CAN WE PROPERLY MEASURE THE COMPRESSIVE BEHAVIOUR OF COMPOSITES WITH HIGH-PERFORMANCE POLYMER FIBRES?

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Abstract

High-performance polymer fibres offer excellent tensile properties, but poor compressive properties. This study was set up to better understand the compressive performance of the composite made of these fibres. Aramid, polyester polyarylate (PAR) and polybenzobisoxazole (PBO) epoxy composites were therefore manufactured and tested in shear-loaded compression. Results showed early onset of yielding in these composites and the need for a short gauge length to avoid buckling. Finite element models were set up to predict buckling and stress concentrations. These models yielded vital information on the validity of the compressive test results. Firstly, they confirmed that short gauge lengths are required to avoid buckling. Secondly, the stress concentrations at those gauge lengths are significant, which strongly limits the accuracy of the measurements. This clearly shows that shear-loaded compression tests are not suitable to reliably test the compressive response of composites reinforced with high-performance polymer fibres.

1. Introduction

High-performance polymer fibres offer a high tensile stiffness and strength at a low density [1]. They outperform glass fibres in tension, and in some cases even carbon fibres (see Table 1). The fabrics/composites made of these fibers offer high impact performance, both at high and low velocities, and excellent fire and chemical resistance [1]. Nevertheless, the number of structural composite applications is limited due to their inherently poor compressive properties. The compressive moduli of these fibres and their composites tend to be lower than their tensile modulus, and their compressive strength can be an order of magnitude lower than their tensile strength [2].

The two most well-known examples of high-performance polymer fibres are aramid and ultrahigh molecular weight polyethylene (UHMWPE). Aramid is well-known under its trade names Kevlar® and Twaron®, and UHMWPE under its tradename Dyneema®. Polyester polyarylate (PAR) and polybenzobisoxazole (PBO), known as Vectran™ and Zylon®, respectively, are two alternatives with excellent mechanical and functional properties.

Since the compressive performance of high-performance polymer fibres is poor compared to that of glass or carbon fibres, it has received significant attention. The measured values for the compressive modulus and strength of these fibres, however, vary strongly [3-5]. This is likely due to the different testing methods employed, and the intrinsic difficulties in reliable compression testing. An important aspect is the difference between the compressive properties of a single fibre versus those of the fibres inside a composite. The absence or presence of lateral support by the matrix may alter the compressive properties.

This paper therefore investigates the compressive behaviour of high-performance polymer fibres inside an epoxy matrix. The composites will be tested in shear-loaded compression tests, and a finite element model will be developed to analyse the effect of buckling and stress concentrations on the test results.

2. Materials and methods

2.1. Materials

Three fibre types were used: Twaron® 2200, Vectran™ HT and Zylon® HM. They will be referred to as aramid, PAR and PBO, respectively. The fibres were supplied in the yarn form with linear densities of 161, 167 and 164 tex, respectively. Their tensile properties are summarised in Table 1.

Table 1. Tensile properties of the high-performance polymer fibres according to their data sheets.

Technical name	Tradename	Modulus [GPa]	Strength [GPa]	Elongation [%]
Aramid	Twaron® 2200	110	3.3	2.1
PAR	Vectran™ HT	75	3.2	3.8
PBO	Zylon® HM	270	5.8	2.5

The epoxy used was a Sicomin SiPreg SR 8500 resin with a SiPreg KTA 313 hardener. The resin/hardener ratio was 100/21 by weight.

2.2. Composite production

The high-performance polymer fibre yarns were drum wound to produce prepregs. This process pulls the yarns through an epoxy resin bath at room temperature, and lays them down on a rotating and translating drum. After removing the prepregs from the drum, they were cut into sheets of 300x300mm and stored in a freezer at -18°C. 0° layups with 35 plies were then autoclaved. The specimens were cured at 60°C for 4 hours and postcured at 120°C for 2 hours. A vacuum pressure of -0.65 to -0.70 bar was maintained throughout the process. The overpressure of 3 bar was added as soon as the curing temperature of 60°C was reached. The fibre volume fractions of the cured panels were measured using light microscopy to be 50%, 51% and 52% for aramid, PAR and PBO composites, respectively.

2.3. Compression tests

The ASTM D3410 standard was followed to perform shear-loaded compression tests. The tests were performed on an Instron 5985 equipped with a 250 kN load cell. The specimens had a nominal width and thickness of 7 mm and 8 mm, respectively. Different gauge length were tried, but the final results were obtained for a 5 mm gauge length. The displacement rate was set to 0.5 mm/min, which corresponded to approximately 0.4%/min.

Random speckle patterns were added to the front and back surface of the specimens and pictures of both sides were taken every second. The average surface strain was then calculated using Vic2D-2009. The difference between the front and back strain was used to detect buckling of the specimen. The compressive modulus was calculated between 0.05% and 0.10% to ensure the measurements were performed in the linear regime.

Compressive failure was not achieved in the aramid/epoxy specimens due to severe slipping.

2.5. Finite element modelling

Two types of finite element models were developed: the first one is a model to analyse buckling, whereas the second predicts the stress concentrations due to the grips in the compression test. In both model types, the specimen was modelled as a homogeneous, transversely isotropic material with the engineering constants in Table 2. The longitudinal modulus E_3 was measured in the compression tests, whereas all others were estimated from the literature combined with micromechanical equations and the measured fibre volume fractions (see section "2.2 Production").

Table 2. Engineering constants of the unidirectional composites with high-performance polymer fibers. All values were normalised to a 50% fibre volume fraction.

Material	$E_1 = E_2$ [GPa]	E_3 [GPa]	ν_{12} [-]	$\nu_{13} = \nu_{23}$ [-]	G_{12} [GPa]	$G_{13} = G_{23}$ [MPa]
Aramid/epoxy	2.7	40.9	0.44	0.0046	1.54	1.50
PAR/epoxy	1.2	26.3	0.52	0.0046	1.50	1.13
PBO/epoxy	2.7	61.7	0.60	0.0046	1.50	1.00

The buckling model used linear C3D8R elements with hourglass control. Pinned-pinned boundary conditions were applied, as they are considered to be more appropriate than fixed-fixed boundary conditions [6]. The boundary conditions in the experiments lie somewhere in between the two. The non-linear compressive behaviour of the composite was included by iteratively replacing the compressive modulus by the tangent modulus in steps of 1 MPa. The simulations were run to determine the stress level, at which using the corresponding tangent modulus led to buckling. The buckling gauge length was identified as the shortest gauge length at which this phenomenon occurred.

The stress concentrations model used quadratic C3D20R elements, and explicitly modelled the steel grips (see Figure 1). A gripping pressure of 1 MPa was applied with a friction coefficient of 0.7. Hard contact was enforced by the augmented Lagrange constraint enforcement method. Models were run at 200 mm to estimate the Saint-Venant stress decay length (see Figure 1) and 5 mm to correspond to the experiments. These models only took into account the linear elastic response of the composites.

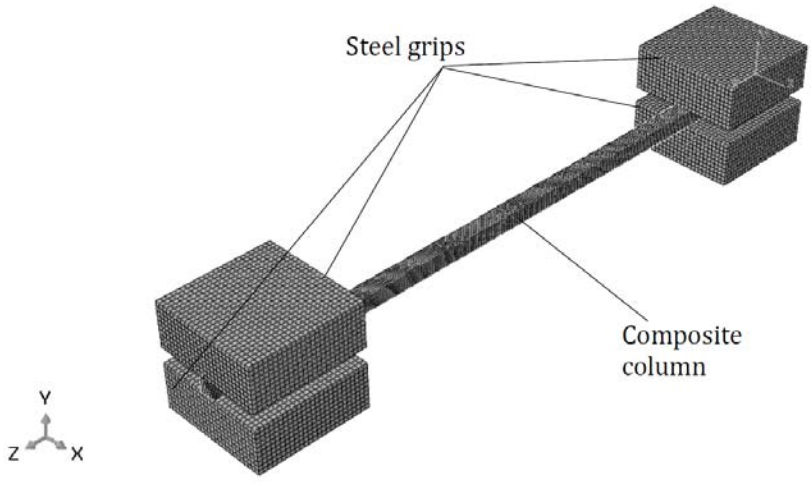

Figure 1. 3D view of the finite element model with a gauge length of 200 mm. This model was used to calculate stress concentrations due to the grips.

3. Results

3.1. Compressive behavior

The compression specimens buckled when the gauge length was 10 mm or higher. Buckling was successfully avoided at a 5 mm gauge length for PAR/epoxy and PBO/epoxy. Aramid/epoxy required higher compressive stresses, which resulted in slipping in the grips. Figure 2 presents representative stress-strain diagrams, revealing that compressive yielding occurred at low compressive stress levels. The compressive modulus of the aramid, PAR and PBO composites were 40.9 $\pm$ 3.8 GPa, 26.2 $\pm$ 2.3 GPa and 64.2 $\pm$ 8.3 GPa, respectively. Note that these values are slightly different from those in Table 2 due to normalisation to 50% fibre volume fraction in the table.

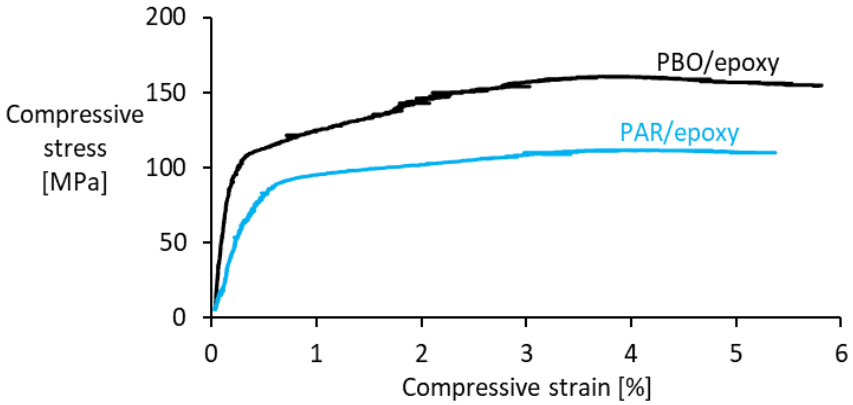

Figure 2. Compressive stress-strain diagrams of PBO/epoxy and PAR/epoxy revealing their poor compressive performance.

3.2. Finite element modelling

The buckling calculations for PAR/epoxy and PBO/epoxy showed that buckling is expected to occur prior to compressive failure from gauge lengths above 15 mm. This could not be confirmed for aramid/epoxy, as the calculations required the compressive stress-strain diagram. The predicted buckling gauge length corresponds reasonably well to the experimental findings, where gauge lengths of less than 10 mm were required to prevent buckling.

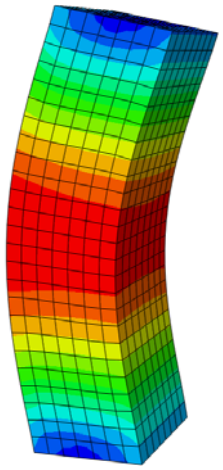

Figure 3. Example of the finite element model predicting buckling for gauge lengths below those predicted by the equation in ASTM standard D3410**.**

The 5 mm gauge length did not satisfy the Saint-Venant principle for avoiding stress concentrations due to the grips. To check the effect that this may have on the measurements, finite element calculations were performed to determine at which distance from the grips the stress concentrations revert down to less than 1%. **Table 3** summarises the results for three different parameters of stress within the cross-section: the average circumferential stress, the average stress at the back and front, and the maximum stress. All these lengths are significantly longer than half of the gauge length used in the experiments. This implies that the stress concentrations from both grips interact with each other, and there was no region of uniform stress in the middle.

Table 3. Distance from the grips after which the stress concentrations drop below 1% in a model with a 200 mm gauge length.

	Average circumferential stress	Average stress at front and back	Maximum stress
Aramid/epoxy	8 mm	10.5 mm	13 mm
PAR/epoxy	6.5 mm	9.5 mm	11 mm
PBO/epoxy	17 mm	22.5 mm	24 mm

The experimental gauge length of 5 mm was therefore clearly too short to achieve a uniform stress state. Since this can influence the accuracy of the measurements, the model for stress concentrations was then run at the experimentally used gauge length of 5 mm. The results were processed in the same way as in the experiments: by using the strain measured at the back and front of the specimen. This calculation underestimated the compressive modulus by 22%, 19% and 34% for aramid/epoxy, PAR/epoxy and PBO/epoxy, respectively. A similar underestimation would be expected for the experimental measurements, which highlights the fact that the experiments cannot be performed reliably in a shear-loaded compression test. The underestimation is most severe for PBO/epoxy, as this composite was the most anisotropic composite (see Table 2).

4. Conclusions

Compressive tests were performed on aramid/epoxy, PAR/epoxy and PBO/epoxy composites. The aramid/epoxy composites slipped in the grips and their compressive failure could not be tested properly. The tests on PAR/epoxy and PBO/epoxy confirmed the poor compressive performance of these composites. At the gauge lengths required to avoid buckling, however, the stress concentrations were significant. It takes between 6.5 and 24 mm for the stress concentrations to drop below 1% of the nominal stress, showing that the 5 mm gauge length is too short. Using the finite element models, it was revealed that the compressive modulus was underestimated by 19% to 34%. A larger anisotropy results in a larger underestimation. These results show that the shear-loaded compression tests are not capable of reliably measuring the compressive response of this type of composites. Other testing approaches, such as the sandwich beam method, need to be tried to assess whether they can overcome these limitations.

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