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ABSTRACT

The influence of transverse damage on compressive strength in fiber direction for carbon fiber reinforced epoxy materials is investigated by an experimental approach. Several experimental methods are proposed. The first study focuses on tubular samples. Theses samples are damaged by torsional and cyclic load and next submitted to compressive load. Results show that the transverse damage affects the compressive strength. Yet the stiffness is not modified. A model is then proposed with these results. The second study focuses on plates with stress concentrations. A non-local criterion is introduced in order to take the stress concentration into account. Results are in good agreement with the model identified on tubes.

1 INTRODUCTION

Design of composite structures asks for more and more complex models. The quality of these models is linked to the ability to simulate the material behavior. Many researches investigate the compressive strength of laminates by using micro-models [1]. Failure is described by introducing kink-band models. Continuum damage mechanic can also be added to kink-band theory in order to describe the effect of damage on the compressive strength [2].

Nevertheless, experimental studies are still limited and focus rarely on the impact of damage on compressive strength. Moreover compressive load lead to buckling which not permits to conclude about the material characterization. That's why micro-model validation remains hard.

It was demonstrated that transverse damage causes a drop of the tensile strength [3]. This drop is only visible for high damage ($d > 0.8$). Similarly, it can be assumed that compression strength will be affected by transverse damage. When the matrix is completely destroyed, the slenderness of the fibers leads to instantaneous micro-buckling or more globally to the catastrophic failure of the laminate. Researches show that the increase of temperature (which causes matrix damage) leads to the progressive reduction of compressive strength for glass/polypropylene composites [4]. In this paper, we therefore propose an experimental research in order to quantify this impact of damage on compressive strength for CFRP.

The choice of a test is not trivial [5]. The standard test (ASTM D 3410/A and EN ISO 14126) is Celanese which is used in many publications [6, 7, 8]. The main advantage of this test is a simple geometry of the sample. However, the results show a strong variability due to structural effects (buckling or stress localization close to the fixture) [7]. In order to improve these results, researchers have tried to change the sample geometry [6, 9, 1] or to add anti-buckling systems [4, 10]. Despite this improvements, variability remains large and maximum strain still small.

That's why many alternative tests are proposed in literature. The idea is to use bending and to focus on the face in compression. The mains are 3 point bending [11, 12], 4 points bending [13, 14, 15], pure bending [7] and constrained buckling tests [16]. Two difficulties are linked to this type of test. Firstly the gradient in thickness created by bending affects the compressive strength. Secondly these tests necessitate a complex inverse problem to take into account the nonlinear comportment in compression and in traction. Moreover, in our case, it remains hard to damage the sample before study compression.

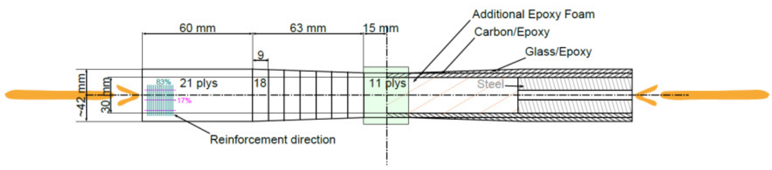
A new tube is also proposed to perform a pure compression test on damaged samples. This experiment permits an easy identification of material behavior. This identification remains easy because the strain field in the gage area is homogeneous. Structural effects are studied in order to prove they are negligible during the test. Experiments are then focused. First samples are submitted to cyclic torsion in order to shear the matrix and create damage. Next compression is performed to measure compressive strength. Tests are followed by digital image correlation in order to measure strain on the external face of the sample and detect structural effects. Results will show a decrease of the compressive strength when damage increase. This behavior will then be modelized.

2 SAMPLES AND METHODS

2.1 Description of the sample

The sample studied (fig. 1) is a tube which have a $[0]_{11}$ stack in the direction of cylinder. Samples are manufactured by wrap rolling [17]. Internal and external diameters are measured in order to access the thickness of the ply. Mantles in steel are incorporated in order to resist to the tightening.

(a) Picture



(b) Size of the sample

Figure 1 - Sample geometry

2.1.1 Sample validation

The aim of the paper is to show that transverse damage will affect the compressive strength. Unfortunately assessment of the strength remains complex because various mode of fracture are possible. Firstly compressive load can lead to buckle. Given the brittle behavior of CFRP buckle will quasi immediately lead to collapse. It is also hard to conclude if the failure is caused by material limit or by buckle. Secondly the manufacturing of the composite will generate plies drops which create stress localization and complex structural effects. With these localizations, the strain field is not uniform with strong gradient and also the measure of the compressive strength becomes complex.

Carbon/Epoxy				Glass/Epoxy			
E_{11}	E_{22}	E_{12}	ν_{12}	E_{11}	E_{22}	E_{12}	ν_{12}
53000	53000	4000	0.035	36000	18000	4000	0.19

Table 1 - Elastic parameter of G802/914 and unbalanced glass/epoxy used in buckling prediction

Numerical studies are implemented in ABAQUS Standard/Explicit in order to prove that structural effects would not affect the measurement. Nevertheless numerical buckling prediction is complex and overestimate the capacity of the structure [18]. It is then considered that numerical tools are not robust enough to design sample able to avoid buckling. The trend of the buckling stress can however be determined (fig. 2) by using an eigenvalue buckling prediction. This prediction is in good agreement with the analytical model proposed in literature [19] and expressed in the following equation :

$$\sigma_{buckle} = \frac{E_{11}}{\sqrt{3(1-\nu_{12}{}^2}} \frac{t}{R} \tag{1}$$

where t is the thickness and R is the mean radius of the tube.

To have a better correlation with experiments, it is also proposed to correct the stress buckle obtained analytically by the knock-down factor proposed by Castro [18] :

$$\sigma_{buckle}^{kdf} = \sigma_{buckle} \left[0.901(1 - e^{-\frac{1}{16}\frac{R}{t}}\right] \tag{2}$$

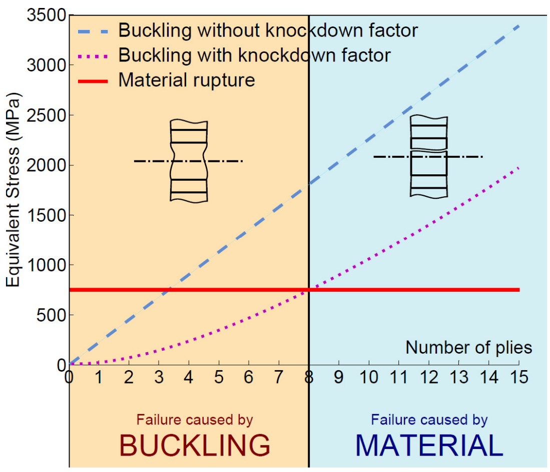


Figure 2 - Failure stress according to the number of plies of the tube - theoretical curve

An experimental procedure is then proposed in order to know when failure of the samples will be caused by global buckling. The method consists to analyze the number of ply (equivalent to the thickness). Theoretically when the thickness of the sample is small the collapse will be caused by buckling. In this case, the strength of the tube increase linearly according to the number of ply in the center of the sample. Contrarily when the thickness is larger, the collapse is determined by the compressive strength of the material. In this case the compressive strength remains constant. Different tubes with different thickness will then been manufactured and tested in pure compressive test in order to know when buckling occurs. The figure 3 represents the results obtained for different thickness. This figure shows clearly that when the number of ply is more than 5, buckling is avoided.

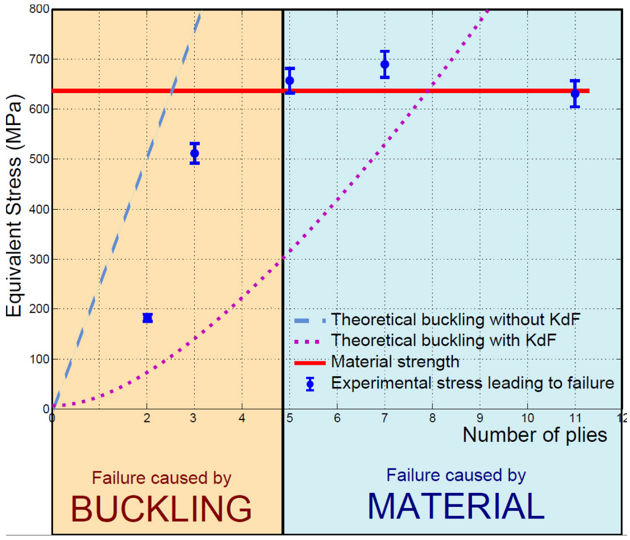


Figure 3 - Failure stress according to the number of plies of the tube - experimental curve

Another problem is linked to the ply drop which is responsible of stress concentration localized close to the ply drop (fig. 5(a)). The maximum of strain is so localized that it is impossible to measure. Figure 5(a) shows the more the central area is thick the less the stress concentration is strong.

Numerical simulations (ABAQUS Standard and elastic lamina shell) show that bending created by ply reduction generates stronger strain inside the tube. This effect become negligible when the tube is thick. That's why it is decided to work with an internal $[0]_{11}$ carbon tube and unbalanced glass/epoxy which is less stiff in tube direction.

2.1.2 Method to introduce damage

Tests are performed on a bi-axial MTS machine (torsion-compression). In a first time we impose a cycling torsional load by controlling rotation (step of 10, 50, 200 and 500 cycles) (fig. 4). This torsion generates plastic deformations which misalign the fibers. We also compare actual state with the first image saved in order to identify the inelastic deformation. This one is deleted by imposing machine rotation. Finally compression test can be executed.

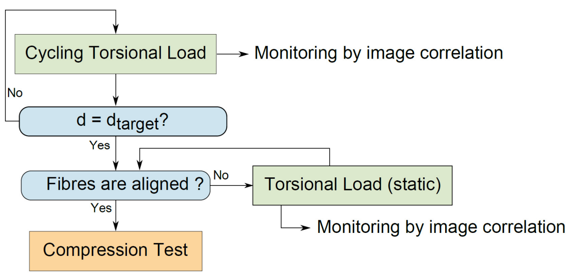


Figure 4 - Method to analyze damage effect on compressive strength

2.2 Results and discussion

2.2.1 Experiments on undamaged samples

In a first time we focus on undamaged samples. This part investigates structural effects caused by the plies drop (fig. 5(a)). Stress localization is strong for $[0]_7$ sample but remains negligible for $[0]_{11}$. An average of longitudinal strain is measured in central area by post-traiting images (MATLAB). This average is ε =-1.35 % for $[0]_{11}$ sample just before collapse. This value is close to the compressive strength in traction (ε_t = 1.5 % [20]).

Failure for this type of sample is sudden and catastrophic. Moreover the propagation of the crack is limited to a concentric line around the tube in central area. This test shows also the nonlinear behavior of material. A stiffness reduction model is proposed for compression ([21, 14]) as follow :

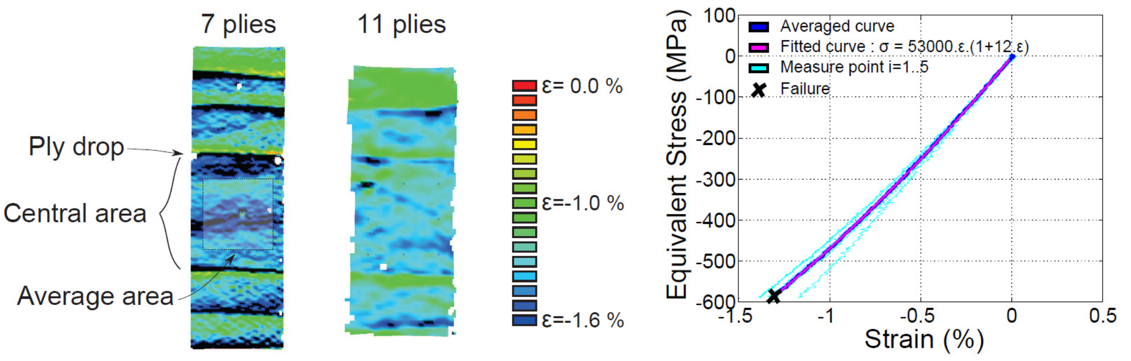
$$\sigma_{11} = E_{11}\varepsilon_{11}(1 + \alpha\varepsilon_{11}) \tag{3}$$

The experimental strain-stress curve are plotted in 5 different points in central area and an average is calculated in order to access an homogenized value (fig. 5(b)). Stress is computed by considering the stress field is homogeneous is central area. That wants to say :

$$\sigma_{11} = \frac{F}{S} = \frac{F}{\pi\,(R_e^2 - R_i^2)} \tag{3}$$

where R_e is the external radius and R_i is the internal radius.

Finally material coefficients of eq. 4 can be identified by polynomial fitting (E_{11} = 53000 MPa and α = 12). The correlation between this model and experiment seems to be correct.



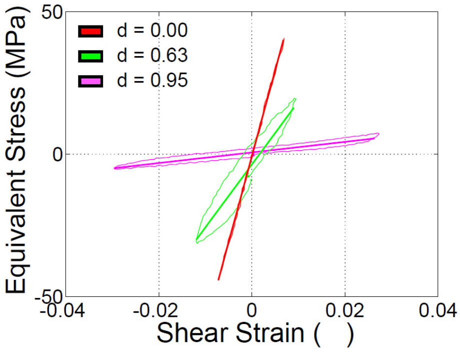
(a) Strain field before collapse **(b) Behavior of undamaged sample**

Figure 5 - Strain for undamaged sample just before failure

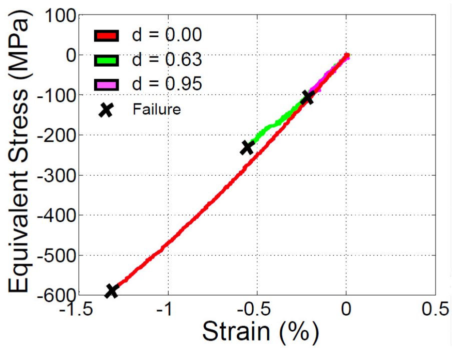
2.2.2 Effect of damage on compressive strength

Effect of damage on compressive strength is now studied. Composite tubes are damaged with torsional load (fig. 6(a)). The loss of transverse stiffness is used to calculate the different damage values. Next tubes are tested in compression up to failure (fig. 6(b)). The comportment identified previously is not modified when damage increase. Yet the compressive strength has significantly and progressively decrease. The picture 7(b) shows the collapse area just after failure. It appears that collapse is caused by micro-buckling of tows as described in [22]. This observation is only possible for a strong damaged sample because failure is more progressive.

In figure 7(a), the strain leading to failure has been plotted. We also propose a simple engineer model in order to take into account strength reduction when damage increase. Identification remains really easy because it introduces just one parameter ($\varepsilon_{d=0}$) in the model which can be measured with an undamaged sample.

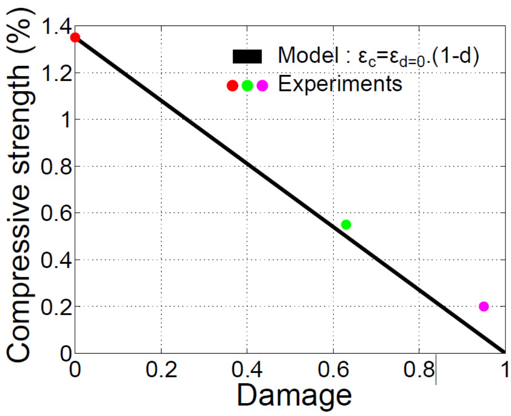


(a) Loss of stiffness in torsion

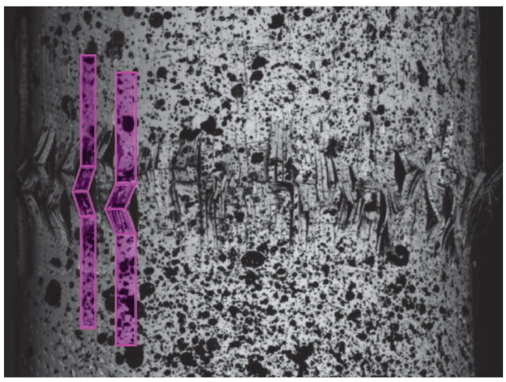


(b) Compressive test on damaged tubes

Figure 6 - Test on damaged samples



(a) Model proposed for compressive strength reduction



(b) Micbrobuckling of tows (d~0.95)

Figure 7 - Strain Analysis of experiments on damaged samples

3 CONCLUSION

The aim of this paper was to propose an experimental research in order to quantify impact of damage on compressive strength for CFRP. A first step was to choice an experimental procedure. The geometry has been fixed after simulations and many experiments. It was demonstrated that buckling does not appears during the test and that influence of ply drop remains negligible.

A second step was to demonstrate that transverse damage affects compressive strength. Three damage states have been targeted (d = [0;0.63;0.95]) by cyclic torsional load. Next compressive tests have been performed to show the strength decrease when damage increase. And finally an engineer model has been proposed in order to take into account this reduction.

These results permit also to give an evolution of strength following damage state for pure compressive test. Yet design of composite in compression still complex especially because strain gradient seems to significantly affect compressive strength [9, 11]. Structural tests are also planned in order to investigate the relationship between compressive strength, damage and strain gradient.

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