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Research on the Z-Direction Compression Failure Mode of 3D Woven Composites

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Abstract. In this paper, the 3D woven composite materials with guide sleeves were made by a novel 3D composite woven process. The compression test and SEM were used to investigate z-direction compression failure mode of the 3D woven composites with guide sleeves. The results show the guide sleeves were the main bearing structures while the load direction was along the thickness direction of those composites with guide sleeves. That is the rigid guide sleeves could improve the z-direction compressive property. The z-direction compression failure modes of the 3D woven composites with guide sleeves mainly include matrix cracking, guide sleeve/matrix debonding, axial cracking of guide sleeve, fibre fracture and shear fracture of guide sleeve. Furthermore, the deformational behaviour of guide sleeves played a key role in the z-direction compression failure mode of 3D woven composites with guide sleeves.

1. Introduction

3D woven composite have been used in areas of aircraft, rocket, civil airplane, high-end vehicle, sports equipment and so on because of their outstanding performance such as high specific strength, specific modulus, fatigue strength, impact Strength and outstanding design ability [1, 2]. It's different from the two-dimensional composites, the 3D woven composite contained z-yarns in z-direction. That is the production of 3D woven composite could improve interlaminar strength, enable to realize the replacement main bearing elements of composite materials [3].

State key lab of advanced forming technology & equipment of china [4, 5] have invented a novel 3D composite, which brought guide sleeves as z-directional reinforcements into manufacturing process for 3D weaving composite. A lot of research has been done by the researchers [6-8] in state key lab of advanced forming technology & equipment of china on the characteristics of guide sleeve, such as materials, structures and so on. Furthermore, Shan Zhongde, Shi Youling and Kang Huairong [9, 10] have studied on the micro model, elastic property and performance prediction. But there are no systematic studies on the compressive property and failure mode of 3D weaving composites with guide sleeves.

In this paper, the compression test and SEM were used to investigate z-direction compressive property and deformational behaviour of the 3D woven composites with guide sleeves. The compression failure modes were observed by field-emission scanning electron microscope. Thus it could provide theoretical basis for development of high-precision 3D woven process and equipment.

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2. Experiments

2.1. Materials

In this paper the guide sleeves were made of carbon/vinyl bars by pultrusion. The preforms were made by a novel 3D woven process. According to the designed route, the fibres weaved layer by layer; the unit cell of the completed 3D woven preform is shown in figure 1.

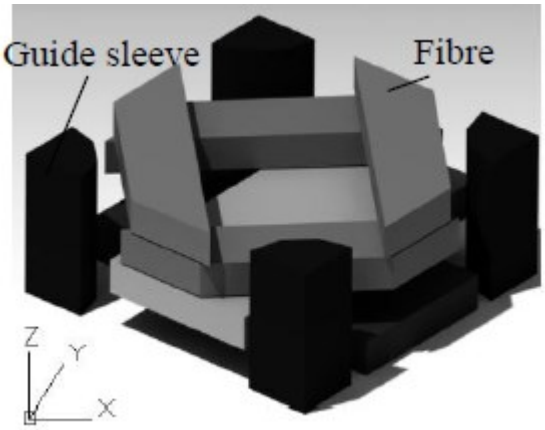


Figure 1. Unit cell of 3D woven composite

The resin matrix chose self-developed epoxy resin LY1564/XB3486 (viscosity is 200-300 cP at 25 °C, working time is 560-620 min at 23 °C, tensile strength is 70-80MPa). The preforms were impregnated use vacuum assisted resin infusion (VARI) process.

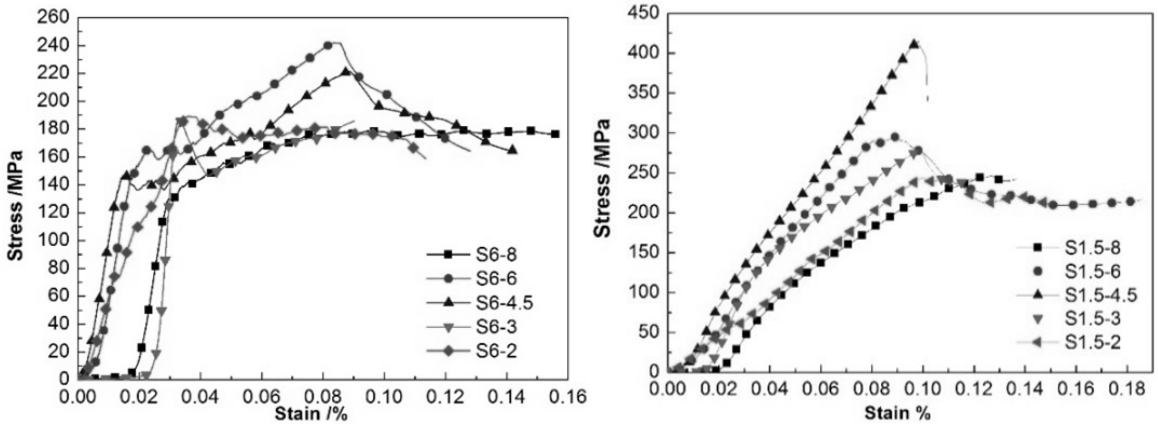
2.2. Compression Test

The z-direction compression samples were machined to rectangle, with the axial direction of guide sleeve as the z-direction of samples. The compression tests are conducted in WDW-200 universal testing machine, with loading speed of 1mm/min and environment temperature of 20°C.

Furthermore, the compression deformational behaviours of 3D woven composite with guide sleeves were observed by optical camera and ZEISS ULTRA 55 field-emission scanning electron microscope.

3. Result and Discussion

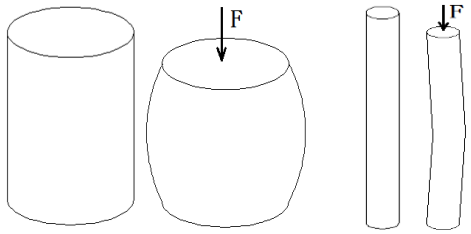
The stress-strain curves of 3D woven composites show the features of plastic deformation, as shown in figure 2. It is shown that the guide sleeves set along the loading direction acted as the main bearing elements during the initiation of loading. At this stage, the guide sleeve, fibres and resin matrix deformed cooperatively. The resin matrix cracked for the different deformability of guide sleeve, fibre and resin matrix with load increasing. In the meantime, guide sleeve/matrix cracking or guide sleeve axial cracking of samples produces a shear stress which leads to plastic deformation of samples. Thus the linear stress-strain curves transformed to nonlinear. The main bearing elements changed to the fibres with further loading, which leads to further improving of compression stress. After that fibres and guide sleeves fractured successively for the combined action of compression stress and shear stress [11]. Finally, the 3D woven composites fractured with increasing of plastic deformation.



(a) (b)

(a) Diameter of guide sleeve is 6mm; (b) diameter of guide sleeve is 1.5mm
Figure 2. Stress-strain curves of z-direction compression test

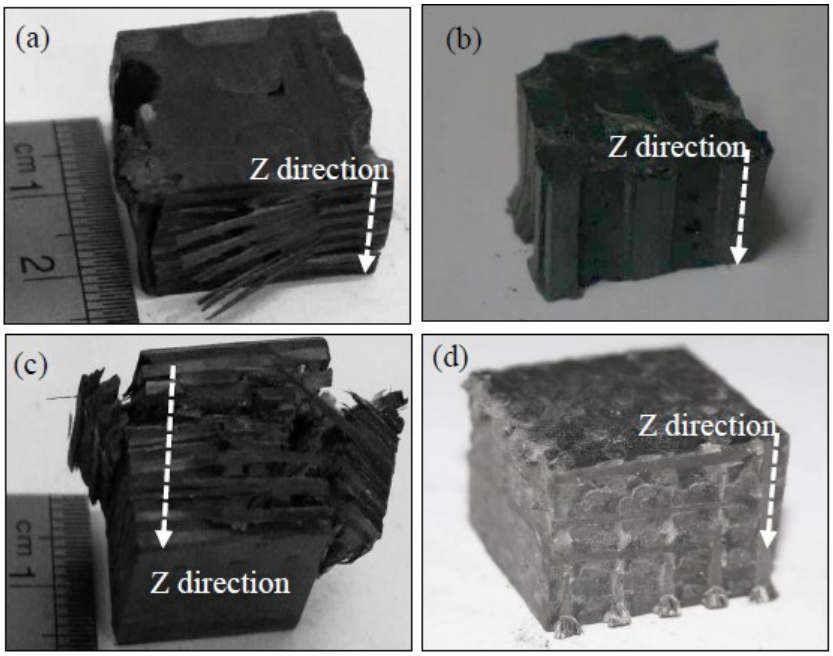
During the z-direction compression test, the guide sleeves performed significantly different deformability to fibres and resin matrix. When the diameter of guide sleeve is 6mm(as shown in figure 2(a)), the stress-strain curves show bigger slope during elastic deformation stage than samples with finer guide sleeve(as shown in figure 2(b)). Furthermore, the plastic deformation of samples with larger size guide sleeves appeared earlier than samples with finer guide sleeves. Therefore, the fractures of guide sleeves play a key role in compression fracture mode of 3D woven composites. Figure 3 shows the compression deformation behaviour s of guide sleeve. When the diameter of guide sleeve is larger, the guide sleeve performed typical bulging, as shown in figure 3(a). Then with the microcracks extending along the interface of guide sleeve and resin matrix, the compression fracture modes are mainly matrix cracking, guide sleeve/matrix debonding and fibres fracture. When the diameter of guide sleeve is smaller, the guide sleeves disperse compressive stress homogeneously to whole sample as the main bearing structures. Thus the samples with finer guide sleeves show high modulus of z-direction compression. The fracture mode of guide sleeves with smaller diameter changes to shear fracture by combined action of compressive stress and shear stress, as shown in figure 3(b). However the compression strength increase with increasing deformation energy by fracture mode transformation of guide sleeves.



(a) (b)

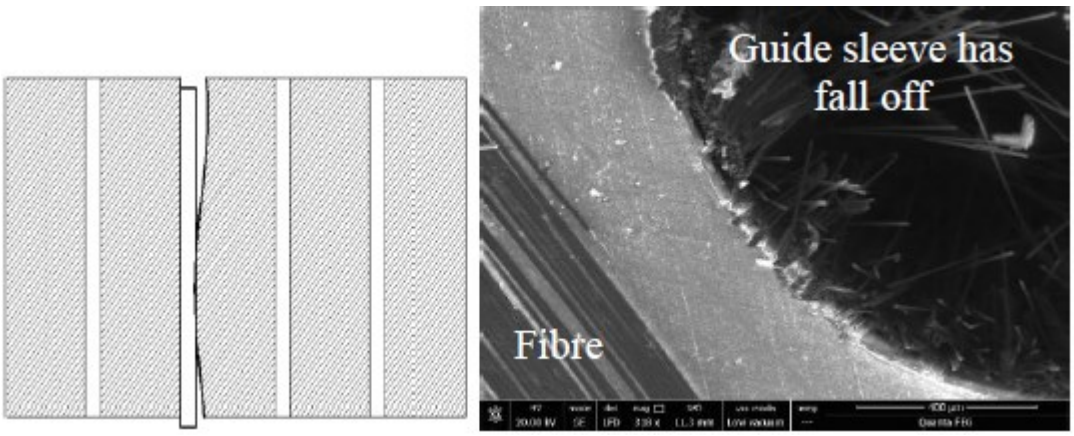
Figure 3. Sketch of compressive deformation of guide sleeve with different diameter

Figure 4 shows the fracture figures of z-direction compression samples. The guide sleeve is the main bearing structure of 3D woven composites during z-direction compression test. The compression behaviour performed a coordinating deformation relation during the initiation of loading [12]. When the guide sleeve is larger, bulging is the typical performance. The microcrack occurs in the interface of guide sleeve and resin matrix for the stress concentration. At this point, the main fracture mode of guide sleeve is guide sleeve/matrix debonding. In some case, guide sleeves located in the surface could fall off resin matrix, as shown in figure 4(a).

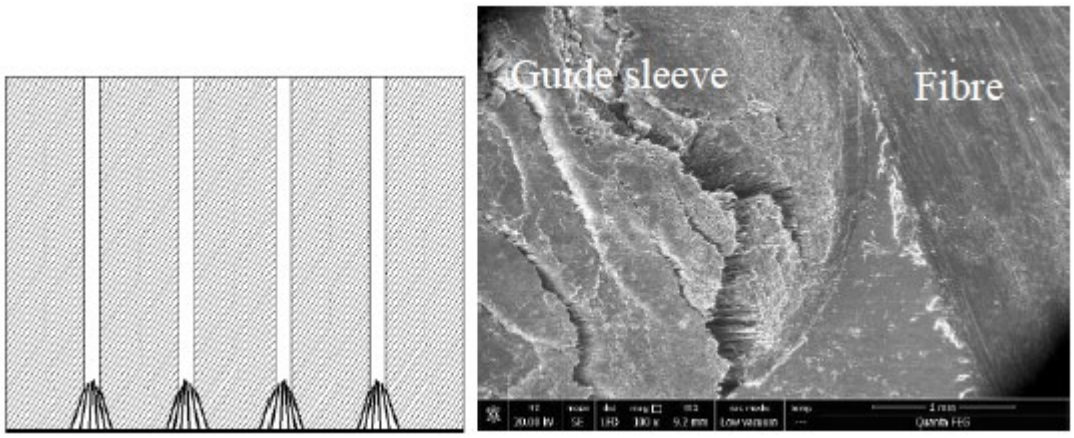


(a) Sample S6-4.5, (b) sample S6-3, (c) sample S1.5-4.5, (d) sample S1.5-3
Figure 4. Fracture figures of z-direction compression

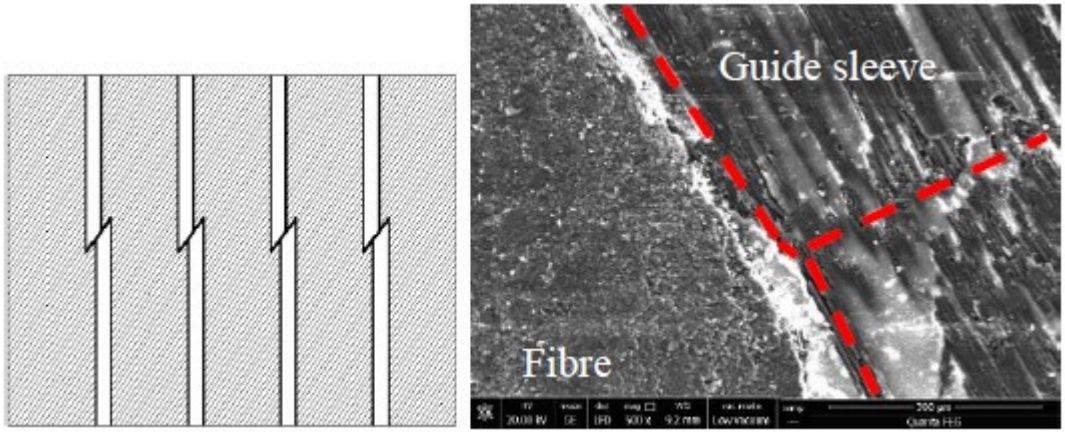
The guide sleeve is the main bearing structure in most case with setting along the thickness direction of samples. The main stress was compressive stress during compression test. Therefore the fracture mode of axial cracking (seen in figure 4(b)) is the typical failure mode of guide sleeves, which were shown in most fracture figures of samples. When the diameter is smaller, the guide sleeves performed feature of shear fracture) by the stress concentration at the crack tips. Then the compressive stress extends to fibres. The samples with finer guide sleeves appeared the obvious reduction in thickness (seen in figure 4(d)), even compressive crushing (seen in figures 4(c)). It means there must be rational design of diameter, center distance and other parameters for guide sleeve array, with aiming to maintain the max strength of fibres by avoiding buckling or torsion.



(a)



(b)



(c)

(a) Guide sleeve/matrix debonding, (b) axial cracking, (c) shear fracture
Figure 5. Compression fracture modes of guide sleeves

In conclusion, during the compression test the guide sleeves set along the thickness direction appeared three different fracture modes: guide sleeve/matrix debonding, axial cracking and shear fracture. Then the z-direction compression fracture modes of 3D woven composites with guide sleeves are as follows (1) matrix cracking and guide sleeve/matrix debonding, guide sleeve fall off in some case. (2) Axial cracking of guide sleeves, the guide sleeve were used to be the main bearing elements under the z-direction loading. Thus the axial cracking of guide sleeves is always along with compression fracture. (3) The fracture of fibre and guide sleeves, the guide sleeves with smaller diameter failure by shear fracture under combined action of compressive stress and shear stress.

4. Conclusion

1. During the z-direction compression testing, guide sleeves were the main bearing structures. The deformational behaviours of 3D woven composite with guide sleeves show the features of plastic deformation.

2. The main fracture modes of guide sleeve include guide sleeve/matrix deboning, axial cracking and shear fracture.

3. The compression failure mode of guide sleeve changed from guide sleeve/matrix deboning to mixed mode with shear fracture and axial cracking. That improved compressive fracture strength of 3D woven composites with guide sleeves.

5. Acknowledgments
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