INFLUENCE OF TEXTILE DESIGN PLAN ON THE PERFORMANCE OF 3D WOVEN CARBON/EPOXY COMPOSITES

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Abstract: *3D fibre reinforced composites have the potential to reduce delamination, improve through-thickness strength and damage tolerance, the full potential of these materials in the aerospace and automotive industry is yet to be explored. This can be partly attributed to the fact that the manufacturing process of 3D woven composites can be challenging due to the requirement of unfamiliar processes and a limited understanding of the influence of textile weaving parameters on the performance of final 3D woven composites. The structure of the 3D woven composites is predominantly controlled by the textile design plan during the 3D weaving process. A lack of in-depth understanding between the textile design plan and the physical/mechanical performance of 3D woven composites has inspired this investigation. This paper presents a detailed investigation of the influence of two textile design plans for the same architecture on the physical and mechanical properties such as tension, compression, and flexure in 3D layer-to-layer carbon/epoxy woven composites. The two textile design plans (design 1 and design 2) for 3D layer-to-layer architectures were achieved by changing the grouping of warp and binder yarns without modifying the loom set-up, which significantly reduced the manufacturing time and cost. The two designs in 3D woven layer-to-layer architecture were woven with a constant warp density of 12 warps/cm using T700-50C-12k carbon fibres. On the transition from design 1 to design 2 of 3D woven composite, the resin rich areas, tow misalignment and yarn crimp were significantly reduced. The tensile properties were improved by 55% and 37% along warp and weft directions, respectively. The compression properties were improved in the longitudinal direction with a slight deterioration in the transverse direction. This work has helped prove how slight fundamental changes in textile preforms can significantly change the performance of 3D woven composites without increasing the manufacturing cost and time.*

Keywords: 3D woven composite; textile design plan; mechanical properties; microstructural properties

1. Introduction

Traditionally metals have been used for wide applications in automotive and aerospace industries due to their superior toughness, ductility and uniform weight distribution properties (1). However, due to the design flexibility, high strength, reduced weight, low density and optimised levels of stiffness/strength as per the loading conditions (2), metals have been increasingly replaced by laminated composites. The problem with the UD or 2D laminated composites is their propensity to delaminate under the influence of out-of-plane loading. With the addition of through-thickness binders in 3D woven composites, delamination failure is initiated, allowing the composite to carry increasing loads well beyond first crack initiation (3). Moreover, 3D weaving is gaining popularity in the industry over 2D weaving due to its capability to manufacture near-net-shape preforms reducing the manufacturing/machining cost (4). However, the ability to produce complex integrated structures and excellent through-thickness strength and toughness of 3D woven composites is tempered by lower in-plane performance compared to 2D woven or unidirectional composites (5). This may be further exacerbated by process induced defects or variability. In order to obtain optimum high-performance composite structures, it is essential to have a comprehensive knowledge of the effect of 3D fibre content, architecture and manufacturing defects on the properties of composites. Although 3D woven composites show promising potential for various applications, their practical utilisation in structural components on a mass scale is limited by high initial equipment cost and the lack of a thorough understanding of the effect of weaving parameters in the textiles on the mechanical and impact performance.

A substantial amount of work has been performed to characterise three fundamentally different architectures of 3D woven composites (layer-to-layer, angle interlock, and orthogonal) for their failure mechanisms and mechanical performance (6)(7)(4). In addition, there are limited studies on geometrical flaws like misalignment, voids, resin rich areas, and some topological features caused by changing the weave architecture and its influence on the mechanical properties and their subsequent failure mechanism (8)(9). However, the effect of weaving parameters in one constant architecture on the mechanical and impact performance along with their failure mechanisms has not yet been explored substantially in the literature.

This paper investigates the influence of textile design, an easily adjustable weave parameter, on the physical and mechanical performance of 3D woven layer-to-layer composites. In this study, the architecture was kept constant, and only the textile design was changed, which dictated the arrangement of warp and binder yarns in the unit cell. The textile design changes in 3D woven preforms can be achieved by a slight change in the manufacturing process (by changing the lift plan) instead of rethreading the entire loom, which takes up to over 100 hours. Also, rethreading the entire loom can cause severe damage to the warp yarns which knockdowns the mechanical properties of the subsequent composite materials (10). Textile design controls the grouping of warp/binder yarns in a unit cell, which dictates the spacing between yarns, indirectly influencing the composite material's tow misalignment, resin-rich areas and void content. Hence in this study, keeping the warp density constant of 12 warps/cm, two textile designs with two grouping plans were developed and compared against each other for their mechanical and physical properties. In-depth failure mechanism analysis in both the designs of layer-to-layer 3D woven composites under different loading was carried out using optical microscopy.

2. Material

2.1 Manufacturing of 3D woven preforms

Two different textile designs (design 1 and design 2) with a constant warp density of 12 ends/cm in a layer-to-layer architecture were designed using ScotWeave software (Figure 1). Design 1 and design 2 textile design plans were created by splitting the unit cell structure (12 warps/cm) into two and four groups respectively. In design 1, binder and stuffer/warp yarns were placed alternatively, whereas, in design 2, three binders were followed by three stuffer/warp yarns. To manufacture these two designs on the DATAWEAVE controlled jacquard loom, the creel was set up for 600 bobbins to weave 12 ends/cm for a 50 cm wide textile preform. The architecture consisted of three warp layers, four weft layers and three warp binder layers which connect weft layers immediately above and below each binder. In Figure 1, binder yarns are shown in red, stuffer/warp yarns in blue and weft yarns are light green. T700S-50C-12k (800 Tex) (11) carbon fibre was used to manufacture all specimens in all three directions.

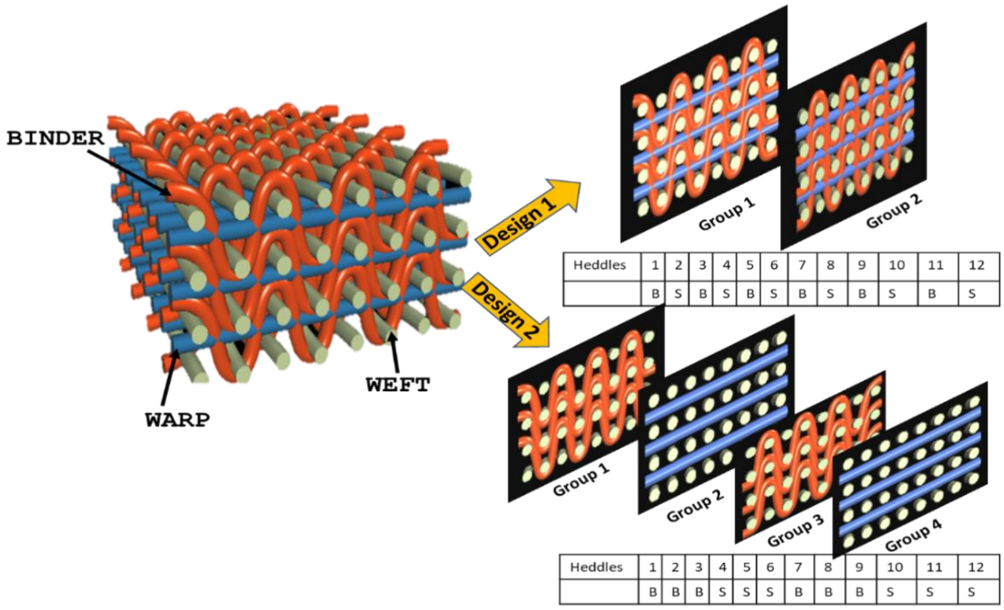


Figure 1: Grouping of two textile designs of layer-to-layer 3D woven preforms

According to the grouping of a unit cell, two textile design plans for design 1 and design 2 were developed on the ScotWeave CAD software to operate the Jacquard loom (1152 hooks) at Ulster University (Figure 2). Both the textile design plans were divided into 12 warp yarns (X-axis) and 8 weft yarns (Y-axis). By manipulating the lift of the heddles in a jacquard loom, grouping determined the placements of these yarns in the architecture. It can be understood from the textile design plan for design 1 (Figure 2a) that for the first weft insertion, heddle one was lifted, for the second weft insertion, the first, second, third and seventh heddles were lifted. This was continued until the 8th weft insertion, which completed a one-unit cell.

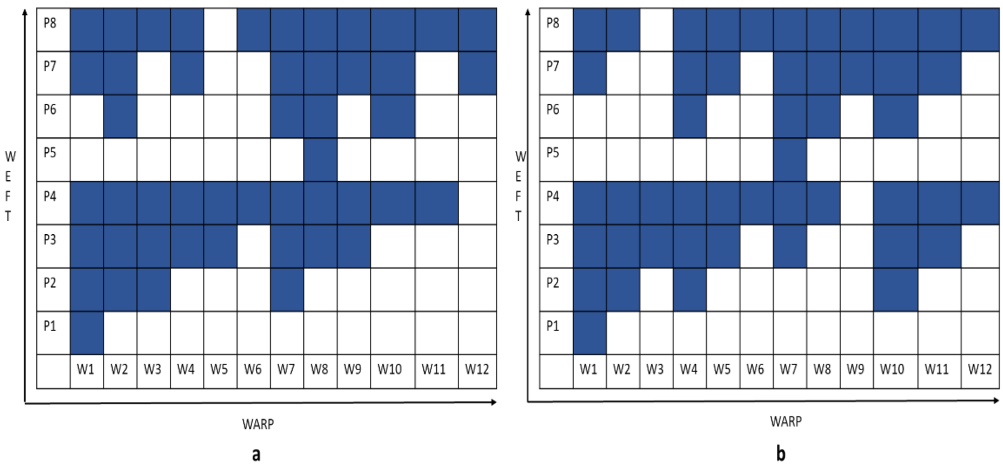


Figure 2: Textile lift plan (a) design 1 (b) design 2 of 3D woven layer-to-layer architectures

2.2 Manufacturing of 3D woven composites

The textile preforms woven in two textile designs (design 1 and design 2) were consolidated via Resin Transfer Moulding (RTM) using a Gurit Prime 37 epoxy resin system (12). Resin and hardener were mixed in 100:29 by weight ratio and stirred for two minutes in order to ensure uniform mixing. Before infusion, the mixture was degassed in a homogeniser for 30 minutes and then injected into a room temperature RTM tool designed to consolidate 400x400 mm preforms. The injection pressure was maintained at 1.5 bar throughout the infusion. After injection, the part was cured at 50°C for 16 hours.

3. Experimental

The physical properties of the textile preforms, such as the weft density (number of transverse yarns per cm of the fabric), warp density (number of longitudinal yarns per cm of the fabric) and thickness were measured according to ASTM standards, respectively. In addition, crimp measurements were made in accordance with BS 2863:1984. Percentage crimp is the ratio of the difference between the yarn length and fabric length over fabric length. It is calculated using the following equation:

$$\%\ \text{Crimp}=\frac{L_{yarn}-L_{fabric}}{L_{fabric}} \tag{1}$$

Five specimens each in warp and weft directions were tested under tension in accordance with ASTM 3039 using a Zwick Universal Testing System (UTS) with a 100kN load cell. A crosshead displacement of 2mm/min was used to perform these tests. An extensometer was used to record strains up to 0.6%, after which it was detached to prevent it from damaging due to shock waves. Five specimens in each direction (warp and weft) were tested for compression in accordance with a Boeing modified ASTM D695 using an electromechanical Instron 5500R UTS machine with a 100kN load cell and anti-buckling fixture. The original test was modified by changing the specimen shape and reducing the gauge length to 4.8mm in order to avoid buckling of the test specimens. Three-point bending tests were performed on five specimens in each direction in order to obtain the flexural strength and the modulus. This test was performed in accordance with ASTM D7264 standard on an electromechanical Instron 5500R UTS machine with a 100kN load cell. Five specimens with a span to thickness ratio of 32 were tested oriented in both the warp and weft directions at a crosshead displacement of 1mm/min. An Olympus sZ3 stereo microscope was used to study the surface of the area of interest of fracture specimens, which were polished using a Struers TegraPol-31 machine.

4. Results and Discussion

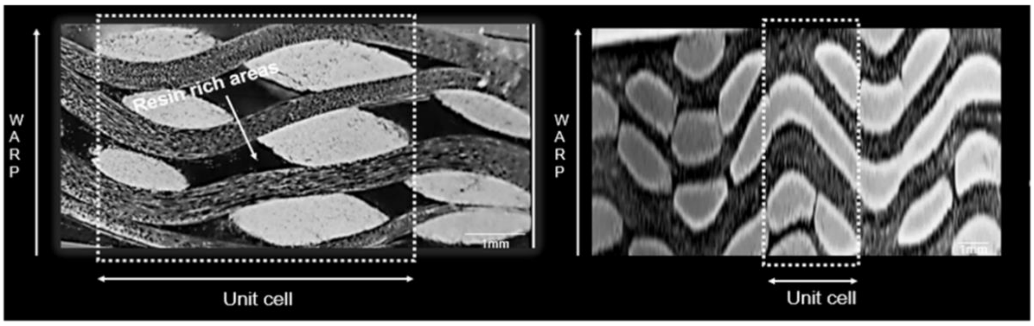
4.1 Physical properties

Physical properties of 3D woven preforms and composites for design 1 and design 2 iterations are listed in Table 1. On the transition from design 1 to design 2, the structure becomes more compact with small inter yarn spacing. As shown in Table 1, the crimp is reduced by 33% and 28% in the warp and weft yarns, respectively, on the transition from design 1 to design 2. Due to the less compact structure in design 1, the yarns are not stacked uniformly compared to design 2 (Figure 3). This resulted in a smaller unit cell size and fewer resin rich areas in design 2 compared to design 1. Although the warp density was maintained constant at 12 warps/cm due to the arrangement of yarns, there is significant yarn distortion evident in design 1 compared to design 2 (Figure 3). Yarn distortion or misalignment quantified in terms of peak crimp angle decreases by 61% in design 2 compared to design 1 (Table 1).

Table 1: Preform and composite properties of Design 1 and Design 2 3D woven composite

Fabric	Weft /cm	Warp/cm	t* (mm)	Yarn content (%)			% Tow crimp in uncompressed preform		Peak crimp angle (°)	$V_{f\,(\%)}$
				Warp	Weft	Binder	Warp	Weft		
Design 1	8	12	2.6	30	40	30	5.5	1.8	27.9	36.7
Design 2	10	12	3	27.2	45.5	27.2	3.7	1.3	10.8	42.8

t: thickness of uncompressed 3D woven preforms*



a b

Figure 3: Micrographs (a) Design 1 (b) Design 2 3D woven layer-to-layer composite

4.1 Tensile properties

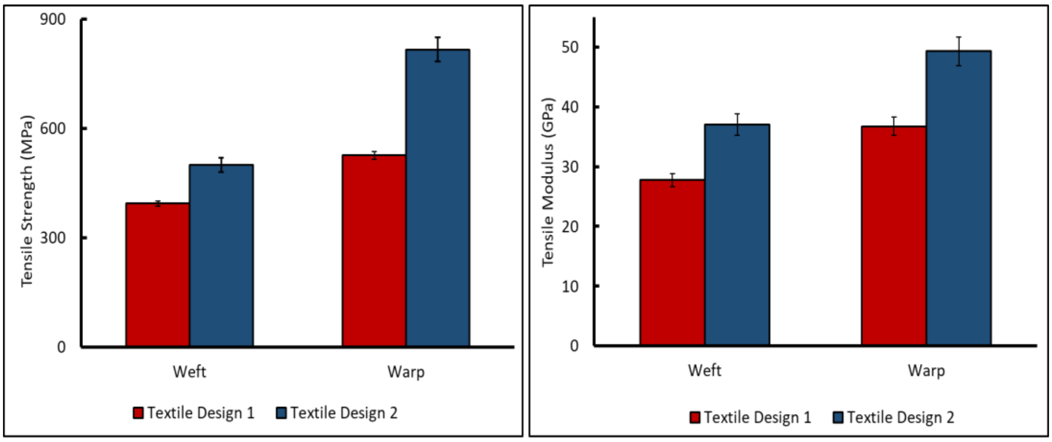


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Figure 4: (a)Tensile Strength (b) Tensile Modulus of two designs of 3D woven layer-to-layer composites

Figure 4 represents the comparative bar graphs of tensile strength and modulus of design 1 and design 2 3D woven composites specimens in both warp and weft directions. In the warp direction, there is a 55% increase in the tensile strength and a 36% increase in the tensile modulus, which can be partially attributed to a decrease in crimp of 33% (Table 1) from design 1 to design 2 specimens. Binder tow straightening and matrix cracking around the binding positions were observed visually on the surface of all the specimens. In design 2 specimens, 54% more transverse surface cracks along the entire specimen were observed than in design 1 specimens. This is thought to result from a greater number of stress concentration bands which corresponds to more frequent binding points at the specimen surface. These stress concentrations result from resin rich regions, which are associated with binding points as well as the tendency of the binders to straighten out during loading. This is accompanied by fibre-matrix debonding, which is likely to initiate at those points. Warp direction failure transitions from being predominantly fibre-matrix debonding dominated in design 1 compared to being dominated by fibre pull out and fibre fracture in design 2 specimens. Also, design 1 specimens have significantly more resin rich regions (Figure 3), whereas negligible resin rich areas are observed in design 2 specimens due to their more compact structure. The presence of numerous resin rich areas in design 1 specimens promotes clean fracture rather than fibre pull-out or fibre fracture.

In weft direction specimens, there is a 27% and 37% increase in the tensile strength and modulus, respectively. This is to be expected as the fibre content of the load carrying yarns was increased to maintain the dimensional stability, leading to a more compact architecture in the design 2 specimens, which results in less crimped weft tows (28% less) and a higher fibre volume fraction (17% more) (Table 1). Design 1 specimens displayed more numerous and larger resin rich regions, larger than in design 2 specimens. These fibre devoid areas promoted clean matrix fracture in the design 1 specimens with only little resistance from weft yarns and no visible interlaminar cracking.

4.3 Compression properties

On the transition from design 1 to design 2, the compressive strength increased by 20% and 9% in warp and weft directions, respectively (Figure 5). Due to the grouping pattern which dictated the arrangement of yarns, the unit cell size in design 2 decreased significantly compared to design 1 (Figure 3). This implies that it takes more than double the length of textile architecture to repeat itself in design 1 compared to design 2. This further implies that the binder interlacement points in design 1 specimens are spread apart in a longer unit cell with a higher yarn spacing. Whereas the binder interlacement points are more concentrated in design 2 specimens, which results in a higher energy failure mechanism under compression loading like through-thickness shear compared to delamination matrix cracks in design 1 specimens in the warp direction. Although the fibre content in the warp direction for design 1 and design 2 specimens remains constant at 12 warps/cm, there is still a significant increase in the compressive properties. The role of fibre strength is insignificant in deciding the compressive properties where the tow misalignment in the yarns is significant (13). Instead, under compression loading, the failure of composite is dictated by the tow misalignment angle and matrix shear strength (14). Peak crimp angles (Table 1), a quantifier for the tow misalignment, decrease from 27.9° to 10.8° on the transition from design 1 to design 2 specimens. The increased tow misalignment is an outcome of the fact that in design 1 architecture due to, improper yarn stacking resulted in increased tow misalignment in the in-plane and out-of-plane yarns. The improvements in the compressive properties in the warp direction on the transition from design 1 to design 2 are an outcome of several properties: 1. increase in the binder interlacement points, 2. decrease in unit cell size results in more resistance for crack arrest mechanism and 3. decrease in the geometrical flaws or irregularities.

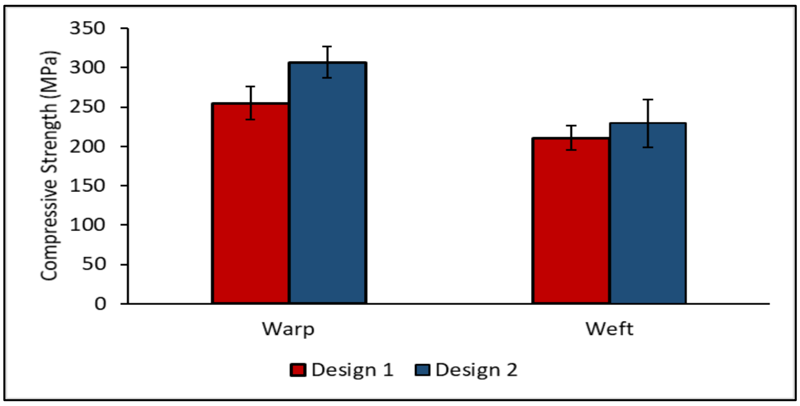

Figure 5: Compressive Strength of two designs of 3D woven layer-to-layer composites

4.4 Flexure properties

Table 2: Flexural properties of two designs of 3D woven layer-to-layer composites

			Warp		Weft	
			Value	% COV	Value	%COV
Flexure	Design 1	Strength (MPa)	310.7	6.4	360.5	2.4
		Modulus (GPa)	12.7	1.8	14.6	0.8
	Design 2	Strength (MPa)	434.4	4.6	470.8	3.1
		Modulus (GPa)	20.9	2.3	26.7	5.1

Table 2 lists the flexural properties of two designs of 3D woven composites in both warp and weft directions. Although the warp density remained constant at 12 warps/cm in design 1 and design 2 specimens, the flexural strength and modulus in the warp direction increased by 40% and 64% in design 2 specimens. This is an outcome of higher interlacement points per unit cell in design 2 specimens compared to design 1 specimen, which has a more spread out unit cell due to non uniform stacking of yarns. The increased binder interlacement points in design 2 tend to resist the cracks compared to design 1 specimens. This is supported by the micrographs of the failed flexure specimens of design 1 and design 2 specimens (Figure 6). It is evident from Figure 6 the cracks are not very well resisted (due to more resin rich areas), and extensive through-thickness cracks are evident in design 1 specimens. Cracks initiate at the resin rich areas at the surface and propagate through the thickness with matrix cracking, debonding, and fibre breakage observed. In design 1 specimens, significant through-thickness cracks were evident, indicating lower flexural properties than in design 1 specimens. Also, tow misalignment (Table 1), quantified in terms of peak crimp angle, is known to have a detrimental effect on the flexural properties (15) in design 1 compared to design 2.

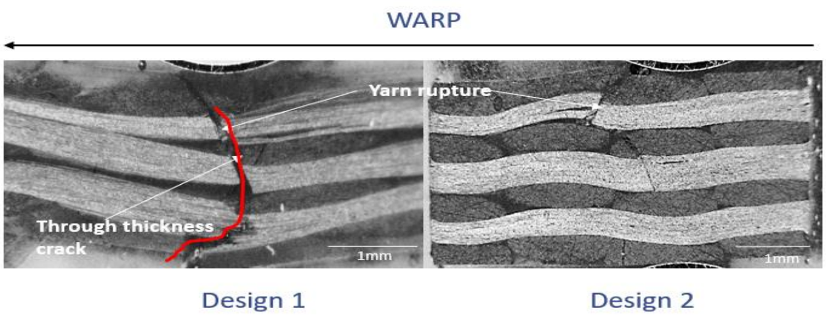

Figure 6: Micrographs of failed flexure specimens of design 1 and design 2 3D woven composite

5. Conclusion

The main objective of this paper was to study the influence of easily adjustable textile design plan on the physical and mechanical properties (tension, compression and flexure) of 3D woven warp interlock layer-to-layer carbon/epoxy composites. The mechanical properties were improved in both the warp and weft directions with a increase in number of groups in the textile design plan. The tensile strength was improved by 27% in the weft and 55% in the warp direction, compressive strength by 9% in the weft and 20% in the warp direction and flexural strength by 30% in the weft and 40% in the warp direction. It was found that althought the fibre content was kept constant along the longitudinal direction, by changing the textile design plan, increases its mechanical properties in both warp and weft directions. This is thought to be result of a combination of several factors- V_f, tow misalignment, interyarn spacing, tow arrangement, crimp, binding points/ unit cell and size/distribution of resin rich areas. The improvements in mechanical performance from design 1 to design 2 were achieved with a relatively small change in manufacturing parameter (lift plan change) rather than a rethreading the entire loom, which is an expensive and time cosuming process.

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