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# EFFECT OF THE INTERLACING PATTERN ON THE COMPACTION BEHAVIOUR OF 3D CARBON FIBRE TEXTILE REINFORCEMENTS

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***Abstract***— 3D reinforcements were introduced to mitigate and overcome limitations arising from the use of traditional textile reinforcements in the construction of polymer matrix composites (PMC), in terms of their resistance to impact and inter-laminar shear strength (ILSS), both resulting from delamination.

Many thick interlaced textile structures were developed towards that end but many more possibilities exist in terms of yarn interlacing patterns, leading to different types of 3D textiles that may potentially be built. The effect of different interlacing patterns on the compaction behaviour of such interlaced 3D textiles is probed in this paper. Trends and differences in the compaction behaviour were observed for 5 series of 3 consecutive compaction cycles applied to 16-layers interlaced 3D reinforcements. Those trends and differences are presented and discussed.

Overall, the maximum recorded volume fraction ranged from 0.58 to 0.86. Values of the volume fraction reached in the first cycle $C_1$ were always lower than in following cycles $C_2$ and $C_3$. Although some elements of behaviour were common to all samples and tests, differences also emerged between samples featuring different interlacing patterns.

***Keywords- 3D reinforcement fabrics; compaction; interlacing pattern; volume fraction***

## I. INTRODUCTION

3D textile reinforcements featuring relatively few through-thickness yarns may be constructed from 2D fabrics, stitching them together using structural thread to enable some level of local load transfer between layers in addition to assembling the 2D layers into a 3D textile. 2D textile layers can also be held together using technologies such as tufting or z-pins [1]. Advantages of such methods for producing simple 3D textile reinforcements include reduced labour and level of uniformity that are largely maintained, without the need for complex textile manufacturing processes. However, a suitable joining method for assembling different layers together is critical for handling of the fabrics, and for the mechanical properties of the final PMC part [2]. For example, Quan et al. reported a multi-layer 3D textile reinforcement consisting of 2D layers of plain weave, 0º unidirectional non-crimp fabric, 90º unidirectional non-crimp fabric, and plain weave laid either side of a foam core and held together by 4 pins [3].

3D reinforcements featuring more interlacing can be produced through dedicated weaving, braiding and knitting processes using specially designed automated looms. These reinforcements are better in the sense that yarn interlacing between layers is more pervasive, more consistent, and it is effectively part of the textile design. Many interlaced fabrics featuring different yarn interlacing patterns can be designed, resulting in numerous types of 3D woven fabrics that could theoretically be built. The University of Ottawa composites group has developed its Steered Preforming Technology (uO-SPT) which enables the design and manufacturing of thick, net-shape, flat drapable 3D reinforcement fabrics featuring variable spacing between either straight or curved yarns [4, 5]. Different yarn interlacing patterns in uO-SPT reinforcements result in different properties in the dry fabrics and final composite parts made from them [3,5]. Comparing with 2D woven fabrics, different yarn interlacing patterns have led to a number of classic patterns becoming standard constructions including plain weaves, 4-harness, 5-harness and 8-harness satin weaves, and twill weaves. These patterns are used routinely in composites construction and constitute the vast majority of 2D weaves used, even as many other patterns could be created. 3D reinforcements can also be built based on a large array of possible interlacing patterns [6]. Some 3D interlacing patterns are referred to more frequently in the literature such as orthogonal and interlock constructions.

The behaviour of different reinforcements subjected to compaction normal to their plane is very important to numerous aspects of the processing of reinforcements into composite parts. Compaction controls the permeability which largely dictates how resin flows through the reinforcement during processing, and it also controls the fibre volume fraction which influences the mechanical properties of the composite parts. A number of 3D reinforcements featuring different interlacing patterns were manufactured and their compaction behaviour are reported and compared.

## II. MATERIALS

The uO-SPT was used for manufacturing 16-layers 3D carbon fibre reinforcements featuring 3 different interlacing patterns. The aim of choosing different interlacing patterns was to probe the effect of yarn interlacing on the compaction behaviour of the reinforcements: one of the reinforcements featured limited interlacing, one featured a high level of interlacing, and one was between these extremes.

Diagrams representing these fabrics were produced using textile modeling software TexGen from the University of Nottingham [7]. It should be noted that vertical dimensions in computer models were magnified for clarity. Stitching lines do not feature in the diagrams. The interlacing patterns of the 3D reinforcements were explained through illustrations of the yarn paths in the reinforcements, also generated using TexGen.

The reinforcement shown in “Fig 1” was labelled preform #1. Preform #1 features no interlacing. Yarn paths for preform #1 are shown in “Fig 2”. “Fig 3” illustrates the second 16-layers 3D reinforcement which features highly interlaced yarns. The reinforcement shown in “Fig 3” was labelled preform #2. The yarn paths of preform#2 are shown in “Fig. 4”. The third reinforcement, which features moderate interlacing is labelled preform#3 and is shown in “Fig. 5”. “Fig. 6” illustrates the yarn paths for preform#3.

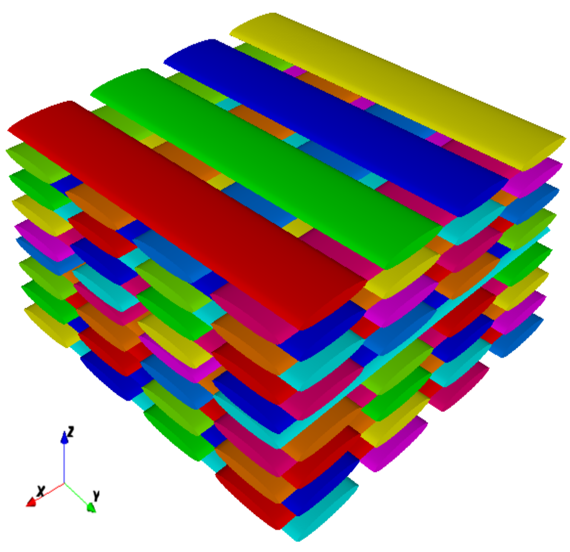


Figure 1. Preform#1, 16-layers, no interlacing

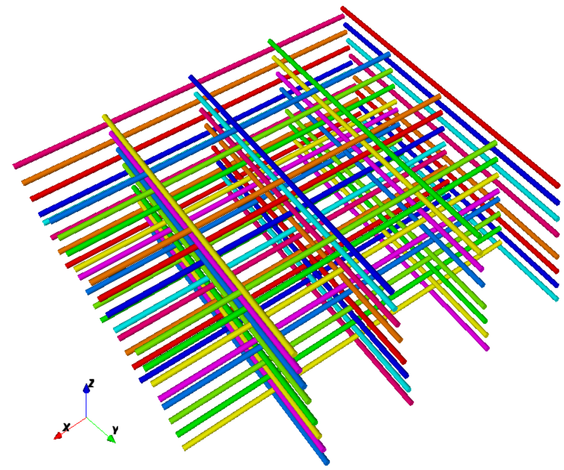


Figure 2. Yarn paths, preform #1

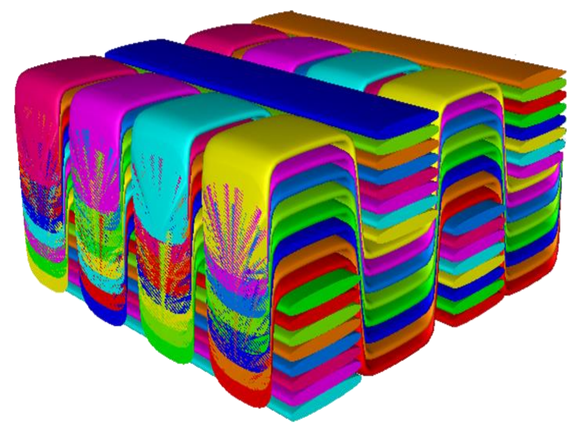

Figure 3. Preform#2, 16-layers, high interlacing

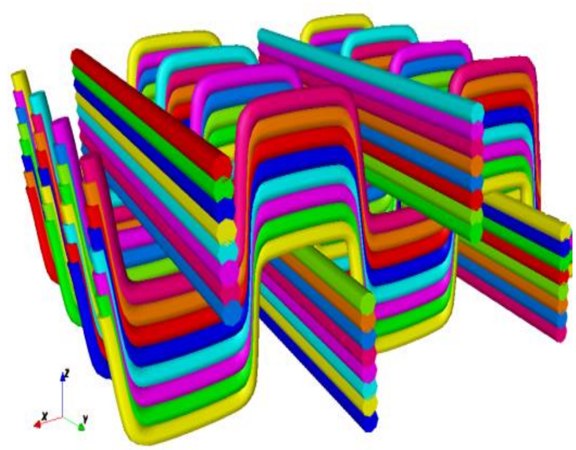


Figure 4. Yarn paths, preform #2

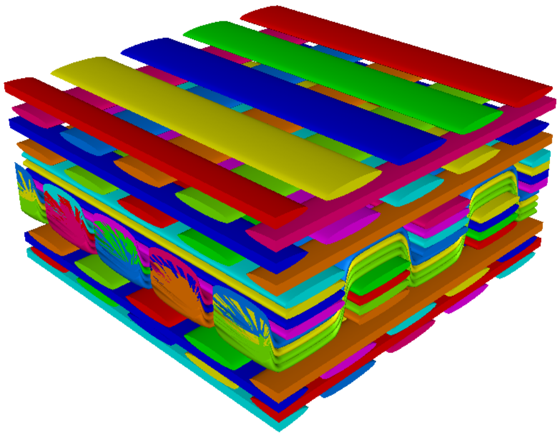

Figure 5. Preform#3, 16-layers, moderate interlacing

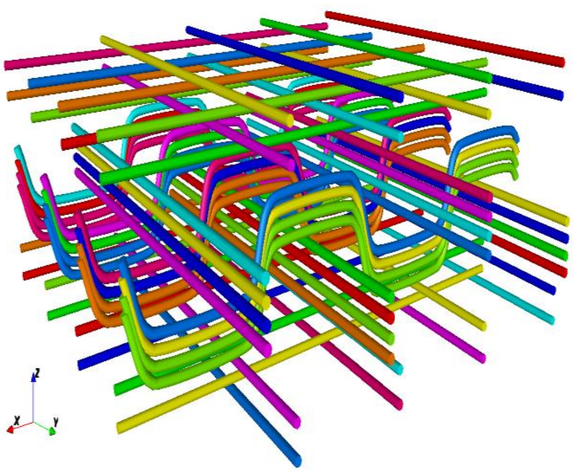

Figure 6. Yarn paths, preform #3

## III. Experimental

All compaction tests were conducted using an Instron 4482 universal testing frame equipped with a 100KN load cell, with an accuracy of 0.25% of maximum load. Compaction tests were conducted using a circular cross-section test rig. “Fig 7” shows the comaction test rig throughout compaction test of preform #2. The test rig includes a lower platen and an upper platen with a diameter of 50mm. Tests were conducted up to a pressure of 0.12 Mpas. All compaction tests were performed by moving the upper platen onto the surface of the reinforcement at a fixed displacement rate of 0.1 mm/min, recording the reaction force applied by the compacted reinforcement on the platen.

Successive compaction cycles were conducted in each test, to investigate the effect of repeated loading cycles on the compaction behaviour of all 3D preforms. Each series of cycles was repeated 4 times to quantify the reproducibility of the data. Recorded values were converted to fibre volume fractions as a function of the compaction pressure, and graphs of average curves were produced. All compaction tests are conducted in room temperature.

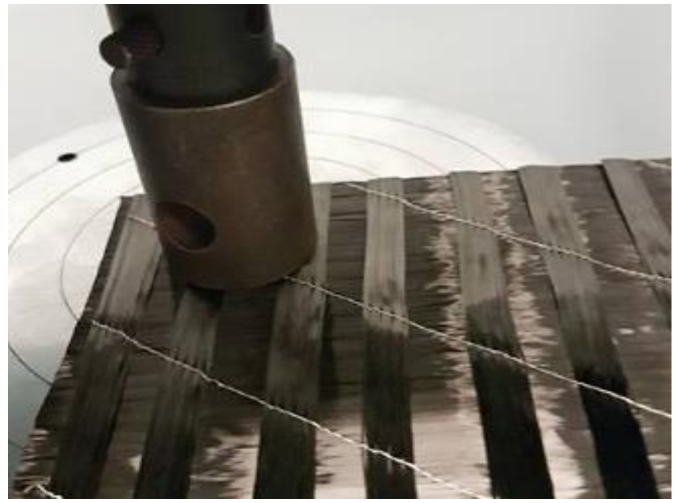

Figure 7. Compaction test on preform#2

## IV. RESULTS AND DISCUSSION

Compaction graphs showing the behavioir of 3D reinforcements in different successive compaction cycles are derived . “Fig 8” shows the compaction behaviour of preforms #1, #2 and #3 in the first compaction cycle. “Fig 9” and “Fig 10” show the compaction behaviour of all three 3D reinforcements in the second and third successive cycles. “*P#1 / C1”* means total average of data obtained for preform#1 in the first cycle. The error bars on the graphs show the vsariability of the data.

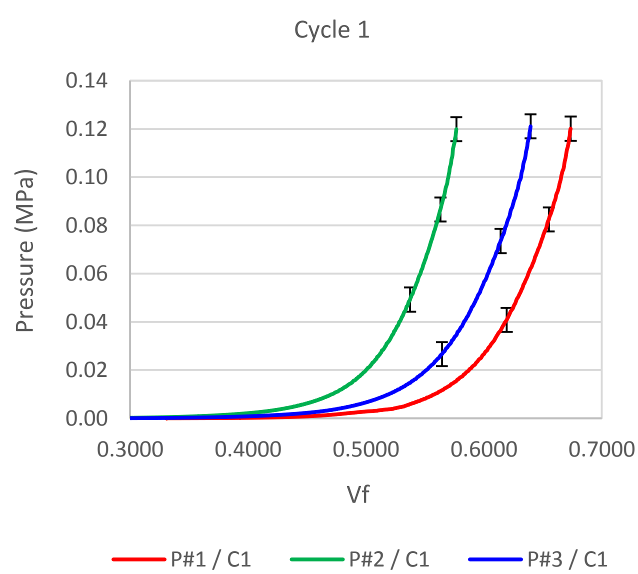


Figure 8. Compaction behaviour, 3 fabrics, cycle 1

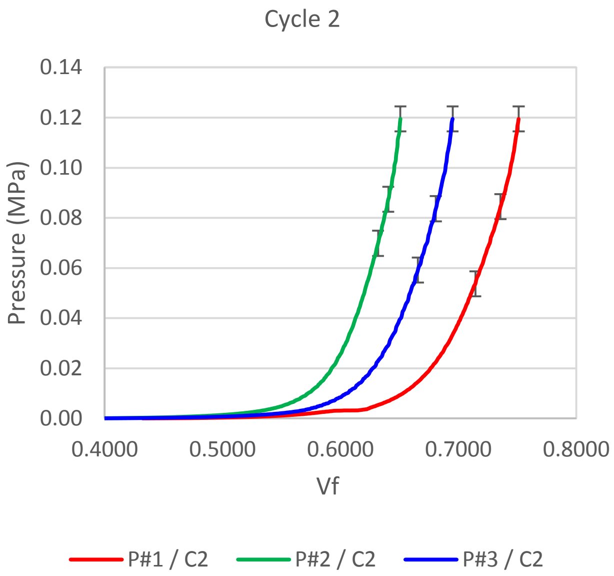


Figure 9. Compaction behaviour, 3 fabrics, cycle 2

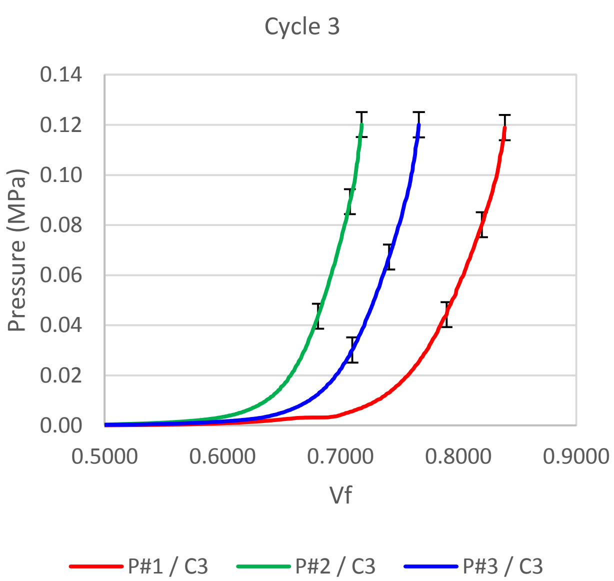


Figure 10. Compaction behavior, 3 fabrics, cycle 3

Different internal interlacing patterns in the reinforcements affect their compaction behaviour and volume fraction.

“Fig 11”, “Fig 12” and “Fig 13” show the effect of compaction cycles on the maximum fibre volume fraction.

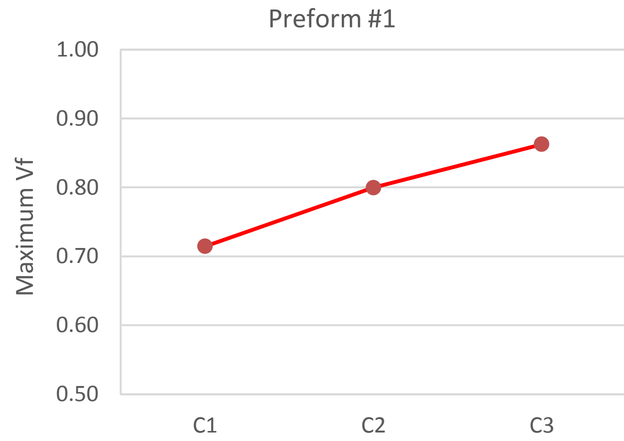


Figure 11. Effect of number of cycles on compaction behaviour, preform #1

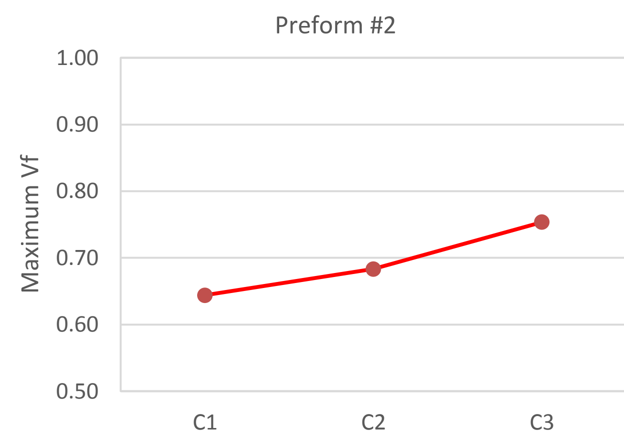


Figure 12. Effect of number of cycles on compaction behaviour, preform #2

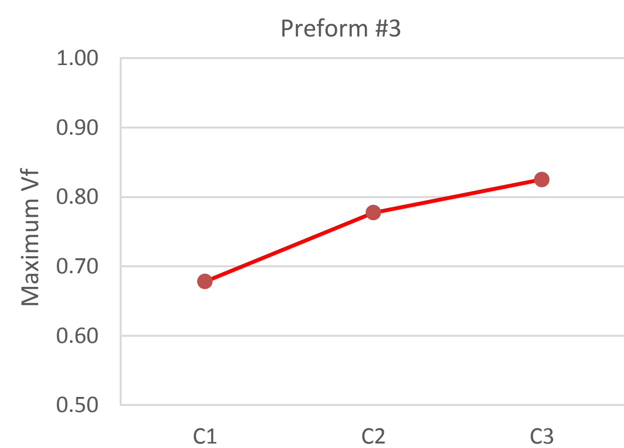


Figure 13. Effect of number of cycles on compaction behaviour, preform #3

An increase in the $V_f$ of all three preforms was observed from conducting successive compaction cycles as seen in "Fig 11", "Fig 12" and "Fig 13".

## V. Conclusions

An experimental study of the compaction behaviour of three different 3D carbon fibre reinforcements with different interlacing patterns is presented. The influence of interlacing on the final volume fraction of the reinforcements was analysed.

3D reinforcements featuring more interlacing show lower volume fractions. Their volume fraction at any pressure is lower than 3D reinforcements fraturing lower interlacing. This shows direct effect of the quantity of the interlacing of 3D reinforcements on their compaction behaviour and volume fraction.

The effect of repeated compaction cycles on the different interlaced 3D reinforcements was also probed. The volume fraction of all 3D reinforcements increased for higher compaction cycles.

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