EFFECT OF TRANSVERSE DAMAGE ON COMPRESSIVE STRENGTH IN FIBER DIRECTION FOR CFRP

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Abstract
The influence of transverse damage on compressive strength in fiber direction for woven CFRP materials is investigated by an experimental approach. Several experiments are proposed in order to show the loss of strength when material is damaged. The first study focuses on sample validation to exclude buckling collapse. Then damaged tubes in torsion are studied in pure compression test. The tests are followed by digital image correlation to analyze structural effects affecting the material characterization. It is finally shown that the transverse damage affects the mechanical performance in compression.

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 behaviour. 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 ($d \gtrsim 0.8$). Similarly, it can be assumed that compression strength will be affected by transverse damage. When the matrix is completely destroyed, the slenderness of the fibres 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.

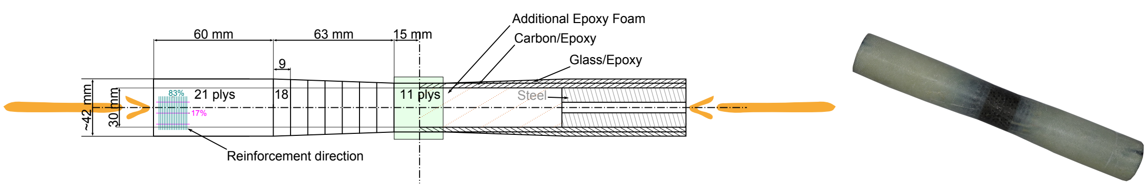
In a first time, a new tube is also proposed to perform a compression test on damaged sample. This experiment permits an easy identification of material comportment. Structural effects are studied in order to prove they are negligible.

In a second time, experiments are 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.

2. Sample 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. In some experiments, samples are filled with epoxy foam to delay buckling.



(a) Size of the sample (b) Picture

Figure 1. Geometry of sample

2.2. Sample validation

The aim of the paper is to show that transverse damage will affect the compressive strength. Unfortunatly assessment of the strength remains complex because various mode of fracture are possible. Firstly compressive load can lead to buckle. Given the brittle behaviour of CFRP

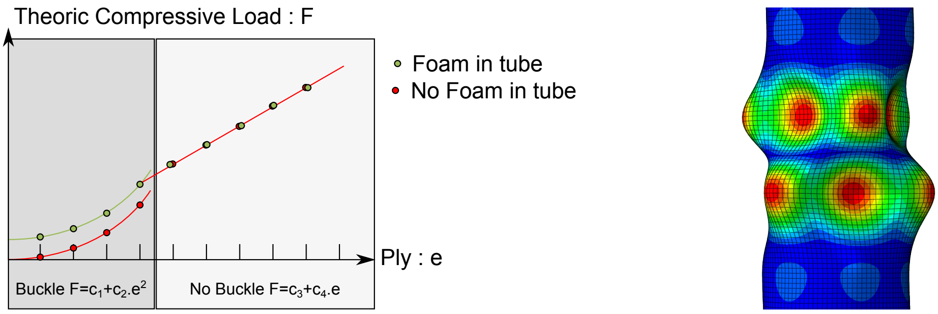
Carbon/Epoxy				Glass/Epoxy			
E_{11}	E_{22}	E_{12}	ν	E_{11}	E_{22}	E_{12}	ν
53000	53000	4000	0.035	36000	18000	4000	0.19

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

buckle will quasi immediately lead to collapse. It is also hard to conclude if the rupture 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.

2.2.1. Buckling

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, 19]. We can however determine the trend of the buckling load (fig. 2) by using an eigenvalue buckling prediction.



(a) Theorical compressive load for material or buckle collapse (b) Visualization of the shell buckle in the central area

Figure 2. Abaqus analysis of the compression

A first point of view to distinguish the two case of collapse is to focus on the foam. The add of foam delay buckling but has a negligible impact on the compressive load when the collapse in caused by material.

An other point of view is 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 resistance of the tube increase following the square of 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 increase linearly with the thickness (for thin plate). We can also write :

R	Medium radius
e_{ply}	Thickness for one ply
n_{ply} / m_{ply}	Number of ply
$F^{rupture}$	Collapse load

$$F^{rupture}_{n_{ply}} = 2\pi R n_{ply} e_{ply} \qquad (1)$$

In order to validate the test, we define two ratios λ and ∂ (eq. 2 and 3). λ represents the proportionality between compressive load and thickness. $\lambda^{experimental}$ is calculated by using load and $\lambda^{theoric}$ is calculated by using the number of plies. Concerning ∂, it is a criteria to characterize the mode of failure.

$$\lambda^{theoric}_{n_{ply}/m_{ply}} = \frac{n_{ply}}{m_{ply}} \quad \text{and} \quad \lambda^{experimental}_{n_{ply}/m_{ply}} = \frac{F^{rupture}_{n_{ply}}}{F^{rupture}_{m_{ply}}} \tag{2}$$

$$\partial_{n_{ply}/m_{ply}} = \frac{\lambda^{experimental}_{n_{ply}/m_{ply}}}{\lambda^{theoric}_{n_{ply}/m_{ply}}} \tag{3}$$

When the ratio $\partial_{n_{ply}/m_{ply}}$ is closed to 1, we conclude that rupture is caused by material. Complementary test on $[0]_3$ tubes (not presented in this paper) have been realized to quantify the dispersion in order to specify the border of a valid $\partial_{n_{ply}/m_{ply}}$. We also take $\partial_{n_{ply}/m_{ply}} \in [0.85; 1.15]$ for a valid test.

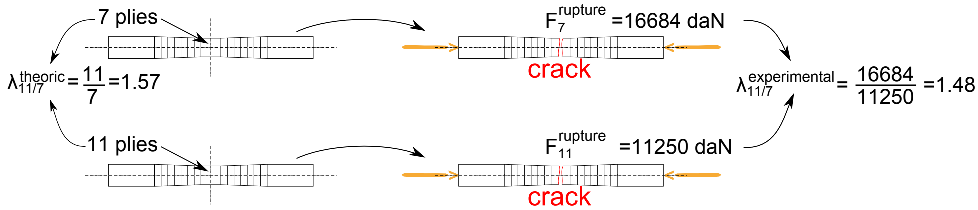


Figure 3. Method for λ calculation

This trend permit us to conclude that a $[0]_{11}$ and a $[0]_7$ stack which present a ratio $\partial_{11/7} = 0.94$ (fig. 3) are not submitted to buckling. Unfortunately this validation is not good enough.

2.2.2. Ply drop and stress concentration

An other 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.

2.3. Method

The test is 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.

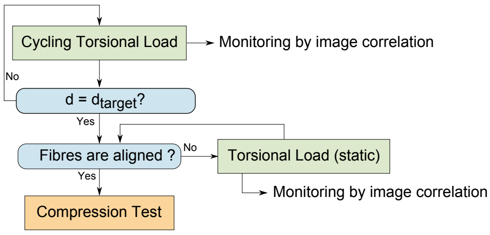


Figure 4. Method to analyze damage effect on compressive strength

3. Results and discussion

3.1. 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]).

Rupture 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 non-linear behaviour of material. A stiffness reduction model is proposed for compression ([21, 14]) as follow :

$$\sigma_{11} = E_1 \varepsilon_{11}(1 + \alpha \varepsilon_{11}) \tag{4}$$

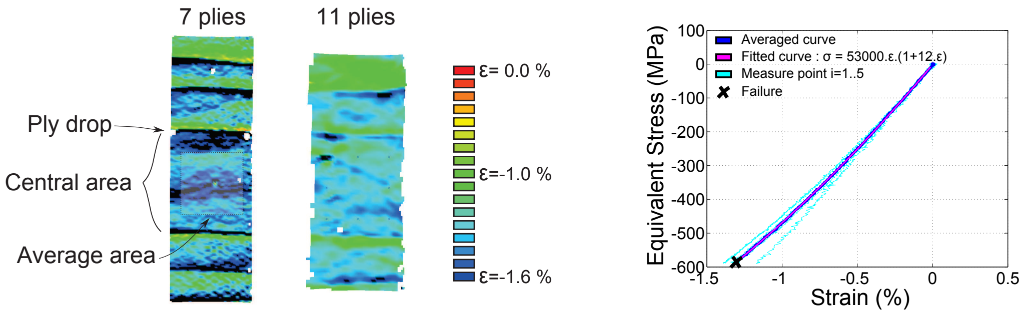
The experimental strain-stress curve are plotted in 5 different points in central area and an average is calculated in order to access an homogenized value (fig. 5(b)). Stress is computed by considering the stress field is homogeneous is central area. That wants to say :

$$\sigma_{11} = \frac{F_{load}}{S_{central-area}} = \frac{F_{load}}{2\pi R n_{ply} e_{ply}} \tag{5}$$

Finally material coefficients of eq. 4 can be identified by polynomial fitting (E_1 = 53000 MPa and α = 12). The correlation between this model and experiment seems to be correct.

3.2. 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

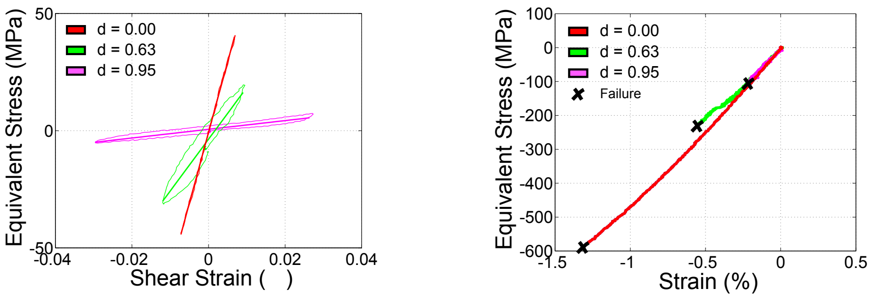


(a) Strain field before collapse

(b) Strain stress curve for undamaged sample

Figure 5. Strain for undamaged sample just before rupture

identified previously is not modified when damage increase. Yet the compressive strength has significantly and progressively decrease.



(a) Shear stress vs Shear strain after cyclic load

(b) Compression with damage

Figure 6. Test on damaged samples

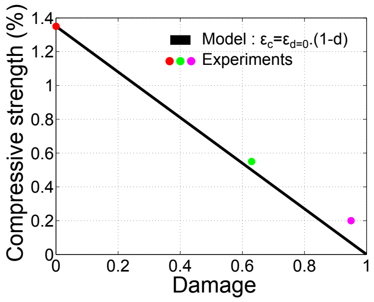
The picture 7(b) shows the collapse area just after failure. It appears that collapse is caused by micro-buckling of tows as described in [22]. This observation is only possible for a strong damaged sample because failure is more progressive.

In figure 7(a), the strain leading to rupture 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.

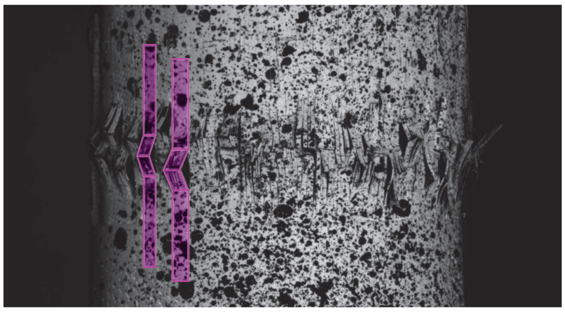
4. Conclusion

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 com-



(a) Model proposed for compressive strength reduction



(b) Microbuckling of the tows (case d~0.95)

Figure 7. Analysis of experiments on damaged samples

pressive 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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