ASSESSMENT OF COMPOSITES REINFORCED WITH INNOVATIVE 3D WOVEN HOLLOW FABRICS

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Abstract
Composites are extensively used in automotive, construction, airplanes, wind turbines etc. because of their good mechanical properties as high specific stiffness, high specific strength and resistance against fatigue. The main issues with composites are delamination and the manual labour in the production process. If hollow structures like stiffeners need to be manufactured, these problems become even more apparent. As a result, there is a lot of interest in hollow 3D woven fabrics for composites as they reduce the manual labour, have a higher resistance against delamination and can lead to special properties and applications. In this work several of these 3D woven fabrics are designed and produced in high-tenacity polyester yarns. Then, the possibility to use these 3D fabrics in composites is explored: compatibility of polyester yarn and polyester resin, reproducibility of the production process and static testing. A reproducible production process is currently under development and static testing show promising results.

1. Introduction

There is a lot of interest in complex 3D woven fabrics for composite because they can lead to special mechanical properties and applications. The two main advantages are the improved resistance against delamination and the reduction of manual labour. Since the fabrics are produced in one single run, a stacking sequence is not needed as this is already implemented at the weaving loom and all the different layers are connected to each other to improve the resistance against delamination. This work focusses on the production and processing of hollow 3D woven fabrics.

These hollow 3D fabrics are made in a totally different way than the commonly known spacer fabrics [1]. In spacer fabrics, loose yarns connect two flat fabrics to each other. With 3D fabrics all the connections between different layers are woven connections i.e. they consist out of warp and weft yarns instead of single yarns. Therefore, these fabrics will lead to different properties.

The research with respect to the different geometries and design possibilities of these complex hollow 3D woven fabrics is very limited. Chen et al. [2, 3] described a first production process for honeycomb fabrics. This is a proof of concept with a very low density of cotton fibres where no investigation of different weaving patterns is conducted nor is an attempt made to maximize the potential of these fabrics. The honeycomb fabric has a maximum of four honeycomb cavities on top of each other. A composite

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was made using a self-developed mould with wooden sticks. Mountasir et al. [4] described a possible production method for 3D woven fabrics with rectangular openings. For the production of these fabrics a weaving loom was developed because of the used weaving patterns and movements which cannot be achieved on a standard loom. This fabric was made out of hybrid yarns GF/PP so a composite was made by using hot pressing in a newly designed mould.

In this work the following three topics will be discussed: the development and production of the 3D woven fabrics, the production of the composite and the static testing.

2. 3D woven fabrics

2.1. Different types of 3D fabrics

Several different geometries of hollow 3D woven fabrics have been developed but they can be divided into two groups: honeycomb structures and structures with square cavities. A total of seven variants have been made with different amount of layers and different geometries of the honeycomb structures. In Figure 1 a honeycomb with alternating five or six (5-6) cavities on top of each other is displayed. In this fabric all layers are single woven layers. Other fabrics consist of 2-3 or even 1-2 cavities on top of each other. All these different geometries are woven with different amounts of layers so the impact of the number of layers and the geometry can be investigated.

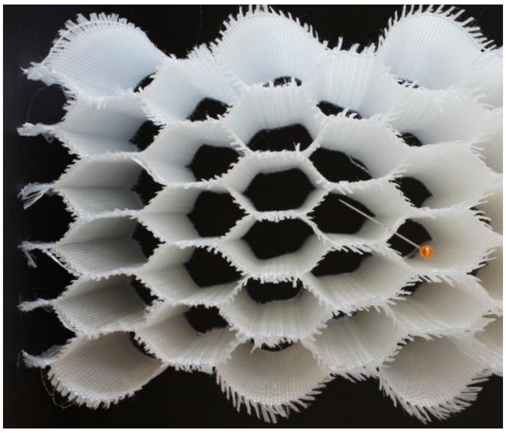

Figure 1. Honeycomb fabric; a pin needle illustrates the dimensions.

The second type of hollow 3D woven fabrics have square cavities. These fabrics are woven on modified conventional weaving looms at an industrial speed in contrast to the fabrics produced by Mountasir et al. [4] Two variants have been made of this fabric. The first one is a fabric with one square cavity. The second, shown in Figure 2, is a fabric with two square cavities on top of each other. Again, the amount of woven layers between the two geometries varies so the impact of the number of layers and the geometry can be investigated.

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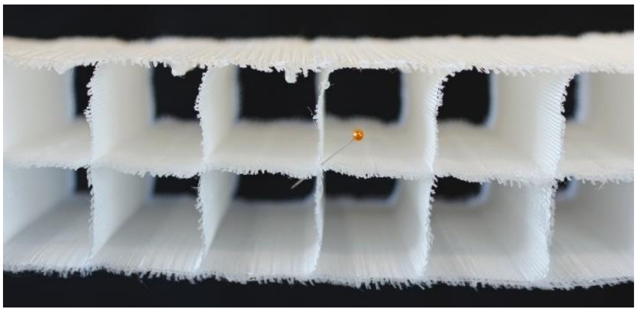

Figure 2. Fabrics with squared cavities; a pin needle illustrates the dimensions.

Multiple weaving patterns are used in the 3D structures. In the honeycomb structures there are free walls and bonded walls (see Figure 3), where two free walls join. In the work of Mountasir et al. [4] these bonded walls have the same weaving pattern as the free walls but the yarn density in warp direction is doubled. Here, a multilayer is constructed with the two free walls that join together. All the different weaving patterns used in the hollow 3D woven fabrics are also woven as flat fabrics. This to produce flat composite plates with vacuum assisted resin infusion (VARI) to compare the properties of the flat plates and the 3D structures to see the influence of the geometry.

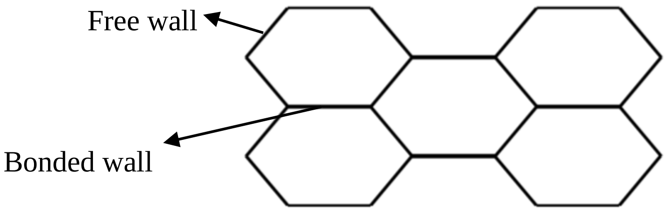

Figure 3. Difference free and bonded wall.

All these fabrics are made in HT (high tenacity) polyester yarns for two reasons. The first one is the ease of handling. The for composites more conventional glass or carbon yarns have a low resistance against friction and are more difficult to process on a weaving loom. Due to the high density of yarns in the loom (120yarns/cm) and the adaptations that were needed during the production of these complex 3D fabrics a HT-polyester yarn was chosen to avoid the above mentioned problems. A second advantage is the cost of the yarn with respect to glass and carbon.

A polyester resin is chosen to combine with these HT-polyester yarns because of the price and the expected compatibility with the fibres.

2.2. Optimizing adhesion of fibres and matrix

The HT-polyester yarn which is used for the different composites contains a spin finish that can have a negative influence on the adhesion between the fibres and the matrix. Two different cleaning processes were attempted: one was provided by the yarn manufacturer, another one was proposed by the authors. In the first cleaning cycle the fabric is kept in boiling water for five minutes with alkali (caustic soda) and detergent. Afterwards the fabric is washed with warm water and dried. The second alterative, cleaning cycle consist of a ultrasonic cleaning process with isopropanol. Here the fabric is cleaned for ten minutes at a temperature of 25°C. Composites have been made of these different cleaned fabrics with polyester resin via hand lamination. A composite of a non-cleaned fabric was made as a reference.

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Short 3-point bending tests have been conducted on these different composites according to the ASTM D2344 standard [5]. For each cleaning cycle five specimens were tested but for the composite made out of fabric cleaned with alkali and detergent only four tests were conducted. The F^{SBS} (short-beam strength) is determined for each specimen and the results are list in Table 1. The force used for the determination of the F^{SBS}, is indicated in Figure 4 with a red circle. This is the moment where visually the first movement of the layers over each other is observed hence indirectly a sort of delamination is present. It is clear that the cleaning cycle with alkali and detergent has a negative effect on the F^{SBS} and that the standard deviation is higher. The specimens were unloaded to determine their final shape and permanent deflection.

Table 1. F^{SBS} of the different cleaning cycles.

F^{SBS}	Alkali and detergent	Ultrasonic with isopropanol	Not cleaned
μ [MPa]	19.296	22.847	22.706
s [MPa]	1.488	0.784	0.905

In Figure 4, the stress-displacement curves of the short 3-point bending hysteresis tests are displayed, both loading and unloading of the specimens. The green curves are the fabrics cleaned with alkali and detergent, the blue curves are with non-cleaned fabrics and the orange curve are with ultrasonically cleaned fabrics. Although the short-beam strength is the same for the ultrasonically cleaned fabrics and the non-cleaned fabrics, there are three main differences in the stress-displacement curves. The first difference is the bending stiffness which is higher for the ultrasonically fabrics. The second difference is the higher yielding point of the ultrasonically cleaned fabrics. These two facts indicate that there is better adhesion of the fibres and matrix than with the non-cleaned fabrics. The third main difference is that there is a significant load drop in the stress-displacement curve with the composites consisting of ultrasonically cleaned fabrics. With the non-cleaned fabrics and the fabrics cleaned with alkali and detergent there is no load drop but visually the layers move over each other during the test without delaminating, in the sense that a visible crack is formed. This phenomenon is visualised in Figure 5.

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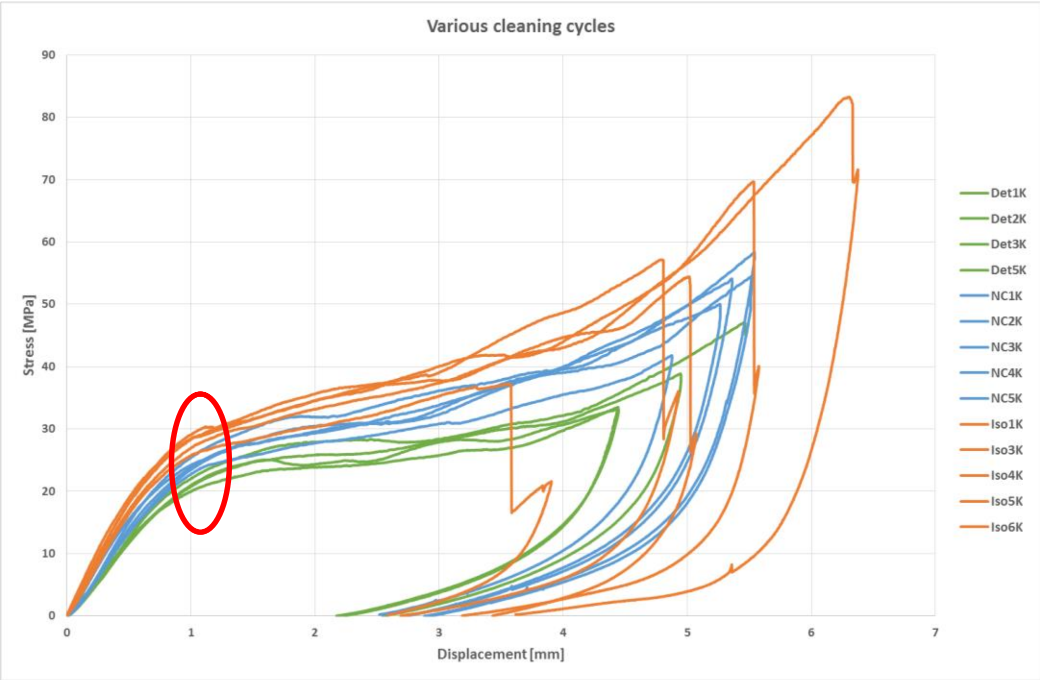

Figure 4. Comparison of short 3-point bending tests.

Not cleaned Ultrasonically cleaned

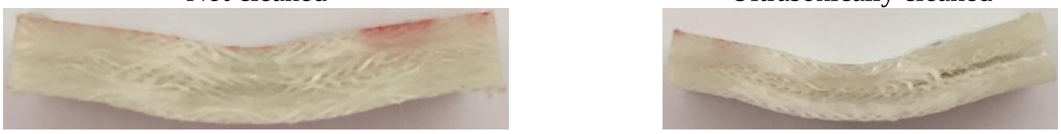

Figure 5. Visualisation of delamination.

3. Production of composites

3.1. VARI process

Due to the fact that the polyester resin has a high viscosity an alternative VARI process was used where inlet is at the centre of the plate. Also a hot plate (35°C) was used to lower the viscosity of the resin during impregnation. The main problem for impregnating the fabrics is that styrene (component in polyester resin) starts to boil under full vacuum. Therefore, only a vacuum of 30% can be used for the impregnation. The produced composites contain fabrics that are not cleaned as the plates have dimensions of 30cm by 45cm. The ultrasonic cleaning process is only feasible on fabrics with limited dimensions.

3.2. 3D composites

For the production of the 3D composites a mould is under development to get a fast and reproducible process. The first lab-scale specimens with this mould are displayed in Figure 6. Further investigation is needed for the upscaling of the production process.

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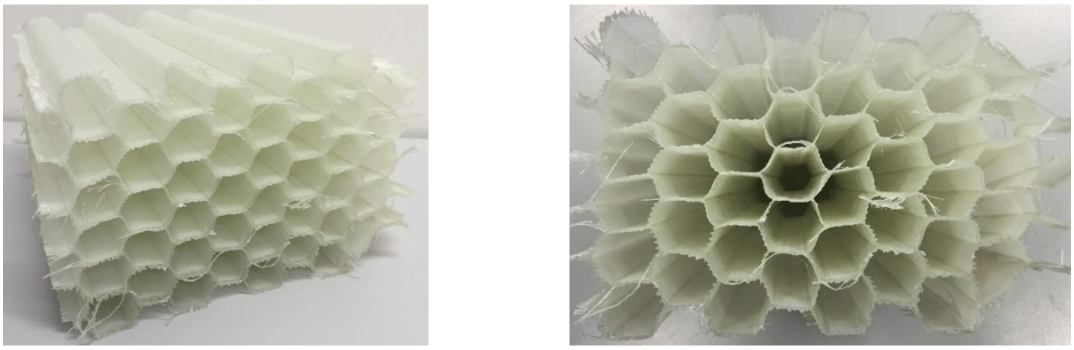

Figure 6. Composite of 3D woven honeycomb fabric.

4. Static testing

4.1. VARI plates

Tensile tests have been performed on the flat VARI plates according to the international standard ASTM 3039 [6]. These tensile tests are instrumented with an extensometer and a transverse strain gauge. The results for warp and weft of the fabric used in the free walls of Figure 1 and Figure 6 are shown in Figure 7. The green graphs display the results of the warp direction, the blue graphs display the results of the weft direction. Both in warp and weft direction the composite material shows a very non-linear behaviour and a stiffening effect. This stiffening effect is due to the fact that the yarns are curved in the woven fabric (depending on the used weaving pattern) and they align themselves in the test direction but also that fact that the polymer chains in the yarn align themselves. Another point of interest is the large failure strain of the material: in warp an average strain of 15.5% is reached and in weft 27.3%. This results in a high energy absorption of the composite material which can compensate the lower stiffness compared to the more common composites for certain applications.

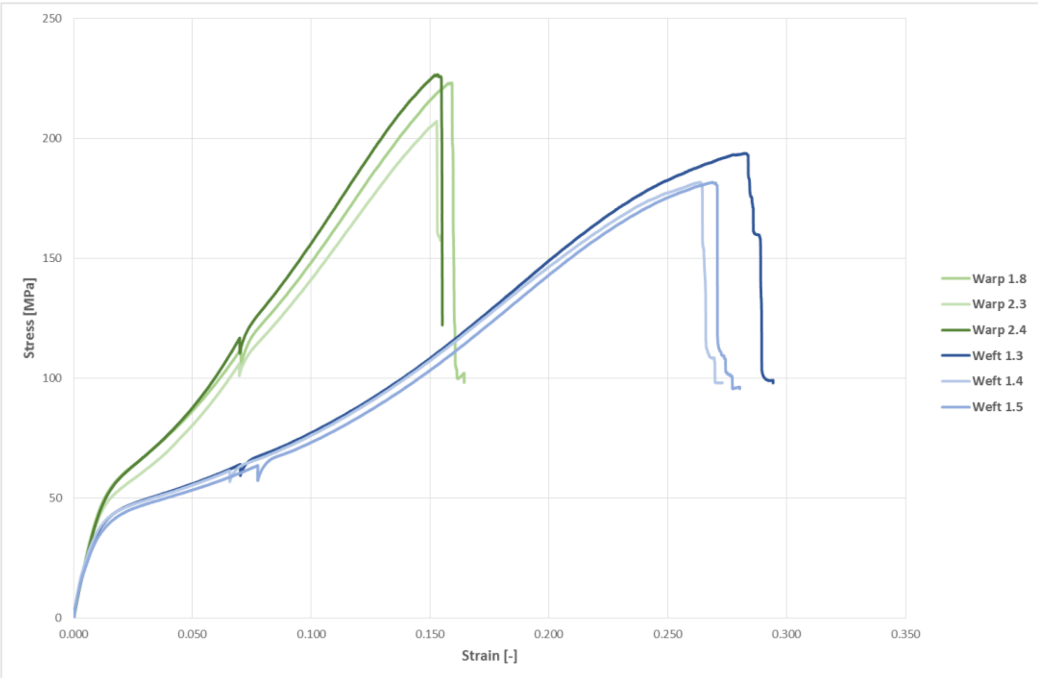

Figure 7 Stress-strain curves of the free walls.

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4.2. 3D composites

A first bending test has been performed on a single cavity of the 3D composite in Figure 6. The test setup is displayed in Figure 8. The length of the specimen is 250mm with a span of 200mm.

Figure 8 Bending test one hexagonal cavity.

The result of this bending test is shown in Figure 9. The main issue is the local indentation of the cavity at the indenter, causing the plateau from 10mm displacement.

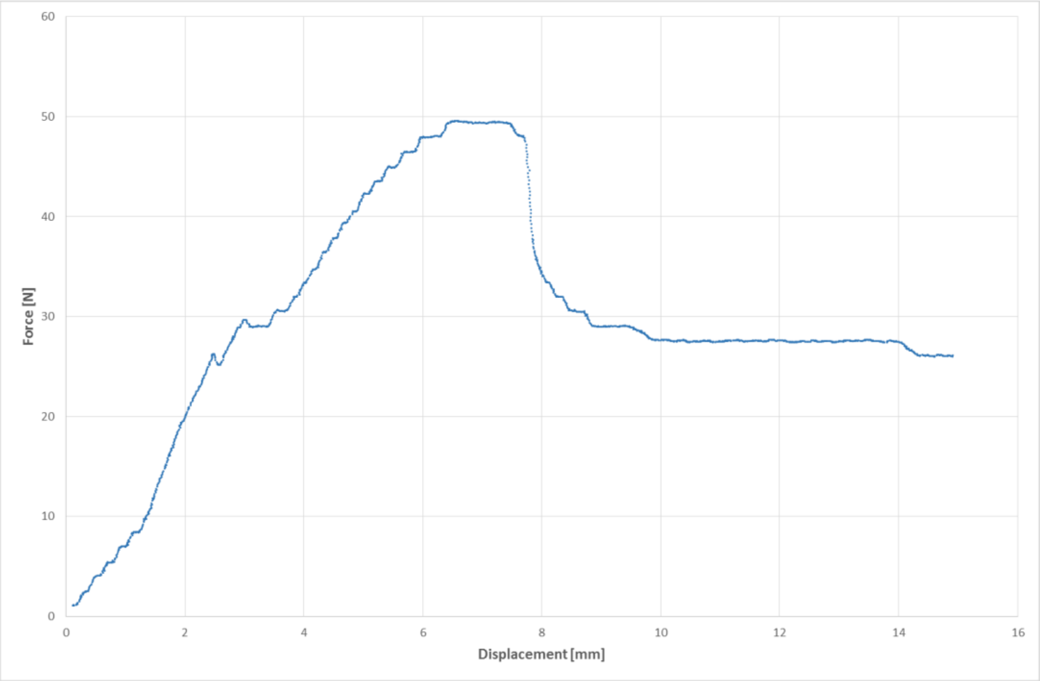

Figure 9 Force – displacement curve of a bending test of one hexagonal cavity.

5. Conclusion

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The different hollow 3D woven fabrics that are divided into two groups were presented: honeycomb structures and structures with square cavities. Within these two groups several geometries are produced. All the used weaving patterns in the 3D woven fabrics are also woven as flat fabrics to compare the properties of the flat plates and the 3D composites. To optimise the adhesion between the fibres and the matrix two cleaning cycles were conducted where cleaning the fabric ultrasonically with isopropanol gave a better result with respect to the adhesion. Using VARI, flat composite plates are produced with the flat woven fabrics and subjected to tensile testing. The results of these tensile tests show great potential. The stress-strain curves of the composite material shows a very non-linear behaviour and a large strain. This leads to a high energy absorption of the material. First 3D composites have been produced at lab scale and a first bending test on a single hexagonal cavity has been performed.

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REFERNCES

[1] Li, M., et al., *Effect of Structure on the Mechanical Behaviors of Three-Dimensional Spacer Fabric Composites.* Applied Composite Materials, 2009. **16**(1): p. 1-14.
[2] Chen, X.G., Y. Sun, and X.Z. Gong, *Design, manufacture, and experimental analysis of 3D honeycomb textile composites Part I: Design and manufacture.* Textile Research Journal, 2008. **78**(9): p. 771-781.
[3] Chen, X.G., Y. Sun, and X.Z. Gong, *Design, Manufacture, and Experimental Analysis of 3D Honeycomb Textile Composites, Part II: Experimental Analysis.* Textile Research Journal, 2008. **78**(11): p. 1011-1021.
[4] Mountasir, A., G. Hoffmann, and C. Cherif, *Development of weaving technology for manufacturing three-dimensional spacer fabrics with high-performance yarns for thermoplastic composite applications: An analysis of two-dimensional mechanical properties.* Textile Research Journal, 2011. **81**(13): p. 1354-1366.
[5] ASTM International. ASTM Standard D2344/D2344M, 2000, "Standard Test Method for Short-Beam Strength of Polymer Matrix Composite Materials and Their Laminates", West Conshohocken, PA, 2000.
[6] ASTM International. ASTM Standard D3039/D3039M, 2002, "Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials", West Conshohocken, PA, 2002.

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