Measuring UD fibre direction compressive strength and the factors affecting it

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At a previous workshop it was proposed that the strength of a unidirectional fibre-reinforced composite should be defined as the maximum stress that the material can sustain under uniform uniaxial loading [1]. A second workshop discussed UD tensile strength [2] and we now consider the significantly more difficult question of how to measure UD fibre direction compressive strength and the factors affecting it.

First of all, it is clear that special care must be taken to avoid buckling. Consistent gauge section failures may in fact be initiated by overall buckling, which occurs at a much lower stress than the simple Euler equation would suggest due to the effect of shear deformation, and the substantial reduction in modulus with applied compressive strain in carbon fibre composites [3]. The obvious solution is to reduce the gauge length, which typically is of the order of 10 mm, but this causes the stress state to be non-uniform along the length, creating uncertainty about whether the obtained strength is representative of the behaviour of the same material under uniform stress. It is also important to eliminate bending which may be caused by transverse displacements between the grips of the test machine or non-uniformities in the tabbing.

There is also the question of whether to introduce the load by compression at the ends of the specimen or by shear. The latter is more straight-forward, but causes stress concentrations at the ends of the tabs. Also unlike in tension, shear stresses greatly reduce compressive strength, as has been shown in combined compression and torsion tests on tubes, Fig. 1. In conventional specimens loaded through tabs, interlaminar shear stresses inevitably occur, as shown in Fig. 2. Hence failure typically initiates at the grips unless there is some form of defect or stress concentration in the gauge section. There are also indications that transverse tensile and compressive stresses can be important [e.g. 6,7].

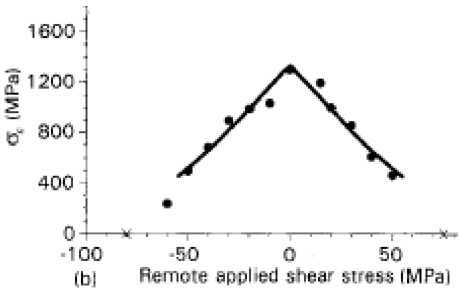

Fig. 1. Effect of shear stresses on compressive strength [4]

If specimens are end-loaded, they need to be ground very flat and perpendicular and even with extremely careful preparation tend to fail by splitting or brooming. Combined end and shear loading therefore tends to give the best results [8]. Tabs should carry just enough load to avoid end failure, but be as thin as possible to minimise the stress concentration at the start of the gauge section. This can be further reduced by encouraging the tabs to debond at the tips [8]. Accurate alignment of the specimen and fibres is crucial, and local misalignment induced at the exit from the test fixture by gripping pressure may have an effect.

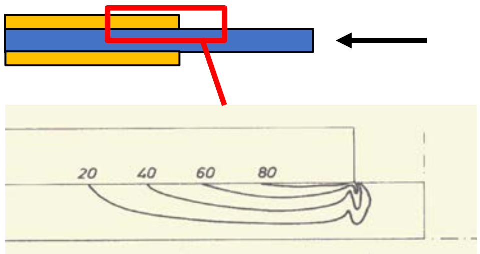

Fig. 2. Shear stress concentrations at end of tabs [5]

Bending tests can also be used to measure compressive failure strain, provided tensile and interlaminar shear failures are avoided. Care has to be taken to avoid roller failure due to stress concentrations. This can be done by using very large rollers or by pin-ended buckling tests where a long specimen is allowed to buckle and then fail in compression in the middle. Scaled pin-ended buckling tests have shown a strong size effect, Fig. 3, which is mainly due to the strain gradient [9] although there could be a contribution from the difference in stressed volume. Recent tests with wood sandwich beams have separated these factors and demonstrated the effect of strain gradient on specimens with the same stressed volume [10].

A different approach is to use a specially designed laminate that when subjected to tensile loading, fails in compression in its central 90°-ply due to the Poisson effect. It has been shown that gauge section failures can be obtained, although transverse tension is also present [11].

Strain rate, temperature and humidity have all been demonstrated to have significant effects on compressive strength since these conditions can greatly affect the matrix behaviour [e.g. 12,13]. However due to the difficulties in testing, there is limited evidence on other factors. Sandwich tests on thin ply specimens have shown that failure strains increase with decreasing ply thickness [14], believed to be due to greater homogeneity and better fibre alignment. This highlights the importance of the manufacturing process, and the possibility of much lower compressive strength in full scale structures than small test coupons of the same material due to misalignment defects such as wrinkles.

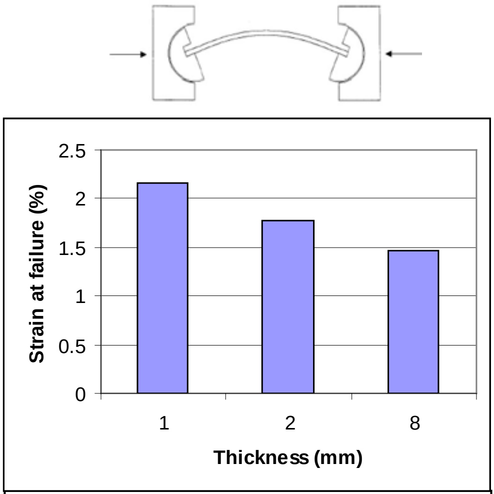

Fig. 3. Strain gradient effect in scaled buckling tests [3]

Hybridisation can also affect compressive failure. For example, compressive failure strains of 2.5% have been reported for high strength carbon/epoxy embedded in glass/epoxy four-point bending specimens [15]. Higher failure strains have been reported for 0° plies embedded in laminates with many 45° plies [16] although the layup may also reduce the stress concentrations. Theoretical modelling has suggested that the stacking sequence affects compressive strength [6] but it is challenging to verify this experimentally.

Further research with reliable test methods is required to fully understand the factors affecting compressive strength.

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