial applications for in-situ or pre-cast concrete column structures.

2. Background

Most soft and transformable formwork utilised fabric as the key material (Bruce A, 1989, Schmitz 2014), with significant developments in fabric formwork already carried out during the late 19th and 20th centuries (Veenendaal et al., 2011). Since then, the fabrication method and exploration of fabric as flexible formwork has been widely investigated by architects such as Miguel Fisac, Mark West and Kenzo Unno (Schmitz, 2014) and other researchers (Kallegias & Erdine, 2015; Pedreschi & Chandler, 2007; Thomas, 2015; West, 2016). However, the use of robotics in fabric formwork is limited.

Four case studies are relevant to this research. Two of which utilised robotic arms to manipulate the formwork using tailored fabric based on developable surfaces or templates. The others utilised 3D-knitted textiles to create non-developable and three-dimensional shapes that minimised seams and the need to join the textile panel.

Culver & Sarafian's 'Fabric Forms' (2016) and HYPAR by Yang et al. (2017) both use synthetic polyurethane elastane fabric (more commonly known as lycra), which has up to 200% elastic elongation. In 'Fabric Forms', the fabric is deployed with two robotic arms to manipulate the form into a resulting cast. In these cases, the material's elasticity is necessary compared to traditional fabric casting techniques using woven textiles with limitations in their stretch (West, 2016, p52-54). It enables the creation of complex forms by manipulating the material before casting the concrete.

More recently, Pal et al.' s 'Knit Concrete Formwork' (2020) utilised 3D knit fabric to produce a kit-of-parts to form a shell-like geodesic frame connected using a 3D-printed joint. The KnitCandela developed by BLOCK Research Group at ETH Zurich utilised 3D-knit fabric as flexible formwork with an embedded cable-net structure tensioned into shape using a combination of steel and timber external frames as rigs (Popescu et al., 2020).

2.1. RESEARCH OBJECTIVE

This research extends the exploration of the existing field of knowledge in fabric formwork outlined above through the following objectives:

- Explore using the robotic arm as a dynamic and variable rig to remove the need for a single-use framing structure. The research focused on creating vertical columns of varying length, width and shape. The experiment also extends to create Y-shape columns, which is outside the scope of this paper.
- Explore the correlation between the 3D-knitted shape and its geometric outcome after casting. The experiment focuses on the interaction between the fabric shape and the hydrostatic pressure of the cast.
- Investigate the feasibility of repeatable use of the same fabric formwork for casting

to understand the geometric deviation between each subsequent cast.

2.2. PROJECT BACKGROUND, HYPOTHESIS AND APPROACH

The research is conducted in collaboration with RMIT university, LLDS Architects and Architectural Research Laboratory. All the fabric was knitted at the School of Fashion and Textile, RMIT University's Textile Laboratory, with a Shima Seiki WholeGarment® flat-bed knitting machine using 100% Australian wool yarn. The experiments are conducted over three phases:

- Phase 1: Experiments with the concrete mix and structural testing of knitted fabric.
- Phase 2: Casting using a robotic arm
- Phase 3: Scanning of the cast for comparative study

At an early stage of the experiment, the research team considered wool and polyester yarns for the formwork and decided to work with wool. Wool is a keratin protein-based fibre composed of long chain molecular chains in a helical shape with a cortex consisting of 2 types (ortho and para-cortex). This makes wool a bicomponent fibre with a three-dimensional crimp or waviness (Thomas, 2022), resulting in a natural elasticity, ideal for industrial knitting. Another advantage of wool fibre is its ability to stretch and recover to its original dimensions with high moisture regain (the amount of water a fibre can absorb). These physical properties of wool make it highly suitable for concrete casting. The initial test demonstrated that the wool yarn could absorb the liquid release agent (required to create a barrier between the formwork and the concrete substrate). In addition, to align with the research goal, there is also the potential to use recycled wool that reprocesses wool garments that may otherwise go to landfill.

Learning from previous experiments in fabric casting, the research team also limits the material's elasticity. Instead, elasticity is built into the design of the knit by balancing the fibre, yarn, and incorporated fabric parameters, such as stitch length, density, tightness, fabric surface cover factor and its 3D shape, which were previously not possible using woven fabric.

Unlike previous experiments outlined in section 2, the research does not rely on the elasticity of the fabric to produce a non-developable surface. Instead, the aim is to exploit the form-building capabilities of the knitted textiles, using advanced knitting technology of Shima Seiki WholeGarment® machinery to create integrally knitted 3D seamless forms. This technology allows for a fully automated manufacturing process, making it possible through a combination of knitting techniques such as tubular knitting, transferring and holding stitches into a vast range of complex double curvature forms. This manufacturing method eliminates the need for cutting, seaming or overlaying post-knitting. Compared to woven textiles, the technique provides significant cost savings in time, labour and material efficiency with little to no material waste generated. At the same time, the ability to stretch is critical in the casting process using the robotic arm as a dynamic scaffolding rig. Therefore, the spacing of the knit will need to be balanced as looser knit spacing will cause the concrete to spill out of its mould; this is further expanded in section 3.1.

3. Re-usable fabric formwork

A vital aspect of the experiment lies in removing the knitted fabric after each cast and reusing the fabric for a new cast, thereby demonstrating the potential of 3D-knit fabric formwork as a sustainable and waste-reducing process alternative to existing casting methods. With these parameters in mind, we have chosen to start with the simple rectangular shapes and tapering of the two edges as the experiment variables. Two sets of fabric formwork were produced. The first set is 600mm nominal in length. The second fabric set is 1200mm nominal in length; see Figure 1.

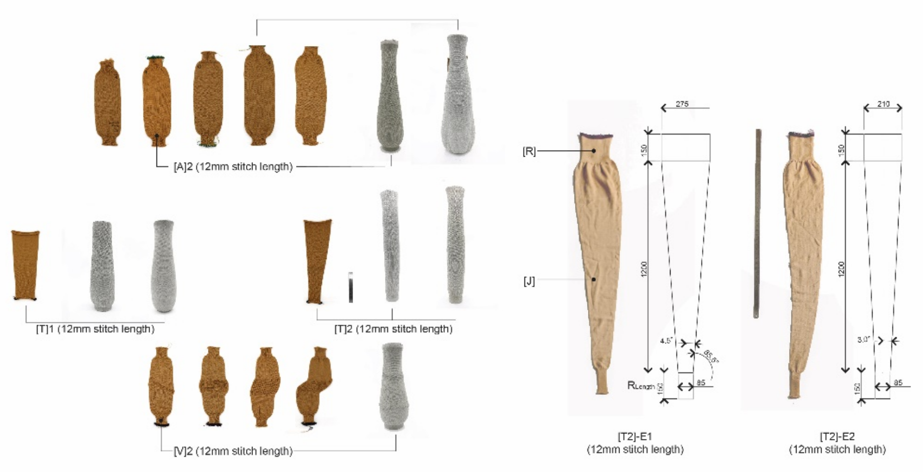

Figure 1. Left, first fabric set with the resulting casts. Right, the second fabric set shows the tapered material at 1200mm length only.

3.1. FABRIC DESIGN AND KNIT ARCHITECTURE

The initial knitted formwork design was a tubular 3D form, with a nominal length of 600mm and diameter of 100mm (Fig. 1, A2), knitted in a single jersey fabric (J) with a 100mm 3x3 rib (R) at the start and end edges of the tube. The rib provides a more significant stretch, while the single jersey offers more stability in the 3D form. The design was programmed using the packaged software of the Shima Seiki's Knit paint program in the SDS-ONE APEX3, an integrated knit production system. The knitting program consists of a structure pattern based on Shima Seiki's stitch code colour number system. Figure 2A illustrates the stitch type as represented by a colour pixel and option lines that provide technical information for controlling and adjusting input variables of the program when knitting (Underwood, 2009). Variables include the stitch length, takedown, knitting speed and economisers (the ability to repeat a sequence) at specific program sections as it is being knitted. The development pattern was processed, and a knit simulation was run to check for conflicts using the digital control simulation within the SDS-ONE APEX3 system (Fig. 2B).

The program was then knitted on the Shima Seiki N.SES183-S.WG 14 gauge flat-bed knitting machine at haft gauge using three yarns of 100% wool, each with a count of 2/48Nm (Numeral metric).

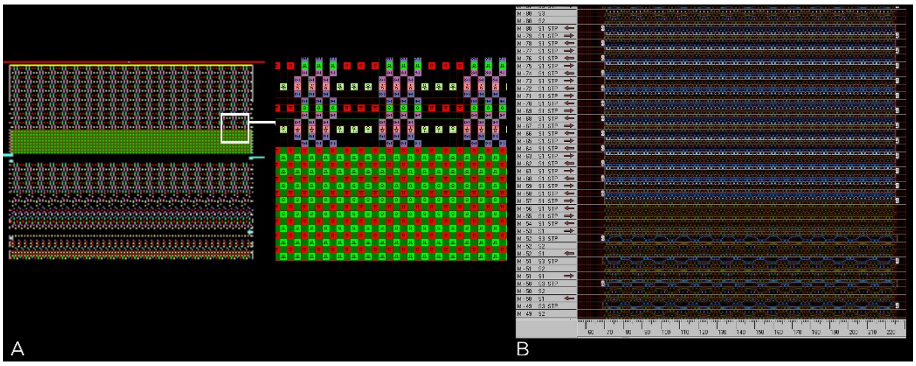

Figure 2: A, the digital knit program of tube form and B, digital knit simulation SDS-ONE APEX3 system.

The first set of knit (Fig. 1, A & T) utilised one program to test a range of stitch lengths ranging from 11.25mm to 13.00mm for the single jersey using the Digital Stitch Control System (DSCS) on the knitting machine (Fig. 2). Shima Seiki's DSCS controls the length of the loop being formed through continual adjustments to the yarn feed and tension for a consistent and accurate measurement of the loop length. These initial samples provided a comparison of the fabric surface cover factor. The fabric surface cover factor is the percentage area of the fabric covered by the yarns compared to the spaces between the yarns (how open or tight the knit fabric is). This accounts for the variations in the overall dimensions of the tubular forms; through evaluating the ease of knitting and how this set of knitted tubes performed during the concrete casting process, we determined the optimal stitch length as 12mm for the single jersey and 10.50mm for the rib component of the formwork (Fig. 1, A2). The wool yarn and a stitch length of 12mm were used for the 2nd set of knitted samples (Fig. 1, T2).

In the first set of knit, the research also explored a range of tube diameters and the addition of lattice-like lace stitch structures (balanced and unbalanced) positioned within the tube, see Figure 1, [T] and [V]. Lace patterns are formed by transferring the selected stitch to the adjacent needle to the left or right. When the transferring of stitches was in one direction only, it resulted in the most significant deformation of the tubular shape see Figure 1 [V].

The 2nd set of fabric formwork tested a range of knitted 3D shapes scaled up to a nominal length of 1200mm, including tapered tubes (Fig. 1, T2-E1 and T2-E2) and Y-shape forms (Y-shape form is excluded from the scope of this paper). Lessons learned from the first set of casts informed this set of knit. For example, the rib length [R] is increased to 150mm, and four 5mm nominal diameter holes are added (created by transferring stitches) about a quarter from the inner ribbed edge. The additional holes are useful to secure the knitted formwork to the end-effector for the casting process.

3.2. PHASE 1: PRELIMINARY TESTS AND EXPERIMENTS

The research conducted two sets of preliminary tests. The first is in the concrete mix. The aim is to reduce the mix slump to minimise the hydrostatic pressure on the fabric mould. The second experiment examines the tensile strength of the fabric formwork. The aim is to understand the elasticity and strength based on the knit architecture.

3.2.1. Concrete Slump Admixture

For this research, we use an adjusted standard glass-fibre reinforced concrete (GRC) mixture with an added slump admixture (Fritz-Pak Super Slump Buster) to control the plasticity of the concrete during the casting process. We use a 100mm dia x 135mm tall PVC cylinder pipe as mould. Five concrete mixture with a varied proportion of slump admixture is mixed for 15 seconds. The mix is poured into the mould and allowed to stand for 5 minutes as working time before being de-moulded; 5 minutes is deemed adequate time to transfer the mixture into the mould base on previous experience. Figure 3 illustrates the results of the test. The graph demonstrates plateauing of the slump once the admixture passes 0.15% (by weight) of the GRC. This proportion is used for the rest of the experiments.

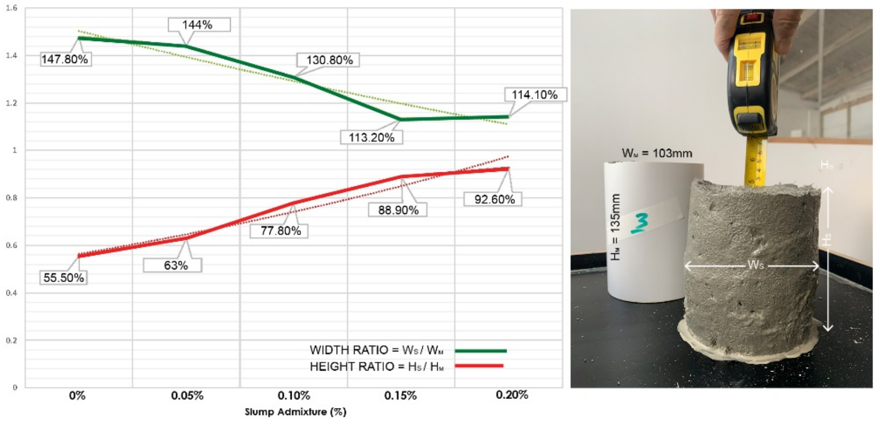

Figure 3. Left, a graph illustrating slump test results with an incremental increase in slump admixture expressed in width and height ratios. Right, an image of the slum test sample. 0% admixture is the control sample.

3.2.2. Tensile Strength of Knitted Fabric

Two 3D-knit fabric samples are tested for destruction (fig. 4). Sample 1 (A and B) is 100mm in width, and Sample 2 is 65mm in width. All the samples have standard 12mm stitch length and were tested using an Instron 5589A Universal Testing system with 500N capacity. Table 1 outlines the result, indicating the elongation at Break for the fabric to be between 189.9 - 200.7% with a typical tensile strength of 8.08-10.3 MPa.

Sample	Force (first point of failure) (kN)	Initial length (mm)	Displacement (mm)	Tensile Strength (MPA)	Elongation at Break (%)	Strain	Young's modulus (MPa)
1A	2.04	137	137.96	10.20	200.7	1.007	10.1
1B	2.06	127	117.59	10.30	192.6	0.093	11.1
2	1.05	136	122.26	8.08	189.9	0.898	9.0

Table 1. Summary of tensile strength tests.

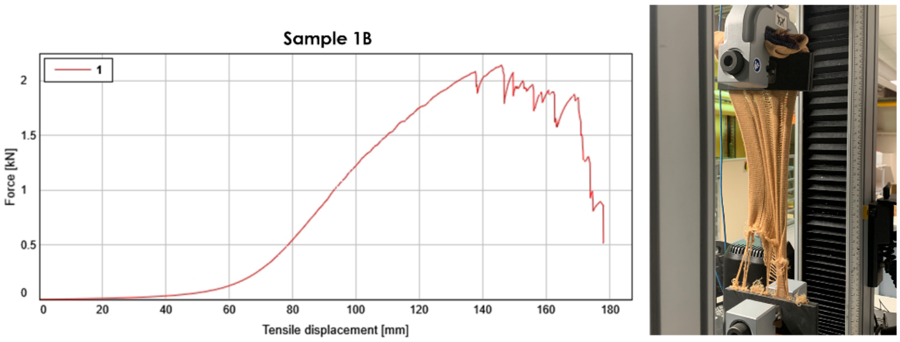

Figure 4. Right, Displacement and Force graph of sample 1B. Left, tensile strength test to destruction.

3.3. PHASE 2: CASTING USING A ROBOTIC ARM

Two sets of casts were produced, both with 12mm stitch length. T2-E1 measured 1200mm in length from ribbed end to end with a taper angle of 4.5 degrees, an upper diameter of 175mm, and a base diameter of 54mm. T2-E2 measured 1200mm in length from ribbed end to end with a taper angle of 3 degrees, an upper diameter of 133mm, and a base diameter of 54mm, see figure 1.

A bespoke aluminium clamping device was designed as an end effector for a Kuka KR120 robotic arm. The clamping device holds the fabric formwork by the ribbed ends and is programmed using Kuka PRC. The fabric formwork is also clamped on the base fixed to the concrete floor, see figure 5. The fabric is soaked in a liquid release agent immediately before the concrete is mixed and poured into the formwork. The detail of the end-effector design is outside the scope of this paper. The robotic arm is raised vertically in 50mm increments from a starting position of 1355mm (from the base of the clamp). It is stretched to a maximum height of 1705mm, with a 125.85% elongation across all casts. The hydrostatic pressure of the concrete provides considerable resistance to the stretching process, and through several trials and errors, the maximum height is determined as adequate. The timing between the concrete mix and the pour is typically limited to 5 minutes as the slump admixture reduces the working life of the concrete. When the cast reaches 1m in height, a 10mm diameter steel rod is inserted into the formwork to act as reinforcement. An additional steel rod is inserted when the cast reaches its height limit.

Two casts were produced from T2-E1, so the mould was reused once. Three casts were made from T2-E2, so the mould was reused twice. After each cast, the fabric formwork is demoulded from the column, washed by hand in cold water (16-17 Celsius), and laid flat to dry.

3.4. PHASE 3: SCANNING OF THE CASTS FOR COMPARATIVE STUDY

Fourteen days after de-moulding, the cast was scanned. A turntable with registration marks was designed to take the column. Using a SICK Trispector P1000 laser scanner, each column was scanned in three equal segments (fig. 5). The SICK scanner used laser triangulation to produce an image of the laser line, which contains the height profile of the cast, through SICK SOPAS® software. The image was translated using Rhino 3D Grasshopper into point clouds.

Figure 5. Right, fabric formwork clamp to the base of the fixture and hold up by the robotic arm. Centre, after the concrete pour. Left, scanning with a SICK laser scanner.

The point cloud of each set is compared (fig. 6). The gradient map shows the deviation where red is +/-10mm or greater, yellow is +/-6mm, and green is within +/-1mm. The outcome illustrates that the first repeat use of the mould typically preserves the geometry to within +/-1 to 6mm. The third cast using T2-E2 formwork shows a more significant deviation to the top where the hydrostatic pressure is at the greatest.

Variation of up to 15mm is observed on both ends of the cast. This is primarily due to the clamping fixture, which sometimes results in fabric pull-out with repeated mould usage. The ends of the fabric formwork are typically the most worn out after repeat casts, with some stitch breaking after two repeat washing and de-moulding.

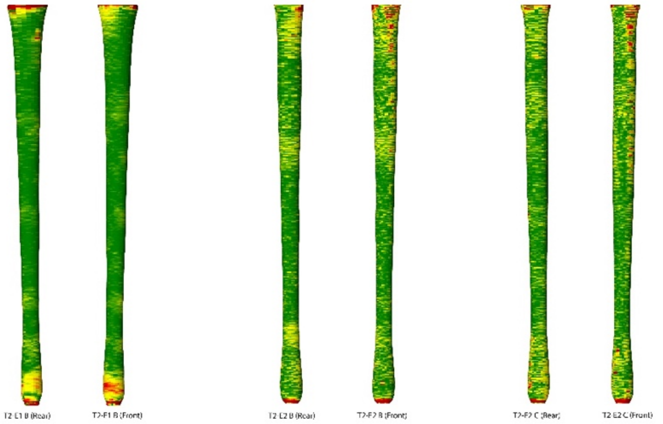

Figure 6. Right, deviation analysis of T2-E1 B, where B refer to the second cast using the same fabric formwork. Centre and Left, deviation analysis of T2-E2 B and T2-E2 C, where B refer to the second cast using the same fabric formwork and C the third cast from the same formwork.

3.5. FUTURE TRAJECTORIES AND IMPROVEMENTS

At the point of writing, the scan data are translated into a simulation model. The aim is to enable designers and architects to simulate resulting concrete column shapes using a defined set of parameters such as tapering angle, formwork length and the number of truncations along the formwork length as design tools to determine the formwork shape. Future research will focus on correlating the Shima Seiki's stitch code colour number system with the pre-stretch fabric formwork and cast geometry. The deviation observed in this research will be used to inform future knit design.

The study would benefit from further repeat casts. While the outcomes are reasonably tall in scale, for practical application, the diameter of the column will need to get wider, which will become more challenging for the fabric formwork. Part of our next investigation step is to increase the diameter of the fabric formwork and use the knit architecture to reinforce the formwork to counteract the increased hydrostatic pressure.

4. Conclusion

The paper presents a novel concrete casting technique through a waste reduction construction technique that contributes to a more sustainable future and societal development. Here, we examined the potential to produce variable-shaped columns using fabric formwork using a robotic arm as scaffolding. The research demonstrated the feasibility of using biomaterial such as knitted wool as repeatable formwork for up to three uses. The form-building capabilities of the knitted textiles through the seamless jersey using tubular knitting, transferring, and holding stitches provide means to control the shape of the cast. Experiments in slump admixture to the concrete and tensile testing of the fabric contribute new knowledge and inform the physical prototyping process. Two large-scale fabric formwork were tested with repeat usage to create multiple casts, and the resulting geometries were analysed to understand the surface deviation. The outcome demonstrated the resilience of the knitted fabric as formwork for concrete casting.

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