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Editorial

This collection contains the proceedings of the 21st European Conference on Composite Materials (ECCM21), held in Nantes, France, July 2-5, 2024. ECCM21 is the 21st in a series of conferences organized every two years by the members of the European Society of Composite Materials (ESCM). As some of the papers in this collection show, this conference reaches far beyond the borders of Europe.

The ECCM21 conference was organized by the Nantes Université and the Ecole Centrale de Nantes, with the support of the Research Institute in Civil and Mechanical Engineering (GeM).

Nantes, the birthplace of the novelist Jules Verne, is at the heart of this edition, as are the imagination and vision that accompany the development of composite materials. They are embodied in the work of numerous participants from the academic world, but also of the many industrialists who are making a major contribution to the development of composite materials. Industry is well represented, reflecting the strong presence of composites in many application areas.

With a total of 1,064 oral and poster presentations and over 1,300 participants, the 4-day event enabled fruitful exchanges on all aspects of composites. The topics that traditionally attracted the most contributions were fracture and damage, multiscale modeling, durability, aging, process modeling and simulation and additive manufacturing.

However, the issues of energy and environmental transition, and more generally the sustainability of composite solutions, logically appear in this issue as important contextual elements guiding the work being carried out. This includes bio-sourced composites, material recycling and reuse of parts, the environmental impact of solutions, etc.

We appreciated the high level of research presented at the conference and the quality of the submissions, some of which are included in this collection. We hope that all those interested in the progress of European composites research in 2024 will find in this publication sources of inspiration and answers to their questions.

Each volume gathers contributions on specific topics:

- **Vol 1. Industrial applications**
- **Vol 2. Material science**
- **Vol 3. Material and Structural Behavior – Simulation & Testing**
- **Vol 4. Experimental techniques**
- **Vol 5. Manufacturing**
- **Vol 6. Multifunctional and smart composites**
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THE INVESTIGATION OF SHEAR RESPONSE OF EPOXY MATRIX UNDER UNIFORM COMPRESSION

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Keywords: combined compression-shear test, composite matrix characterisation, uniform compressive strain

Abstract

The compression behaviour of unidirectional carbon fibre/epoxy composites is significantly related to the material instability which leads to the formation of fibre kinkbands. At high fibre volume fractions, this instability results from the polymer matrix which is sheared due to the misalignment of the compressed fibres, culminating in yielding or fracture of the matrix or failure at the matrix-fibre interface. The combined compression-shear test has been proposed to characterise the shear response of the matrix. However, it was found that non-uniform compressive strain was developed and thus the specimens were yielded at lower shear stress. In this study, the shear response of an epoxy polymer matrix under uniform compression deformation was investigated with the modified endcap design. Hollow, thin-walled Prime 37 epoxy specimens were manufactured by machining from cured cylinders. Experimental results showed that the specimens exhibited uniform compressive strain and shear strain in the gauge section. The average yield stress (48.2 MPa) and the shear modulus (1.3 GPa) of the compressive-shear specimens with the modified endcap design were measured. The data collected in these tests will be used in finite element (FE) modelling to explore how the compression behaviour of unidirectional composites can be improved.

1. Introduction

Unidirectional carbon fibre/polymer matrix composites exhibit excellent mechanical properties and thus are widely used in structural applications. However, these materials show poor mechanical performance upon axial compression due to the material instability and internal defects leading to kink-band formation [1]. Such instability could arise from within the polymer matrix, since the matrix between adjacent fibres will be subjected to a combined compression-shear loading until the onset of yielding [2]. Experimental and FE results from notched compression test have showed that the formation of a kink band is associated with matrix yielding by shearing which leads to the development of matrix microcracks, splitting and shear bands [3-4]. Later, an analytical model of the fibre kink-band formation with matrix shearing was proposed [5]. Moreover, a study of the composite strength prediction by considering fibre kinking and matrix shearing when subjected to combined axial compression and in-plane shear deformation has been conducted and showed that the kink-band formation is related with the shear response of the matrix [6]. It is therefore critical to understand the shear behaviour of the polymer matrix under combined stress conditions. This could be used for the development of a material constitutive model for the finite element modelling of carbon fibre composites [7]. However, in the previous work [8], the test result of an epoxy matrix under compression-shear test has shown that a

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significant variation in compressive strain in the gauge section of the specimens was observed, which was believed to have arisen due to the nonuniformly stress state globally in the specimen gauge section and thus yielded at lower shear stress.

Therefore, the aim of this study was to investigate the compression-shear behaviour of polymer matrix subjected to uniform compressive stress. This study initially examined the uniformity of the compressive strain over the gauge section of the specimens and then measured the shear modulus, shear yield stress and strain, and the post-yielding behaviour of polymer matrix. For this purpose, we proposed modified endcap fittings that improve compressive strain uniformity in the test region of the specimens. Digital image correlation (DIC) system was used to measure the full-field compressive and shear strains of the polymer matrix.

2. Experimental Investigation

2.1. Materials

Prime 37 epoxy resin and slow-curing hardener supplied by Gurit were used in this study. The epoxy resin and hardener were supplied in the liquid form. As shown in the manufacturer's datasheet [9], the elastic modulus of the cured epoxy is 3.2 GPa and the density is 1.1 g/cm^3.

2.2. Specimen Preparation

For the Prime37 specimens, the epoxy resin and hardener were mixed at the ratio recommended by the epoxy manufacturer, and then degassed in vacuum until no apparent air bubbles were seen. The mixture was then cast into cylinders (25.4 mm in diameter and 53 mm in length) using metal moulds. The epoxy was cured at 21°C for 24 hrs, followed by post-curing at 50°C for 16 hrs in a temperature-controlled oven with the use of a thermocouple, in accordance with the manufacturer's recommended curing procedure.

The Prime 37 solid cylinders were machined to form the hollow, cylindrical configuration with a thin-walled test section shown in Figure 1. The gauge section had outer diameter of 20.6 mm and an inner diameter of 19.6 mm, resulting in a nominal wall thickness of 0.5 mm.

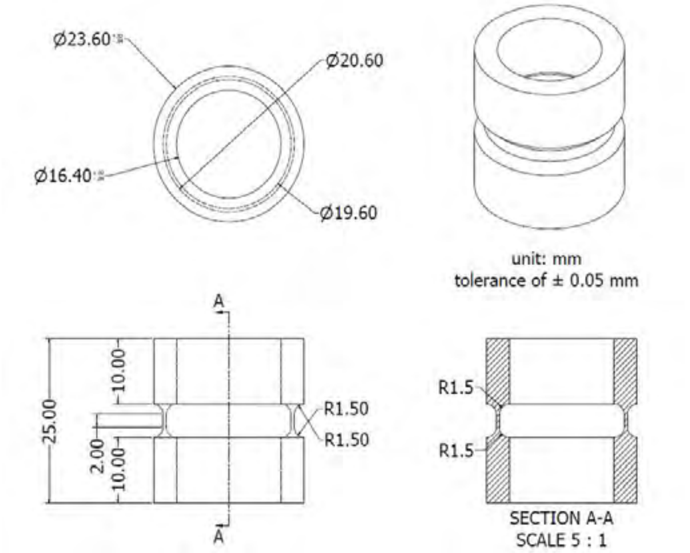

Figure 1. The drawing of the hollow, thin walled Prime 37 specimens for combined compression-shear tests.

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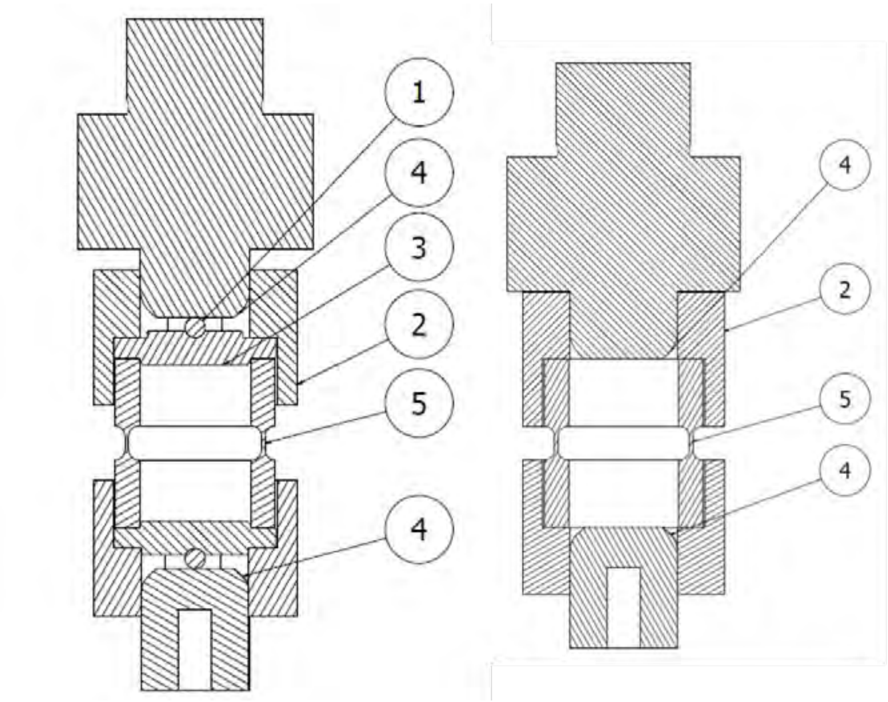
The manufactured specimens were CT-scanned to measure the actual wall thickness which was determined to be 0.51 ± 0.02 mm. The ends of these specimens were bonded with steel plates which contain a circular dimple to locally position a ball bearing to allow self-alignment whilst also transferring the compression force uniformly to the specimen. They were then bonded with stainless-steel endcaps (for application of a torque loading) using an epoxy adhesive which was cured at room temperature for 16 hrs, followed by post-curing in the oven at 80°C for 1 hr. Figure 2 shows the cross section of the compression-shear specimen with the steel plate, ball bearing and endcaps (i.e. the modified endcap design). The endcap contains a hexagonal hole which engaged with a hexagonal nut feature on the test fixture connected to the test machine. The hexagonal nut transmits the axial and torsional loads to the test region of the specimens. The use of the ball bearing helps to achieve good alignment of the compression load with the axis of the specimen.. After this, the gauge section of the specimens was sprayed with a thin white primer layer and then speckled in black using an airbrush, for DIC measurement. The specimens were kept in a desiccator prior to testing.

As a comparison, compression-shear specimens bonded with original endcap design [8] were also prepared.



Part	Name
1	Ball bearing
2	Endcap
3	Compression plate
4	Hex nut
5	Prime 37 specimen

(a) (b)

Figure 2. The drawings of the compression-shear specimen with (a) the modified endcaps and (b) the original endcaps.

2.3. Test Procedure

Compression-shear tests were conducted on an Instron Electropuls E10000 fitted with a 10 kN axial and 100 Nm torsional load cell. Figure 3 shows the test setup. Compression force of 660 N (i.e. compression stress of approximately 20 MPa), was applied to the specimens in 60s without the application of torsional loading. (This applied compression stress was well within the elastic regime of the material.) Once stabilized, the specimens were loaded in torsion at 0.1°/s (whilst under the compression force) until failure. Stereo DIC fitted with two 16 mega-pixel cameras was used to measure the full-field compressive (ε_{yy}) and shear strain (γ) of the specimens. Five specimens were tested.

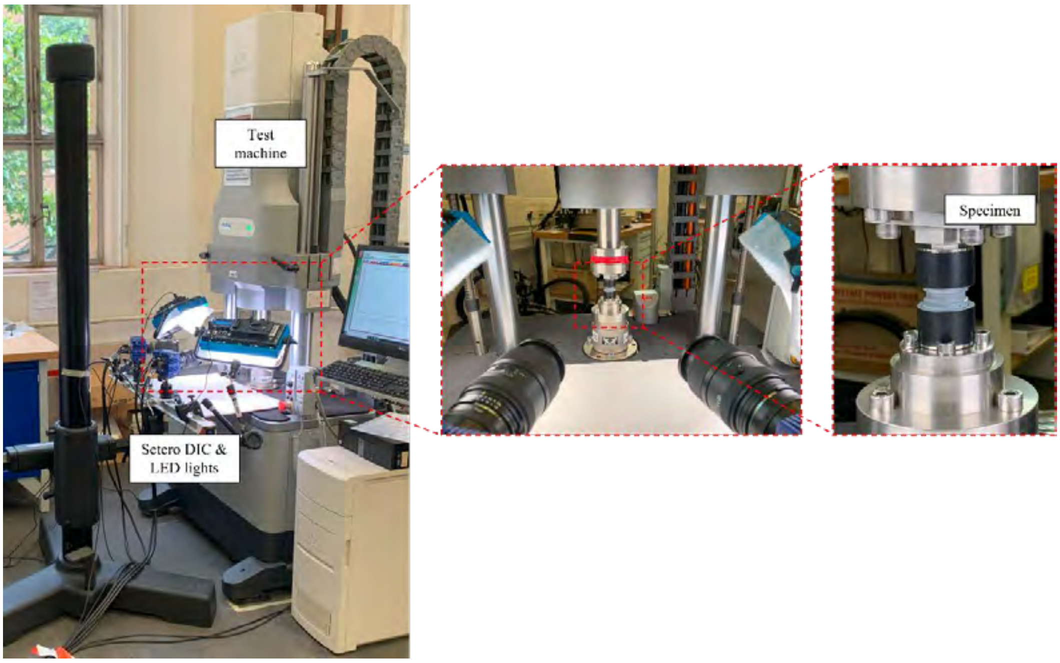


Figure 3. The compression-shear test setup.

The shear stress (τ) was determined from the measured torque (T) using the thin-walled tube equation (1)

$$\tau = \frac{T}{2\pi\bar{r}^2 t}. \tag{1}$$

where $\bar{r}$ = radius at the mid-section of the thin wall and t = wall thickness of specimens.

The engineering shear strain is given by equation (2)

$$\gamma = 2 \times \varepsilon_{xy}. \tag{2}$$

where ε_{xy} is the shear strain tensor from DIC.

The shear modulus (G) of the material is determined from the slope of the shear stress-shear strain plots in the shear strain range of 1% - 3%.

3. Results and Discussion

Figure 4 shows the compressive stress-strain curves of a Prime 37 specimen when the specimen was subjected to axial compression load (i.e., the initial 60 seconds). (The compressive strain was extracted at closed to the upper edge of the constant wall thickness region where localised shear yielding was observed.) It shows that the compressive stress-strain curves across the test section are consistent with a standard deviation of ± 0.01%. The inserted DIC images of the full-field compressive strain was uniform across the width of the specimen in the gauge section the test section of the specimen. However, a strain concentration was observed at the upper and lower edges beyond the test section. This was caused by inaccurate machining of the radii in these locations. The elastic modulus of the specimen from these measurements is 3.2 GPa and is consistent with the value from the manufacturer’s datasheet.

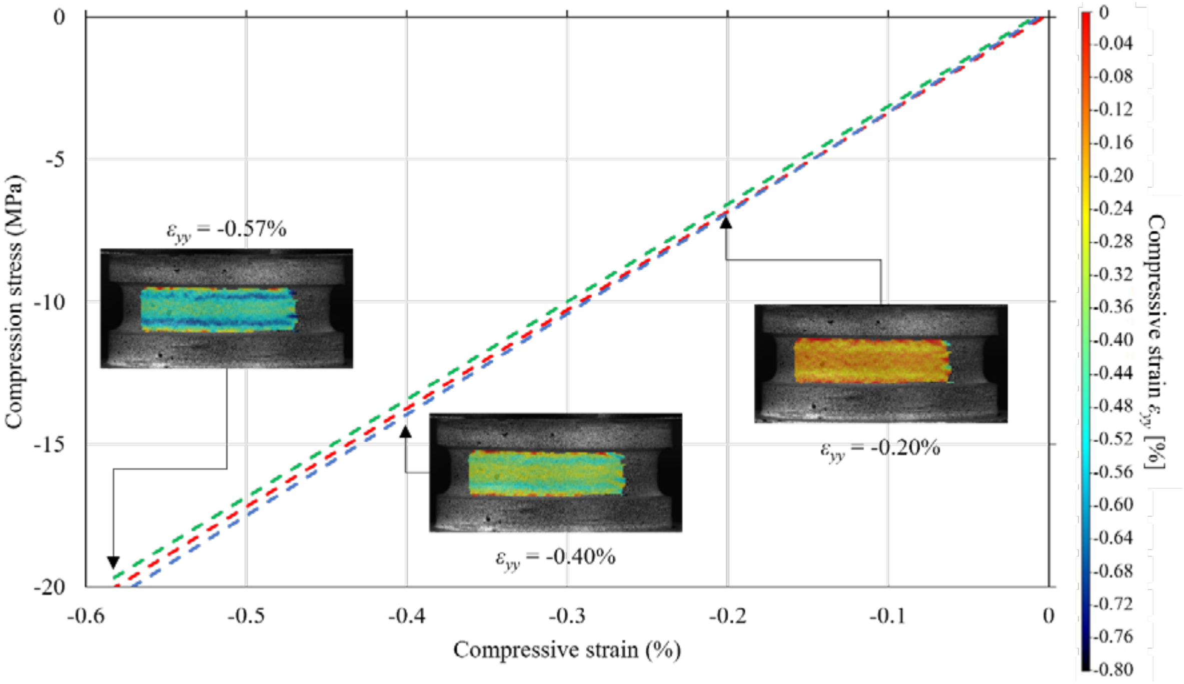


Figure 4. The compressive stress-strain plot of a Prime 37 specimen with the modified endcaps subjected to axial compression load.

Figure 5 plots the shear stress as a function of shear strain of the specimen upon shear deformation through torsion. The figure shows that the specimen exhibits an initially linear shear stress-strain curve, which then yields reaching a maximum stress before a short strain softening stage and then forms a stable plateau, and which is followed by strain hardening stage prior to the formation shear cracks. The yield strength, using a 0.2% offset according to the ASTM D638 standard [10], is 46.8 MPa at the shear strain of 3.6%. The peak stress at the yield point is 67.3 MPa and the associated strain is 8.9%. The shear modulus of the specimen determined between 1% to 3% shear strain is 1.26 GPa. The inserted DIC images at different shear strains showed that the shear strain was in general uniform at the section of the constant wall thickness and later localised yielding was observed. (Therefore, the shear strain was measured closed to the upper edge of the constant wall thickness region.) Again, a strain variation is captured at the upper and lower edges beyond the constant wall thickness region.

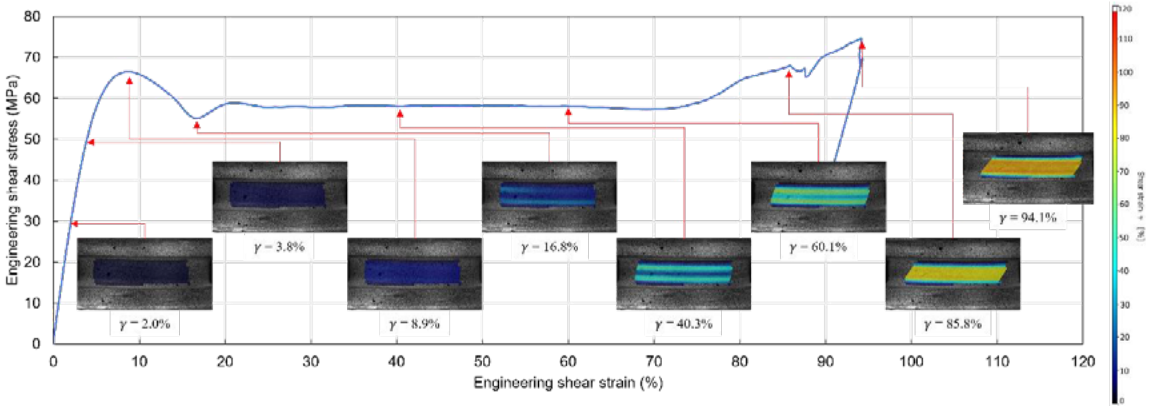


Figure 5. The shear response of the Prime 37 specimen with the modified endcaps subjected to torsional deformation at the applied compressive stress.

Table 1 summarises the average shear modulus, yield stress and strain, peak shear stress at the yield point and shear stress at fracture of the compression-shear specimens with the modified endcaps and with the original endcaps. It can be seen that the shear modulus of the specimens with the modified endcaps are higher by 20% than that of the specimens with the original endcaps and the reason for this will be investigated. Moreover, the specimens with the modified endcaps yielded at higher stress (48.2 MPa) than the specimens with the original endcaps. However, a slightly lower shear yield strain of the specimens with the modified endcaps was observed, and further investigation is needed. Upon fracture, the specimens with the modified endcaps exhibited a more significant strain hardening effect. It seems that the uniform compressive deformation delayed the fracture of the specimen.

Table 1. The shear properties of the Prime 37 specimens bonded with modified and original endcap designs.

Specimens	Average shear modulus (GPa)	Average yield stress (MPa)	Average yield strain (%)	Average peak yield stress (MPa)	Average fracture shear stress (MPa)
Specimens with modified endcap	1.3 (± 0.07)	48.2 (±2.59)	3.5 (± 0.22)	66.1 (±2.01)	77.4 (±3.10)
Specimens with original endcap	1.1 (± 0.06)	39.9 (± 3.18)	3.8 (± 0.06)	52.1 (± 1.05)	64.6 (±2.79)
% difference	+20.8%	+20.6%	-6.4%	+26.9%	+19.8%

4. Conclusions

In this work, the shear response of an epoxy resin subjected to the compression-shear test with the development of uniform compressive deformation via the modified endcap design has been investigated. The uniform shear deformation were achieved in the gauge section of the constant wall thickness of the specimens. The uniform compressive deformation resulted in the improvement of the yield shear stress and a more significant strain hardening effect prior to final fracture. The data collected in these tests will be used in FE modelling to explore how the compression behaviour of unidirectional composites can be improved.

The next step is to test the Prime 37 specimens with the modified endcap design in pure-shear test to examine whether the applied uniform compressive deformation affects the shear deformation response of the material.

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