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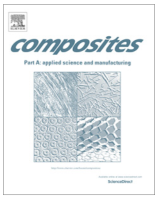

Determination of the out-of-plane tensile strength using four-point bending tests on laminated L-angle specimens with different stacking sequences and total thicknesses

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ABSTRACT

Laminated composite materials are increasingly used for the design of aircraft primary structures subjected to complex 3D loadings. The delamination observed in curved parts ensuring the junction between the different perpendicular panels is one of the most critical failure mechanisms. The present article proposes a complete protocol to identify the out-of-plane tensile strength of specimens composed of unidirectional plies. Firstly, a method to design a four-point bending (4 PB) test on L-angle specimens has been proposed. Secondly, a test campaign on T700GC/M21 laminated L-angle specimens has been performed at ONERA. Thirdly, the analysis of these tests with different methods has been performed to demonstrate that such a test is relevant to determine the material out-of-plane tensile strength, which seems to be independent of the stacking sequence and of the total thickness of the specimen, thus allowing the use of this strength in a 3D failure criterion. Finally, the different advantages and drawbacks of 4 PB tests performed on curved beams are discussed.

1. Introduction

In order to answer the request of aeronautical companies for lighter, safer and less polluting civil aircraft, laminated composite materials, which present high specific properties, are currently massively used for the manufacturing of the latest generation of civil aircraft. Indeed, the percentage of composite materials has increased up to 51% for the Boeing 787 and to 53% for the Airbus A350XWB. The most interesting point consists in the use of laminated composite materials for the manufacturing of primary structures which ensure the structural integrity of the whole aircraft, such as the centre wing box, the wings of the vertical or horizontal tailed planes. The components, presenting complex geometry, are mainly constituted of different stiffened panels. Moreover, these components are subjected to complex through-the-thickness loadings which are mainly supported by laminated composite L-angles which ensure the junction between the different perpendicular panels. These composite L-angles have to carry a part of the membrane loading applied to the different panels and are subjected to bending moments leading to unfold/fold the L-angle. The failure of such components is mainly due to delamination resulting from the out-of-plane stresses induced by the applied moment. It should also be noted that the L-angles can present (i) different thicknesses (*i.e.* number of plies varying from 12 plies up to more than 200 plies) as a function of the intensity of the applied loading and (ii) different stacking sequences as a function of the multiaxiality of the applied membrane loading. Moreover, in some cases, the L-angle can be directly integrated in a stiffened panel during the manufacturing process, thus allowing weight saving. Most often, the propagation of delamination in L-angles is instantaneous and induces the final rupture of the structure. Therefore, the design of such a composite structure is essentially performed through an accurate estimation of the onset of delamination, which is usually done in design offices with different failure criteria [1–3].

However, the most critical point concerns the identification of the out-of-plane strengths and especially the out-of-plane tensile strength. Indeed, only few experimental studies can be found in the literature to identify the out-of-plane tensile strength [4].

The basic method to determine the interlaminar tensile strength consists in applying an out-of-plane uniaxial tensile loading to waisted specimens. Such tests can only be performed on very thick specimens in order to obtain a uniaxial stress state in the gauge section and to avoid premature failure close to the

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edges, due to stress concentrations [5–8]. Although the analysis of such a test is rather simple, the waisted coupons are relatively complex to manufacture and the identified strength is not necessarily relevant for thin specimens, due to the manufacturing process. Some in-plane uniaxial tensile tests on unnotched specimens manufactured with specific stacking sequences, which induce delamination at the free edges [9], can also be used to determine the out-of-plane tensile strength. Although these tests are simple to perform, the analysis is very complex because it is necessary to describe accurately the edge effects inducing local delamination [10,11]. Moreover, these tensile tests can only be performed on few specific stacking sequences, which are not representative of the usual aeronautical stacking sequences. The Arcan test [12] allows arbitrary combinations of out-of-plane shear and tension or even to apply a through-the-thickness uniaxial tensile or a shear loading to thin plain coupons (<5 mm). Although the analysis of this kind of test is rather simple, the Arcan test remains complex to be performed accurately and necessitates the use of specific jaws to limit the edge effects. To our knowledge, this test has yet been applied only to thin specimens. All these test configurations can only be performed on unnotched plates whose manufacturing process is not necessarily representative of that used for the L-angle specimens considered in this study.

Therefore, to identify the out-of-plane tensile strength through the analysis of tests using coupons which have been manufactured according to a process similar to that of the considered aeronautical components, some experimental studies have been performed on different test configurations on L-angle shaped specimens [13,14] or on more complex geometries [15] which are representative of the manufacturing process of the final application. Among these different tests, the Four-Point Bending (4 PB) tests on L-angle specimens, proposed initially by Jackson [16], present the advantages of moderate experimental difficulties (manufacturing of the coupons and complexity of the mechanical tests) and also of an acceptable complexity of the associated analysis methods. Consequently, the four-point bending tests on L-angle specimens have been standardised [17] and the results of these tests can be used in a design office. Moreover, it is possible to test L-angle specimens presenting different total thicknesses, different stacking sequences and different geometrical configurations (such as different corner radii) and to estimate experimentally their influence on the identified out-of-plane tensile strength.

The present article is thus dedicated to (i) the determination of the out-of-plane tensile strength through the analysis of Carbon/Epoxy laminated L-angle specimens subjected to four-point bending loading and (ii) to demonstrate that the identified out-of-plane tensile strength is independent of the stacking sequence and of the total thickness of the specimen.

To fulfil this objective, an experimental test campaign has been performed on T700GC/M21 laminated L-angle specimens subjected to four-point bending loadings and is presented in Section 2. The design of the L-angle specimens, the experimental device and the associated instrumentation, and the different analysis methods used in this study are described, respectively, in Sections 2.1, 2.2 and 2.3. The test results are presented and analysed in detail in Section 3. Finally, the main advantages and drawbacks of the four-point bending tests on L-angle specimens are discussed in the last Section 4.

2. Presentation of the four-point bending tests

2.1. Design of the L-angle specimens

The principle of the four-point bending tests on L-angle specimens is illustrated in Fig. 1. The two cylindrical support bars are fixed and the applied loading is imposed through the two cylindrical loading bars. This loading induces a bending moment at the curved section level, thus leading to unfold the L-angle specimen. In the case of accurately designed L-angle specimens, the observed delamination is only due to the out-of-plane tensile stress generated in the curved section, as illustrated in Fig. 2a, thus allowing the identification of the out-of-plane tensile strength. As illustrated in Fig. 1, the characteristic dimensions of an L-angle specimen are the total length of each leg (L), the width of the specimen (w), the total thickness (t), the inner radius of the corner (R_i) and the angle between the two legs (α). Moreover, the cylindrical bars used in the 4 PB experimental device are defined by their radius (R_r), and the distances between the two cylindrical loading bars (X_1) and between the two cylindrical support bars (X_2). The orientation of the 0^0 plies in the L-angle specimen is also reported in Fig. 1.

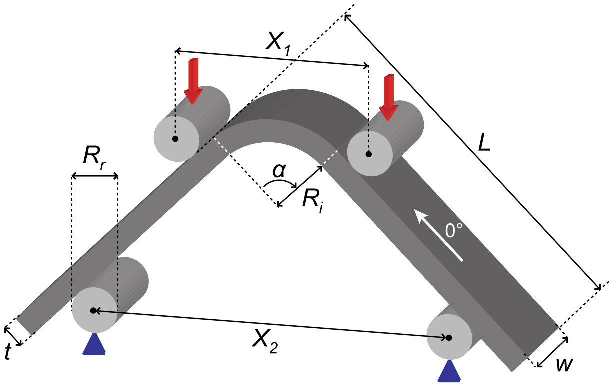

Fig. 1. Configuration of the four-point bending test on L-angle specimens. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Nevertheless, the industrial standard ASTM D6415/D6415M-06a [17] gives a detailled description of the design of an L-angle specimen manufactured with only 0^0 plies and for a given thickness. There is no existing rule for the design of L-angle specimens when different thicknesses or different stacking sequences have to be considered in a test campaign. In order to design laminated L-angle specimens, some preliminary Finite Element (FE) simulations have been performed to determine the most influent geometrical parameters. Some details concerning these FE simulations are given later in Section 2.3.2. The following guidelines for the design of laminated L-angle specimens can be proposed by considering some parameters given by the existing standard, some others fixed by manufacturing constraints and, finally, others determined through FE simulations.

- The angle of the corner is fixed at $\alpha = 90°$ and the radius of the cylindrical bars are fixed at $R_r = 7.5$ mm as proposed by the existing standard [17].
- The width of a specimen (noted w), presenting a total thickness inferior or equal to 4 mm, is fixed at 20 mm, as recommended by the standard [17]. For a thicker specimen, the width is defined as a linear function of the total thickness of the specimen in order to minimise the influence of edge effects on the measured strength.
- The inner radius of the corner cannot be (i) inferior to the total thickness because of manufacturing constraints, but (ii) cannot be too large to avoid fibre failure in compression mode in the upper plies located at the outer radius. In the following, the inner radius is considered as equal to the theoretical total thickness of the specimen $R_i = t$.
- Concerning the distance between the cylindrical loading bars (X_1), these cylindrical loading bars have to be (i) far enough from the area of interest (radius of the specimen) to avoid cre-