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Effect of matrix damage on compressive strength in the fiber direction for laminated composites

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ABSTRACT

An original experimental method is proposed to characterize the influence of matrix damage on the compressive strength of laminated composites in the fiber direction using tubes. These composite tubes have a dumbbell-shaped geometry so that rupture occurs in the specimen center without stress concentration. They can be constituted of unidirectional or woven plies aligned with the axial direction. First, a torsional cyclic load is applied in order to damage the matrix. This damage is measured at the tube scale via the reduction in shear modulus. Second, a compressive load is applied up to failure for various damage levels.

The method is applied to a woven carbon/epoxy material. Results show that the matrix damage affects significantly the compressive strength in the fiber direction. It is yet observed that longitudinal stiffness is not modified by damage. Finally, a simple model is proposed to describe this decrease of strength vs. matrix damage.

1. Introduction

One of the main issues in engineering design of composites is the prediction of failure. In the case of composites, the mechanisms of collapse are manifold [1]. For many years, the introduction of damage mechanics has made it possible to successfully describe the progressive failure of the matrix especially observed in the case of fatigue loads [2–4]. Matrix damage is associated with the growth of micro-cracks in the resin and the development of fiber/matrix debonds and transverse cracks. This leads to the decrease in the stiffness in transverse and shear directions at the ply scale. A matrix damage variable d is generally introduced to quantify this stiffness reduction. Most of the time, these cracks do not lead to the global failure of the laminates. Contrarily, the failure of fibers generates a sudden and catastrophic collapse of the laminates.

Even if the growth of damage does not directly cause the failure of the laminate, it can significantly affect the strength of the ply in the fiber direction. Indeed, in a previous work it was experimentally measured that matrix damage causes a drop in the tensile strength [5,4]. This work was performed on tubes made of Glass/Epoxy unbalanced woven plies. First, a torsion cyclic loading was applied to generate matrix damage. Then, tensile tests were performed to measure the tensile strength. These tests show that the final strength can be equal to the third of the initial strength when damage is high [5,4]. The model proposed by Hochard et al. [4] is that the strength evolves sharply between two values according to a damage threshold value ($d \gtrsim 0.8$).

In a similar way, the aim of this paper is to study the effect of matrix damage on compressive strength in the fiber direction for laminated composites. Interesting work by Gibson et al. [6] shows that the progressive increase in temperature of a glass/polypropylene composite leads to the progressive reduction in compressive strength in the fiber direction. This behavior is directly linked to the drop in matrix modulus. Since matrix damage increase has a similar effect on this modulus, we can imagine that this increase will also lead to the decrease in compressive strength in the fiber direction. These authors also observed that when the matrix is completely burned, the failure in compression of the composite in the fiber direction is obtained for an extremely low stress.

Micro-models give interesting pieces of information about the effect of damage on compressive strength. Rosen [7] has postulated that elastic micro-buckling of the fibers was responsible for the collapse of the ply. This model gives an analytic solution for the compressive strength (see the list of nomenclatures for the symbol definitions):

$$\sigma_c = \frac{G_m}{1 - v_f} \approx G_{12} \quad (1)$$

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Nomenclature

d	matrix damage (–)
E_{11}	longitudinal modulus of the ply (MPa)
G_{12}	shear modulus of the ply (MPa)
G_m	shear modulus of the matrix (MPa)
α	non linear parameter (–)
ε	longitudinal strain (%)
σ	longitudinal stress (MPa)
v_f	fiber volume fraction (–)

Subscript

c	compression
t	tension

Superscript

$d = 0$	undamaged material
d	damaged material

This equation shows that the most significant parameter in compressive failure is not linked to the fibers but is linked to the stiffness of the matrix. On the other hand, it is well known in damage mechanics [1] that the actual modulus is proportional to the matrix damage, which means that:

$$G_{12}(d) = G_{12}^{0}(1 - d) \tag{2}$$

By coupling the equations above, it is shown analytically that the compressive strength is proportionally affected by the matrix damage as follows:

$$\sigma_c(d) = G_{12}^{0}(1 - d) \tag{3}$$

Rosen's model gives an interesting result but the predicted value is not in good agreement with experiments. Many other models have then been developed to improve this prediction by considering the failure as a plastic instability generating a kink-band [8–11]. These models are able to take into account an increasing number of physical phenomena and geometrical defects, e.g., plasticity, matrix damage, fiber misalignment, etc. In particular, Kulkarni et al. [12] and Steif [13] have investigate the influence of the lack of perfect bond between fiber and matrix. Kulkarni et al. show theoretically the large degrading influence of the interface condition on the compressive strength.On the other hand, the experimental validation of these models remains complex because of the difference in scale between the micro models and the experiments (generally at the meso scale). In any case, literature on micro models shows that the state of the matrix is essential in the prediction of the compressive strength.

In this paper, experimental research is proposed in order to quantify the effect of matrix damage on compressive strength for carbon fiber reinforced plastics (CFRP) in the fiber direction. First, the choice of the proposed experimental method will be explained. This method must be able to impose a certain level of damage and to apply compression in the fiber direction up to failure. Then, the experimental setup will be described. Experimental results on undamaged and damaged specimens will be presented and analyzed. Finally, a simple model adapted to an engineer approach is proposed. This model linked the compressive strength to the matrix damage state at the meso scale.

2. Experimental method

2.1. Choice of the experimental method

The aim of this work is to study the influence of transverse damage on the compressive behavior in the fiber direction for laminate composites. To address this problem, it is necessary to propose an experimental method that would make it possible to damage the matrix as well as achieve compression in the fiber direction. Two approaches are possible: one consisting in providing one single experimental setup for both steps and the other consisting in providing one experimental setup for each step.

The compression tests are particularly complex to perform in comparison with tensile tests because of the risk of specimen buckling. The classical compression test, also called Celanese test, is also known for its defects. The results generally highlight low ultimate compressive strain and exhibit high variability mainly because of specimen buckling and large stress concentration at the tabs [14,15]. Many modified compression tests have been proposed to overcome these defects [16,17,6,18]. Despite these improvements, these tests seemed unfavorable for a detailed study of the influence of damage on the ultimate compressive strain.

The other experimental method to study the behavior in compression of laminate composites is the bending test. There are many types of bending tests: classical bending tests with three points [11] or four points [19–21], or more exotic tests like pure bending tests [15,22] and constrained buckling tests [23]. Conventional bending tests generally give higher ultimate compressive strain values. However they show two difficulties: the computation of the stress field requires a complex inverse problem due to the large displacements and the stress concentrations introduced at the support points can lead to premature failure of the specimen. Montagnier and Hochard [15] and then Bois et al. [22] proposed a pure bending test with a dumbbell-shaped specimen in order to circumvent these difficulties. In this case, the bending moment value is perfectly known without assumption, which simplifies the computation of the stress field. In addition, the dumbbell-shaped geometry allows the rupture to be located in the center of the specimen without stress concentration. Finally, Wisnom and Atkinson [23] proposed a constrained buckling test that also achieves very high ultimate compressive strain. Note further that bending tests involve a strain gradient effect in the thickness of the specimen, widely described in the literature [24,23,11]. The stability and precision obtained with bending tests seem to be suitable for the proposed study. However, bending specimens must be especially long and damaging this kind of specimen, with shear for example, seems to be complex to carry out.

Previous tests do not seem satisfactory to our study, we propose then a test on dumbbell-shaped composite tubes constituted of plies positioned at 0° relative to the tube axis. The method is applied here to balanced woven plies. The tubular shape makes it possible to both damage the matrix in shear with a torsion test and then perform a pure compressive test in the fiber direction. This test allows a homogeneous field and therefore a simple calculation for the stress. Specimens of similar form had already been used by Hochard et al. [4] to achieve shear/tension tests. Nevertheless the compression test is problematic for the aforementioned reasons (buckling and stress concentration), a careful development of this test in the case without damage is proposed in [25–27].