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Experimental characterization of the interlaminar fracture toughness of a woven and a unidirectional carbon/epoxy composite

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ABSTRACT

An experimental program has been carried out at the University of Pisa, in collaboration with Leonardo Helicopter Division, to investigate the differences in interlaminar fracture toughness properties of a graphite/epoxy composite material, available in two forms: unidirectional tape and five harness satin fabric.

To this end, tests have been carried out in mode I, mode II and mixed I + II mode on specimens manufactured with the two material systems by Leonardo HD, following their industrial standards. The results show a considerably higher toughness of the fabric, as a consequence of the peculiar features at the delamination interface and of the other local mechanisms, capable of absorbing energy, that are present only in fabric composites. Some fractographic observations confirm these mechanisms. Finally, numerical analyses have been carried out, modelling with Finite Element the various tests, to complement and evaluate the data reduction methods used to derive the toughness values.

1. Introduction

Application of advanced composite materials to aircraft primary structures is continuously growing, and projects like the Boeing 787 and the Airbus A350 XWB in the field of commercial aeroplanes are striking examples of how far current technology can extend. Further developments are in progress in the areas of low cost processes or inclusion of sensors to obtain multifunctional materials, so that predictions are in favour of a wide increase in applications in future aeronautical programs. At present, the main design requirements that must be accomplished by most composite structural applications are relevant to either stiffness, static strength or resistance to low energy impact damage. Similar considerations also hold for the helicopter world, where composite parts must account for challenging loading spectra. In order to avoid structural problems in service, current design procedures have led to the adoption of rather low allowable strain levels. In the certification process, durability and damage tolerance criteria require composite structures containing undetected damage to be acceptable to fly.

Comparing different types of damage, inadvertently introduced during manufacturing or induced in service, delamination growth is considered one of the most important failure mechanisms that can be detrimental for flight safety and consequently, delaminations must be considered not only in the design process, but also in structural verification testing. Delamination growth can occur as a consequence of interlaminar stresses and possible situations that may induce such undesired stresses are quite numerous: local buckling, free edges and notches such as holes, ply drops, impact damage or, in complex structures, unanticipated out-of-plane loading. It is important therefore to improve the knowledge of delamination growth both theoretically and experimentally.

The helicopter community pioneered investigations about how to approach the delamination problem; early works by O'Brien, related to free edge delamination in tension loaded structures date back to the 80-ies [1], and the use of fracture mechanics was fostered, with the strain energy release rate identified as the parameter most suitable for strength and stability analysis.

Since then, a flood of papers have been published on delamination experiments and analysis, but nevertheless the certification process remains very expensive and time consuming, because it is

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based on the so-called building block approach [2] or test pyramid [3]. Therefore, currently there is a great interest in the development and refinement of prediction methods for reducing time and costs of assessments and for evaluating, on a rational basis, problems like: second/alternative material supplier, manufacturing discrepancies, transfer of production from a plant to another, etc.

This paper stems from a collaboration between the University of Pisa (UP) and Leonardo Helicopter Division (formerly Agusta-Westland), a helicopter manufacturer that is involved in research activities in this field since the early times [4,5]. The interest is in the study of rotor area materials, and is focused on the characterization of interlaminar fracture resistance of a carbon/epoxy system, available in two forms: 5 harness satin fabric and unidirectional tape.

Experiments have been carried out for the assessment of interlaminar fracture toughness in various conditions (mode I on DCB specimens, mode II on 3ENF coupons and mixed I + II conditions using the MMB procedure). The carbon/epoxy materials, provided by Leonardo HD, are commonly used in the helicopter rotor area and are manufactured from Hexcel prepregs: they are a 8552S/AGP280 woven fabric in the 5-harness satin style and a unidirectional 8552/AS4 tape.

This choice was not unintentional, as the two materials share essentially the same constituents: the AGP280 fabric is made out of AS4-3K rows and according to Hexcel literature no practical differences exist between 8552 and 8552S resins.

There is a strong interest in comparing the two systems, since recently there have been substantial efforts towards the introduction of fabrics in composite structures because of easier handling and lay-up processing than for unidirectional tape laminates. In addition, woven fabric composites are more damage tolerant in the presence of a delamination. The reasons for this better behaviour are in the nonplanar interply structure of woven fabric composites, so that a delamination, if present, will interact with matrix rich regions and the weave structure during its propagation; this interaction will increase material toughness significantly.

2. Literature review about interlaminar fracture toughness differences between unidirectional and fabric composite materials

In the literature about fracture toughness of fabric composites, a number of papers discuss the influence of the style at the delamination interface on the interlaminar toughness. Indeed, Funk and Deaton make a systematic analysis on the mode I fracture toughness of DCB coupons, made in 4 different styles [6] and show how the different structure at the interface (in particular presence of co-oriented fibers on opposite faces) strongly influences the toughness. Their work moves from the results of the many studies carried out on multidirectional DCB specimens, where the interface may change from the 0/0 of the standard ASTM coupons [7] to other combinations (e.g. θ/0 or θ/-θ or others). This is a more realistic situation, while the 0/0 interface of the standard specimens is rather unusual to be critical in real structures. It was noted that the 90/90 interface resulted in a delamination path that strongly interacted with other damage mechanisms, such as matrix cracks, giving rise to continuous jumps from the upper interface with a non-90 ply to the lower one, and vice versa, absorbing substantially higher energy (see also [8,9]). Ref. [6] discusses the cases of symmetric and asymmetric yarn disposition at the interface, considering anyhow also situations that are not common in engineering practice. For instance, a 5H satin shows a different appearance if seen from one side or from the other: in one case, 80% of yarns are oriented in one direction and 20% in the other, while on the opposite face the ratio is reciprocal, 20% and 80%. It is evident that the interface plays a fundamental role: the situation of two mirror plies interface is evidently quite different from the situation of two equi-oriented plies stacked one on the other. A number of papers available in the literature are relevant to studies on fabric DCB specimens that refer to very specific interfaces, sometimes deliberately particular, that are anyhow unusual as well, in the same measure of the 0/0 interface [10,11].

In this experimental activity, it was decided to address the most frequent case, commonly used in the engineering practice, i.e. the one of a lay-up made of equally oriented plies stacked one over the other. Therefore the fabric specimens were manufactured by stacking 16 plies, equally oriented: this is the most realistic sequence. Therefore, at the delamination interface, the two neighbouring plies offered faces with different characteristics (one with prevailing longitudinal yarns and the other with prevailing transversal yarns), so that the probability of matching equally oriented bundles was intermediate between the extreme cases studied in the literature: the too optimistic, and therefore unconservative, case of complete overlap of the transversally oriented yarns is thus avoided. Too optimistic means that, according to fractographic observations [10,11], there are many failure mechanisms active during the delamination growth in a fabric DCB, and among others the debonding of 90-degrees oriented bundles is particularly helpful in absorbing energy, but also fiber failure, fiber pull-out, fracture of matrix resin, matrix plastic deformation and delamination front deflection are active mechanisms.

Significant examples of test data publication, supported by fractography and failure analysis, can be found in papers by Alif, Carlsson and Boogh [12], Alif, Carlsson and Gillespie [13], Pereira and others [14] and Martin [15]. Recently (2016) Czabaj and Davidson [16] have published an experimental work on the influence of temperature on the interlaminar fracture properties of a fabric carbon/polyimide system; obviously, with such a matrix, the objective of the paper was the study of the influence of the temperature (up to 300 °C) on the interlaminar fracture toughness expressed by that material, but an interesting literature review on fabric interlaminar toughness peculiar behaviour, substantially very similar to the one performed in the present work, completes the paper.

On the contrary, the main fracture mechanisms in unidirectional laminated composites are fibre debonding and matrix plastic deformation. The observation of other failure modes supports the general finding that 2-D woven fabric laminates show substantially higher interlaminar fracture resistance than unidirectional laminates.

3. Experimental program

The experimental program comprised different kinds of tests, i.e. Mode I on DCB specimens, Mode II on ENF specimens tested in three point bending and mixed mode I + II using the Mixed Mode Bending procedure. All of these are covered by ASTM standards, with the mode II procedure that has been published very recently, after the beginning of the experimental activity of this paper. The available ASTM standards [7,17,18] anyhow refer to unidirectional composite systems; in the case of the fabric system, the same approach has been used, even if some adjustments are necessary (e.g. requirement on the specimen thickness, to maintain the applicability of small deformation theory). A representation of the three tests is shown in Fig. 1.

Moreover, the characterization of the same material system at different fracture modes (Mode I, Mode II and Mixed I + II modes) points out the problem of having uniformity among the data reduction methods which are different between Mode I, Mode II and Mixed I + II mode fracture tests.