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MODELLING FRACTURE BEHAVIOUR IN FIBRE-HYBRID 3D WOVEN COMPOSITES

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Abstract. Modelling fracture within 3D woven composites is a significant challenge and the subject of ongoing research due to their complex hierarchical structures. This challenge is heightened when modelling 3D woven composites with multiple fibre types, referred to as fibre-hybrid 3D woven composites. This work addresses this challenge through the development of a novel methodology for modelling fracture in fibre-hybrid 3D woven composites. The bulk of preceding research into fracture modelling of 3D woven composites has focused on single-fibre-type woven composites with limited research into fibre-hybrid 3D woven composites. Research has focused on highly simplified models, often relying on experimental results [1], [2], [3]. In contrast, this work will apply fracture modelling techniques to high-fidelity finite element models of 3D woven composites resulting in simulations of fracture behaviour comparable to the behaviour observed in experimental tests. 3D woven composites possess exceptional properties such as improved out-of-plane strength, stiffness, fracture toughness, fatigue resistance and damage tolerance compared to more traditional 2D woven composites [4], [5], [6], [7]. However, currently the use of 3D woven composites in industry is limited by a lack of knowledge about their behaviour. Manufacturing and testing the required number of samples is prohibitively expensive and time-consuming resulting in the need for accurate models of 3D woven composite behaviour. The novel fracture model for fibre-hybrid 3D woven composites developed in this work will serve as a foundational tool for developing new material designs, paving the way for innovation and the widespread adoption of 3D woven composites in a diverse range of industries.

Key words: *fracture modelling; finite element; 3D woven composites*

1 Introduction

The utilization of 3D woven composites in engineering applications has garnered significant attention due to their exceptional mechanical properties compared to traditional 2D woven composites [4], [5], [6], [7]. However, accurately modeling fracture behavior within these materials, particularly in cases involving multiple fibre types, remains a considerable challenge. This work presents a novel methodology for modeling fracture in fibre-hybrid 3D woven composites, aiming to address this challenge and advance the understanding and utilization of these innovative materials.

3D woven composites (3DWCs) were first manufactured in the 1970s. 3D woven composites are fibre-reinforced composites similar to the carbon fibre found in bike frames or the glass-fibre used in wind turbine blades where fibres are woven together and then infused with a resin. However, 3D woven composites differ from these traditional 2D woven composites in that they also have reinforcements in the through-the-thickness or z-direction, as in Figure 1. These through-the-thickness binder yarns, or Z-tows, inhibit delamination between the layers of woven composite resulting in improved mechanical properties.

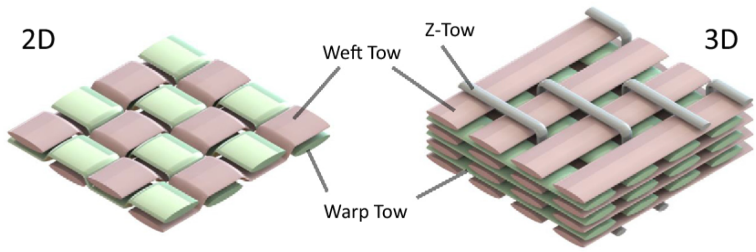

Figure 1: 2D and 3D woven composites with warp, weft and through-the-thickness yarns or Z-tows labelled. [8]

Currently, the reported benefits of 3DWCs include improved through-the-thickness mechanical properties, improved manufacturing processes and better design flexibility compared to 2D woven composites [9]. These benefits make 3D woven composites an attractive prospect in many engineering applications. However, uptake of the technology has been slow due to a poor understanding of the material's behaviour, namely due its intricate hierarchical structure and the complex interactions between the components within the composite. To enable the widespread use of 3D woven composites in industry detailed high-fidelity models of the behaviour of 3D woven composites under loading are required.

2 Problem description

Accurate fracture behaviour models of 3D woven composites are limited to a small number of models. The hierarchical structure of 3D woven composites and the interaction between the fibre and resin within the composite presents inherent complexities in modelling fracture behaviour. This challenge is further compounded in fibre-hybrid 3D woven composites, where multiple fibre types interact within the composite structure.

Fibre-hybrid 3D woven composites can provide greater benefits over 'pure' 3D woven composites with each fibre type contributing towards the overall material properties. For example, in this work, brittle but strong carbon fibre are combined with weaker but tough polypropylene fibres creating a material which is stronger than a purely polypropylene weave but tougher than a purely carbon fibre weave.

Despite their benefits, due to the complexity of their behaviour and challenges in manufacturing, fibre-hybrid 3D woven composites are currently rarely used in industry and modelling techniques of their behaviour are not well-established. No high-fidelity fibre-hybrid 3D woven composite fracture models accounting for the level of detail presented in this work have been previously reported. Previous research efforts have primarily focused on single-fibre-type woven composites or have relied on extremely simplified models and experimental data [3], [10], [11], [12]. Consequently, there exists a gap in the understanding the fracture behaviour of fibre-hybrid 3D woven composites, hindering their widespread adoption in various industries.

The basis of the fibre-hybrid 3D woven composite fracture model developed in this work is a high-fidelity finite element model of the weave produced by a code currently under development at the University of Bristol. This finite-element model is then adapted in this work to model fibre-hybrid 3D woven composites and to model fracture within the material. Before a fracture model can be developed, an elastic model of the fibre-hybrid weave must first be established. This extended abstract will present these initial results. The proposed methodology will integrate advanced fracture mechanics principles with high-fidelity finite element analysis to model fracture behaviour in fibre-hybrid 3D woven composites.

3 Numerical results

The numerical results presented in this section will include a validation of the elastic model based on experimental results conducted on an initial material design and numerical results for different fibre volume fractions and stiffness ratios between fibre types.

3.1 Validating the Elastic Model against Experimental Results

Table 1: Table of numerical and experimental results of warp and weft Young's Moduli for a baseline and fibre-hybrid composite.

		Young's Modulus (Warp) [GPa]	Young's Modulus (Weft) [GPa]
Numerical	Baseline	20	11
	Fibre-Hybrid	16	9
Experimental	Baseline	66 ±5	76 ±5
	Fibre-Hybrid	13 ±1	12 ±1

Tensile tests were conducted for both a baseline 3D woven composite, woven from purely carbon fibre, and a fibre-hybrid 3D woven composite, woven from polypropylene fibres and carbon fibre. Table 1 compares the numerical and experimental results for Young's Modulus for the baseline and fibre-hybrid composites. The warp and weft Young's Moduli are the values of Young's Modulus measured when testing the material unit cell or samples in the warp or weft direction, see Figure 1. In the initial stages of the research, the values for Young's Modulus are within the correct order of magnitude, however the model fails to capture the true behaviour of the material. The baseline model in particular massively underestimates the values for Young's Modulus.

3.2 Fibre-Type Volume Fraction within 3D Woven Composite

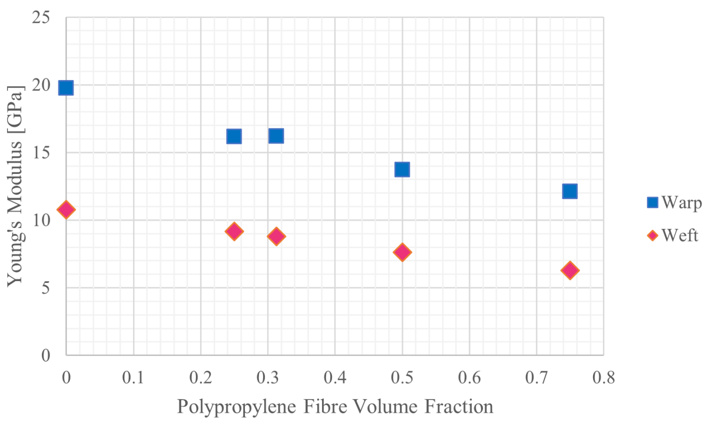

Figure 2: Young's Modulus for both warp and weft directions for polypropylene fibre volume fractions (e.g. compared to carbon fibre) of 0, 0.25, 0.3, 0.5 and 0.75.

The fibre-type volume fraction is the number of one type of fibre compared to the other fibre type within a fibre-hybrid 3D woven composite, e.g. if half of the yarns are one fibre type the fibre-type volume fraction will be 0.5. Figure 2 presents the Young's Moduli in the warp and weft direction for five different fibre-type volume fractions.

3.3 Stiffness Ratio within 3D Woven Composite

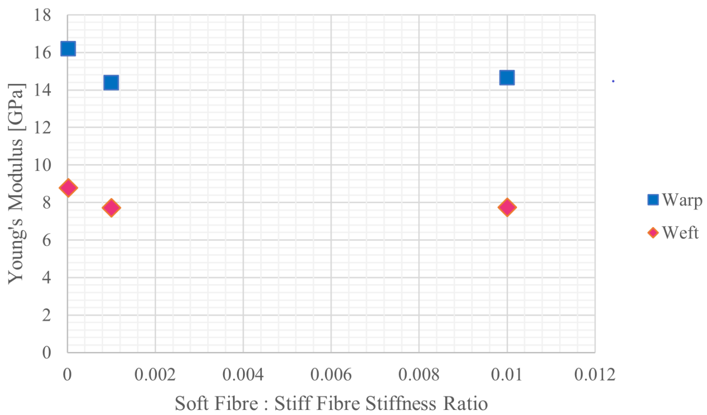

Figure 3: Young's Modulus for both warp and weft directions for three different stiffness ratios between one soft fibre type and one stiff fibre type.

The stiffness ratio within a fibre-hybrid 3D woven composite is the ratio between the stiffness for each fibre-type, if one fibre type has a stiffness that is ten times smaller than the other fibre type the stiffness ratio would be 0.1. Figure 3 presents the Young's Moduli in the warp and weft direction for three different stiffness ratios.

4 Conclusions

In conclusion, the development of a novel methodology for a high-fidelity finite element model of fibre-hybrid 3D woven composites represents a significant advancement in composite materials research and design. By addressing the challenges associated with accurately predicting fracture behavior, this work will further lay the foundation for enhanced understanding and utilization of these innovative materials across various industries. Preliminary results show that an initial elastic model of fibre-hybrid 3D woven composites using the proposed methodology required some further assessment and adaptations to fully capture the true behaviour of the material. Moving forward, continued improvements and the application of an optimisation process to the proposed methodology hold promise for advancing the adoption of fibre-hybrid 3D woven composites within industry.

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