EFFECT OF THROUGH-THICKNESS COMPRESSIVE STRESS AND POROSITY ON THE TENSILE STRENGTH OF CARBON-FIBRE REINFORCED COMPOSITES

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ABSTRACT

Low and high-porosity cross-ply CFRP specimens are manufactured by modifying the autoclave curing cycle. A custom compression setup is designed and integrated with an electromechanical tensile rig to allow biaxial testing of the material. Tensile strength of the specimens is tested at different levels of applied through-thickness compression. A reduction of tensile strength due to through-thickness compression is observed. This effect is magnified by the presence of porosity. The ply level stress state is analysed through a three-dimensional finite element contact simulation.

1 INTRODUCTION

Understanding the mechanical behaviour of fibre-reinforced composites under multiaxial loads is important for their applications in thick-walled and geometrically complex parts. Existing experimental results suggest that through-thickness compression can significantly reduce the tensile strength in the fibre direction [1, 2].

Voids are perhaps the most widely studied type of defects in composites [3]. Nonetheless, little is known about their influence on composite strength under multiaxial loading conditions. This type of loading could be potentially relevant in case of thick-walled filament-wound pressure vessels, which are known to have a significantly more irregular microstructure than that obtained through other methods, e.g. prepregging. In particular, mesoscale voids elongated along fibre direction are commonly observed [4].

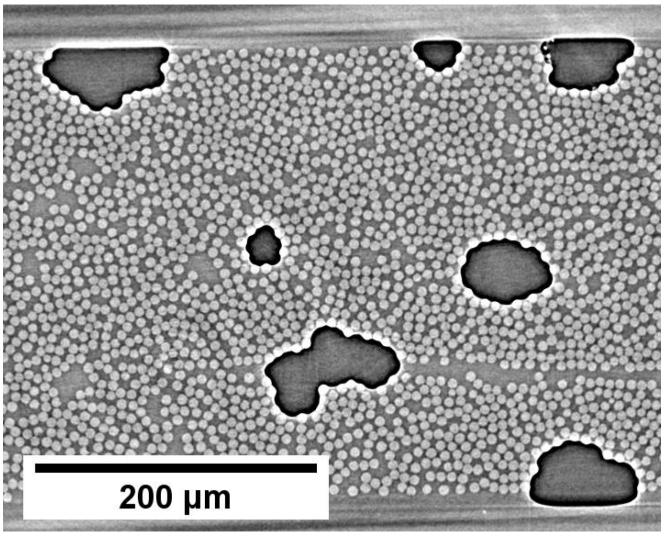

Figure 1: CT view of a cross-section of a highly porous CFRP laminate.

The study described here aims at evaluating the effect of multiaxial stresses on the tensile strength of highly porous carbon fibre-reinforced composites. The response of a carbon-fibre reinforced polymer to a combination of longitudinal tension and through-thickness compression is studied. In addition to a reference low-porosity material, highly porous laminate specimens were manufactured and tested to assess the influence of voids on the material strength under these conditions.

2 MATERIAL

Carbon/epoxy laminate plates of dimensions 30 cm × 30 cm and a stacking sequence $[0/90_2/0]_{2S}$ were manufactured by manual lay-up using an airspace-grade preimpregnated unidirectional tape HexPly 6376C-HTS(12K)-5-35%, with a longitudinal tensile strength of approximately 2500 MPa. After being placed in the stack, each ply was manually rolled to remove excess air. Next, the plates were autoclave-cured. Reference plates (from now on referred to as non-porous) were made following the manufacturer-recommended cycle. Temperature was ramped up to 175 °C over 65 min. Then, it was held constant for 150 min, before starting the cool-down phase. Throughout the process, a vacuum and a 7 bar overpressure was maintained. Highly porous plates were manufactured by modifying the cycle explained above. The temperature was the same as for the reference case. Vacuum was maintained throughout the cycle. However, no overpressure was applied. Low curing pressure is known to lead to formation of voids in fibre-reinforced composites and a similar approach has been used by other authors to obtain a highly porous material [5, 6].

Figure 1 shows a detail of a porous specimen observed using micro-computed tomography. The voids are strongly elongated along the fibre direction, and their cross-sectional dimensions are typically significantly larger than fibre diameter. The voids in the manufactured plates were not uniformly distributed. The highest porosity was usually present near the mid-thickness line. Typically, the porosity fraction observed through optical microscopy was in the order of 5%, although it varied significantly between specimens.

The laminate plates were cut down into rectangular specimens of dimensions 250 mm x 10 mm. The average thickness of the specimens was equal to 2.15 mm for the non-porous and 2.20 mm for the porous ones. Glass/epoxy end tabs of 60 mm length were used to reduce stress concentrations at the tensile machine grips.

3 METHODS

3.1 Tensile testing

The specimens described in the previous section were tested in tension on an electromechanical rig, at a constant cross-head speed of 1mm/min. Selected specimens had their edge polished to allow in-situ observation of damage development at the micro and mesoscale. These specimens were loaded in tension with several intermediate hold phases. During those, an approximately 30mm long section of the edge was mapped using a motorized digital microscope, allowing observation of damage development. For a single porous specimen, the microscope was focused on an approximately 0.75 mm × 0.75 mm region of the specimen edge, where the damage was then recorded in situ without interrupting the test, allowing a more detailed local observation.

3.2 Biaxial testing

A custom hydraulic compression system was developed to allow biaxial testing of the specimens. The requirements at the design stage were that the system be compatible with a standard tensile rig and portable. A motorcycle brake caliper with a load range up to 100 bar was used as a base of the system. A custom-designed indenter support is presented in Figure 2. The load is transferred to the specimens using cylindrical indenters with a 10 mm radius. The alignment of the indenters is controlled through the use of bearing-supported guiding rods.

The compression system described above was mounted on a tensile machine, with four counterweights on pulley blocks used to avoid passing additional loads on the specimens, as shown in Figure 3. To carry out biaxial tests, the compressive load was first applied. The tested pressure levels were 25, 50 and 100 bar. Once the desired pressure was reached, it was maintained using an automatic control unit. The specimen was then loaded in tension until failure at a cross-head speed of 1 mm/min.

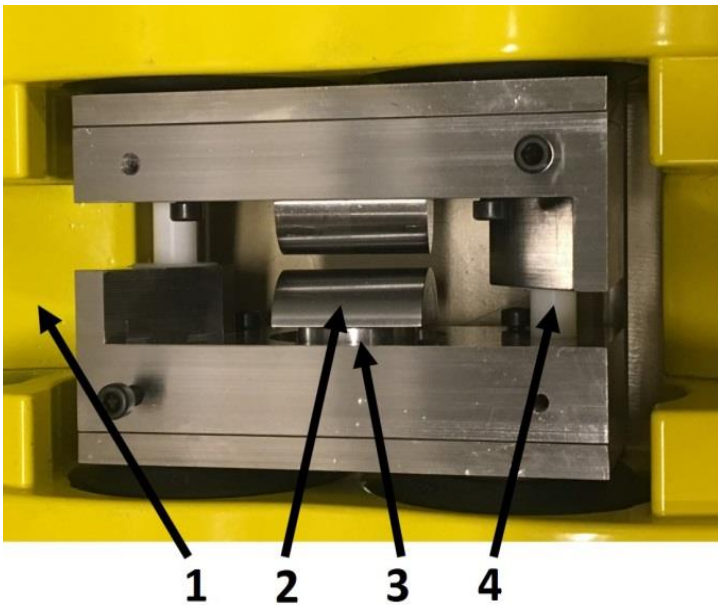

Figure 2: Custom compression setup components. 1) caliper body, 2) cylindrical indenter, 3) load cell, 4) guiding rod.

Figure 3: The compression system mounted on a tensile machine. The inclination of the caliper allows direct camera observation of the compressed specimen section.

3.3 Additional measurements

Several supplementary measurements were taken. A video acquisition setup was used during the biaxial tests to photograph the edge of the specimen in the compressed section every 2 seconds. The indenter displacement was automatically evaluated using in-house image analysis software, based on cross-correlation analysis. Furthermore, a speckle pattern was applied on selected specimens, and a DIC analysis was carried out using VIC-2D software. Contact area was measured at different pressure levels, using the method described by Gan et al. [1]. The contact area was measured at 25, 50, 75 and 100 bar for the non-porous specimens. For the porous ones, it was measured at 20, 40, 60 and 80 bar.

4 RESULTS

4.1 Tensile testing – mechanical properties

Mean tensile strength, strain and modulus are summarized in Table 2. The failure strain was very similar for the two studied materials. However, the highly porous specimens had a lower strength and modulus, by 7% and 6% respectively.

	Low porosity	High porosity
Strength	1044 MPa	972 MPa
Strain	1.49%	1.47%
Modulus	70318 MPa	66163 MPa

Table 1: Tensile test results for low and high-porosity CFRP.

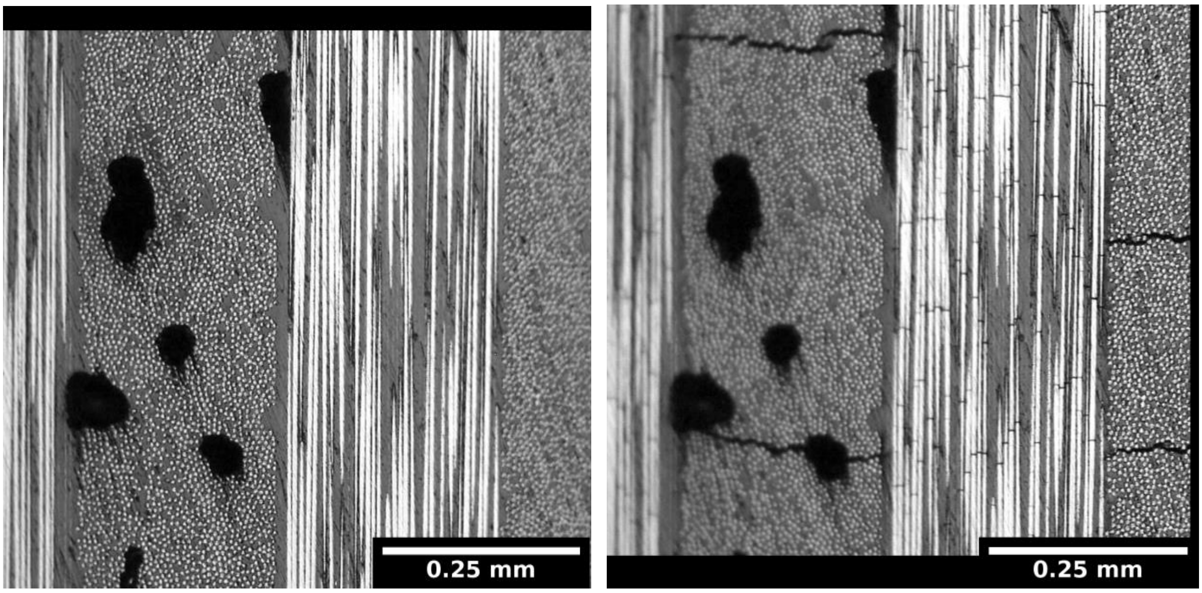

Figure 4: Damage development in a highly porous specimen under tension (applied vertically) observed in situ using a digital microscope. Pristine state (left) and shortly prior to failure (right).

Voids were seen to act as preferential crack origin sites in the transverse plies. The first observed cracks always appeared at the voids, at approximately 30% of the ultimate load. Only later did cracks appear elsewhere. The initial cracks at voids propagated over longer periods of time, while the cracks not passing through the voids appeared instantaneously. In the non-porous specimens, cracks started to appear later, at approximately 60% of the ultimate load and their density at failure was significantly lower. Figure 4 shows the development of transverse cracking and fibre breaks in a porous laminate subjected to tensile loading (in the vertical direction). The first image shows the pristine material, with several voids visible. The second image, taken shortly prior to failure shows several transverse cracks that formed in the cross-ply as well as numerous fibre breaks in the longitudinal ply.

4.2 Biaxal testing

The porous specimens all broke before reaching the maximum compressive load, on average at 84.8 bar. Figure 5 shows the average values of tensile strength at the different levels of applied through-thickness load. For the non-porous specimens, no decrease in tensile strength was observed at 25 bar of compression. For higher pressures, the average tensile strength decreased abruptly, being only 144 MPa at 100 bar. For the porous specimens, the decrease was even stronger. While in tensile tests they did not differ much from the non-porous ones, already at 25 bar they showed an approximately 20% lower tensile strength. This effect was even more pronounced at 50 bar, where the porous specimens were approximately 60% weaker. The porous specimen results were also characterized by a higher scatter.

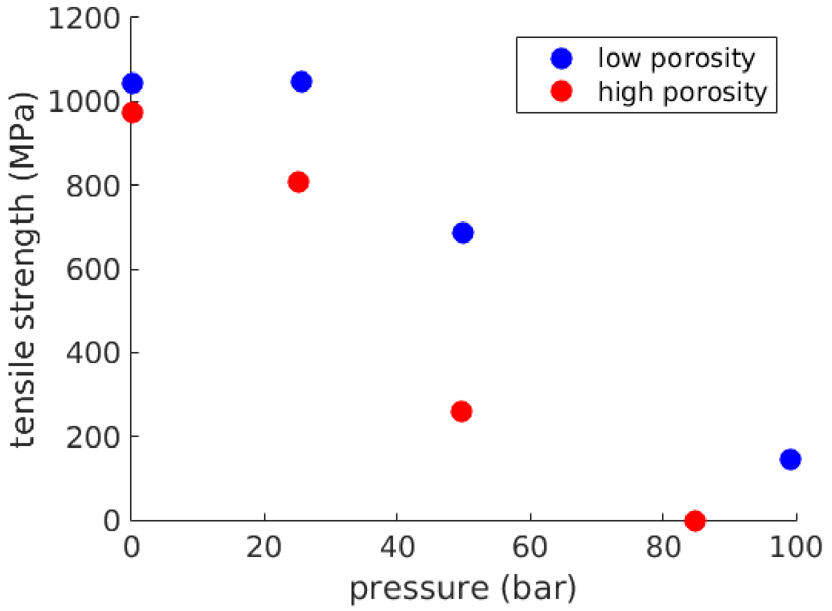

Figure 5: Average values of measured tensile strength as a function of applied compression.

5 FINITE ELEMENT ANALYSIS

Finite element simulations were carried out to compute the stress state in the low-porosity specimens subjected to biaxial loading. The simulations were carried out in an in-house finite element code Z-Set [7]. The composite was modelled using a transversely isotropic linear elastic material behaviour. Only a quarter of the specimen was meshed, taking advantage of the material symmetries. The indenter-to-specimen contact was modelled using a frictionless formulation. Displacement boundary conditions were applied at the top of the indenter (compression) and at the far end of the specimen (tension). A structured mesh of 8-node brick elements (C3D8) was used, with the mesh being most refined under the indenters.

Figure 6 shows the simulated stresses along a through-thickness line, joining the tips of the indenters at mid-width of the specimen. The applied pressure for the case was 100 bar, and the tensile load of 144 MPa was chosen based on the average value at which the non-porous specimens failed at this pressure level. The through-thickness compression leads to the appearance of axial tensile stress in the longitudinal plies. This stress is further increased after the tensile load is applied. However, even at failure it is still significantly lower than the uniaxial tensile strength.

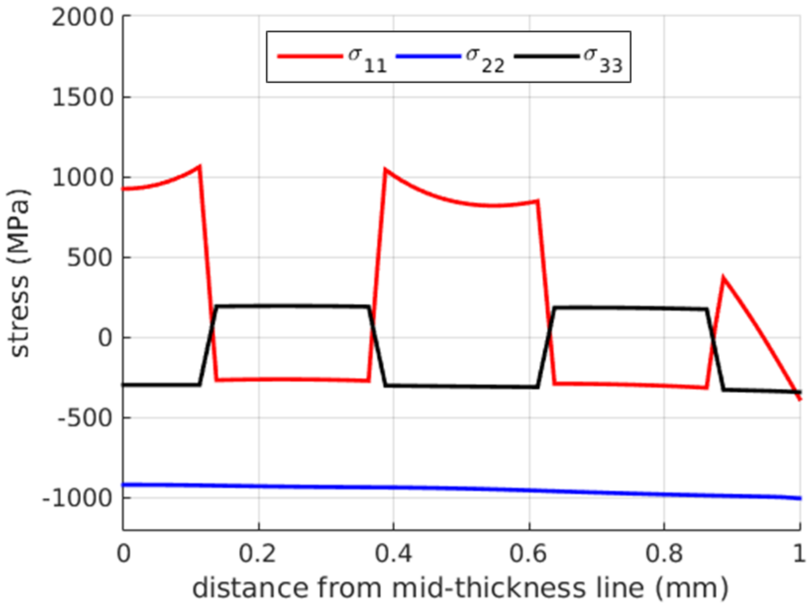

Figure 6: FEM simulation: principal stresses across thickness of a low-porosity specimen at 100 bar compression and 144 MPa applied tension. σ_{11} is oriented along the longitudinal direction, σ_{22} through the thickness of the specimen, and σ_{33} along the width.

6 CONCLUSION

The difference in tensile strength between the non-porous and porous specimens is limited and could be in part attributed to the lower effective volume fraction of porous specimens. This is further confirmed by an approximately proportional decrease in the modulus value. The transverse cracking process is much more intensive in the high-porosity specimens, with voids leading to local stress concentrations, accelerating crack formation.

The biaxial test results suggest that a uniaxial longitudinal strength criterion is not sufficient in the presence of important transverse compressive loads. For a through-thickness compression of 100 bar, the longitudinal plies can fail at a longitudinal tensile load of approximately 1000 MPa, more than two times lower than in the uniaxial case. While a mesoscale failure criterion based on a combination of the three principal stresses could be proposed, it is not clear what is the underlying microscale mechanism leading to the reduced tensile strength. The presented results demonstrate that mesoscale porosity can further strengthen the negative effect of through-thickness compression on the longitudinal tensile strength. This could be caused by local transverse stress concentrations caused by the presence of voids. In this case, the material response would strongly depend on the local void morphology (shape, size, orientation). This would also provide an explanation for the higher experimental scatter observed in porous specimens.

The approach presented allowed assessing the influence of a multiaxial stress state on the strength of a highly porous composite material. A custom compression setup was designed and manufactured, allowing biaxial testing on a standard tensile rig. Three-dimensional finite element analysis was carried out to simulate the stresses inside the specimens. The obtained results suggest that a compressive through-thickness stress negatively affects the longitudinal tensile strength of carbon-fibre reinforced composites. High porosity, although relatively benign under uniaxial longitudinal tension, was found to exacerbate the effect of through-thickness compression.

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