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Residual strength of a damaged laminated CFRP under compressive fatigue stresses

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Abstract

Laminated composite plates are extensively used in the construction of aerospace, civil, marine, automotive and other high performance structures due to their high specific stiffness and strength, compared to the conventional metallic materials. In general, these structures require high reliability assurance for which, the prediction of the maximum load that the structure can withstand as well as the failure process is very crucial. Compressive fatigue tests on damaged specimens of laminated CFRP's showed that the failure is dependent of a minimum delaminated area – allowable delaminated area. There is a correlation between the size of the allowable delaminated area, the critical number of cycles, and the critical fatigue stress. Monitoring the damage propagation by C-scan, different delaminated area growth ratios were defined for the test specimens. Correlating different data, a delamination growth relation was established that enables the evaluation of the residual strength of the CFRP.

Keywords: Composites; Laminated CFRP's; Damage tolerance; Fatigue; C-scan; Residual strength

1. Introduction

Laminated composite plates are extensively used in the construction of aerospace, civil, marine, automotive and other high performance structures due to their high specific stiffness and strength, excellent fatigue resistance, long durability and many other superior properties compared to the conventional metallic materials. In general, these structures require high reliability assurance for which, the prediction of the maximum load that the structure can withstand as well as the failure process is very crucial [1]. Due to the anisotropy of composite laminates and non-uniform distribution of stresses in laminae under several types of static/dynamic loading, the failure process of laminates is very complex.

Unfortunately, laminated composites have relatively poor mechanisms for absorbing energy due to local impact damage where loading is normal to the fibre plane. This is primarily due to the low strain to failure and low transverse shear strength of the graphite fibre and the brittle nature of the epoxy matrix. Since the early 1970s, researchers have been looking for methods to improve impact properties of graphite composites such as fibre and matrix toughening, interface toughening, through-the-thickness reinforcements, and hybridizing.

Considerable attention in the composite community has been given towards the effects of low velocity non-penetrating impact similar to that of a dropped tool, careless handling, or runway debris. This type of damage is most often undetectable by visual surface inspection, and can cause a significant reduction of the compression strength. In previous studies [2,3], it has been shown that low energy impacts may significantly reduce the load carrying capability of a composite component by as much as 50%.

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Crack growth rates in isotropic materials are well characterized and fatigue behaviour of these materials is rather well reproduced in laboratory. The detection an initial flow before it grows to a critical size is possible by the monitoring of the component condition using a maintenance programme based on a set of inspections [4]. The definition of the interval between inspections results from the combination of different parameters like material properties, load spectrum, experimental data and the physic limits of the NDI technology [5].

The composite materials anisotropy substantially turns the implementation of this maintenance approach difficult. Crack growth under in-plane tension cycle stresses, in laminated fibre reinforced composites, is not a major issue. The damage is greatly arrested by the fibres [6]. Resistance to fatigue crack propagation is increased and failure only happens at high stress levels. But, under the influence of compressive cycle stresses, the damage associated with delamination, a separation of the fibre reinforced layers that are stacked together to form laminates must be accounted. The presence of delamination may reduce the overall stiffness as well as the residual strength leading to structural failure. The low delamination resistance causes delamination cracks by slight impacts such as tool drops. In-plane compressive fatigue tends to increase delamination, promoting the accumulation of damage, correspondingly reducing the fatigue crack growth resistance of the composite.

Since the delamination cracks are usually invisible or difficult to find by naked eyes, the delamination causes low reliability for primary structures of laminated composites. In order to improve the low reliability, detection systems for delamination cracks in-service are required.

Apart from a few special cases, there are no generic, reliable models to predict fatigue life and residual strength of composite structures under compressive fatigue loads. The current work is aimed at understanding the mechanics of the degradation of the mechanical properties under these loads. Experimental work was undertaken in order to study the crack growth resistance under compressive loads and to propose a method to predict the residual strength of the damaged composite, based on the rate of the damage growth until an ultimate delamination area.

2. Experimental procedure

This study is concentrated on a laminated carbon-fibre reinforced epoxy matrix composite.

The material used is commercially known by Fibredux® 913C-HTA (12K)-5–40%, and it is supplied by Hexcel Composites Ltd., Duxford, Cambridge, CB2 4QD, UK. The pre-impregnated material (prepreg), was Torayca T300 HTA (12K) carbon fibres into which a pre-catalysed Fibredux® 913 epoxy resin system has been impregnated. Three different stacking sequences were used:

A – $[(45/0/-45/90)_s]_4$;
B – $[(45/0/-45/90)_4]_s$;
C – $(45_4/0_4/-45_4/90_4)_s$

Thirty-two prepreg tapes with 0.138 mm thick each were laid-up into 1000×1000 mm panels. Following the cure, specimens of dimensions 150×100 mm were cut from the panels. Circular holes of 25 mm diameter with a taper angle of 30° were drilled at the centre of the specimens.

Specimen was ultrasonically inspected to establish its quality and evaluate disbands, porosity and void content. Automatic scanning with specimen totally immersed in water using UltraPAC equipment supplied by Physical Acoustics Corp., producing C-scan printouts, was performed.

After the non-destructive evaluation, 39 damaged specimens were considered in the suitable condition.

Compression fatigue tests on laminated composites are not found to be standardized by the major Standard Agencies. Tests were conducting using an anti-buckling fixture in order to transform the complex stress state on the top and bottom edges of the specimen originated from the shear load on the grips in a uniaxial compression stress state on the specimen gage length.

Description of testing fixture (Fig. 1) can be found on Airbus Industrie Test Method AITM 1.0010. This

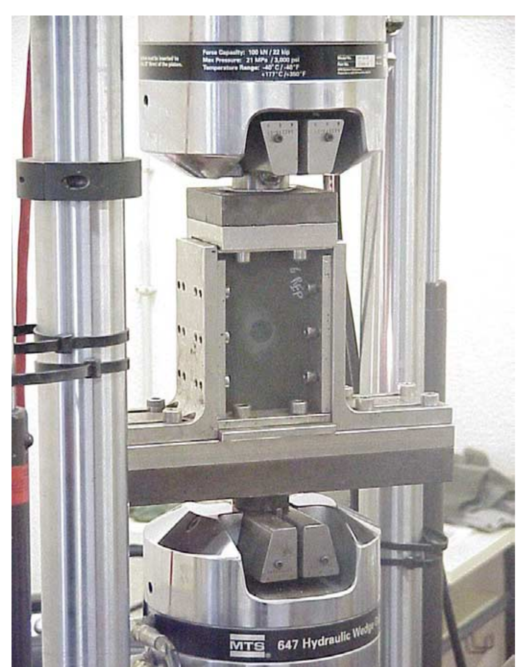

Fig. 1. Testing fixture used on the compressive fatigue tests.

standard testing device, developed for Compression After Impact (CAI) tests, is well suited to the type of tests performed on this work. Its 140×80 mm window size allowed a local out-of plane deformation of the specimen, but the specimen general buckling was prevented.

The compressive fatigue tests were performed on a MTS 810 servo-controlled hydraulic test machine at constant amplitude, load controlled, and with harmonic axial loading at a frequency of 5 Hz, which satisfy adiabatic condition. A cross-head loading rate of 100 N/s was used. The specimens were simply supported at loaded ends.

In order to establish the effects of the different loading parameters on the compressive fatigue damage growth, two sets of tests were performed:

- first set, to correlate delamination area, the number of load cycles and residual strength, per each stacking sequence;
- second set, to correlate the load level, the number of load cycles and the delaminated area, per each stacking sequence.

On the first set of tests, the maximum compressive load level was 70 kN. Ratio of the minimum and maximum compressive loads, R, was chosen to be 0.1 and kept constant during the test. Twenty-four specimens (8 of each stacking sequence) were tested. The specimen tests stopped at 25×10^3, 50×10^3, 75×10^3, 100×10^3, 125×10^3 and 150×10^3 cycles.

During the tests, the damage development on each specimen was assessed by C-scan ultrasonic inspection. At each load level, after every 5×10^3 cycles, an inspection and a delaminated area evaluation were made. Because the resultant damage is restricted to the darker zone shown in Fig. 4, only that zone was inspected.

After the fatigue tests, the specimens were inspected by C-scan ultrasonic inspection for damage assessment. To evaluate the residual strength, the specimens were statically loaded to complete failure rupture.

On the second set of tests, 15 specimens were tested. Maximum compressive load levels of 75, 80, 85, 90 and 95 kN were used.

The tests stopped at 1.5×10^5 cycles.

Damage was imaged by ultrasonic C-scan methods (Fig. 2).

After the tests, 2 of each type of specimens were removed and together with the residual strength test survived specimens, were sectioned for microscopic examination of the damaged areas for evaluation of the degree of damage imparted to the specimens due to the compression fatigue loading. Microscopic examinations on sectioned specimen damaged surfaces, using a MAXTASCAN 200 microscope, were performed. Output image data was managed by a computer data acquisition system and digitized images were produced.

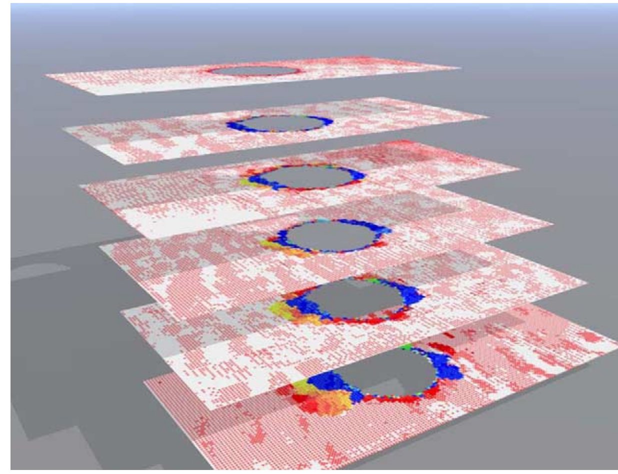

Fig. 2. Sequence of ultrasonic C-scan images showing damage evolution.

These section studies were useful for identifying the failure mechanisms.

The effect of an incorrect positioning of some specimen at the anti-buckling fixture was its premature failure. Collection of reliable data from these tests was not possible.

3. Results and discussion

Bergmann and Prinz [7] proposed a specific model for delamination growth correlating the delaminated area and the maximum amplitude of the energy release rate of a ply. The present work correlates the delaminated area of the laminated composite with its fatigue life and its static residual strength.

From recorded data [8], it is possible to observe that the normal projection of the different delaminated zones on a plane, here known by ‘delaminated area’, has an elliptical configuration which major axis is transverse to the load direction. The elliptical configuration of the accumulated damage remains, during cyclic loading, until the composite failure. The ellipse major axis rate of growth is much bigger than the minor axis rate of growth, that is why this one will be assumed constant (Fig. 3) [9].

When the delaminated area has the critical size, A_{cr}, the behaviour of sublaminates is similar to an unbalanced laminated bearing the entire compressive load. The sublaminate buckling leads to its failure, the loads transference by the remaining intact cross-sections is not even, the residual strength abruptly degrades and the composite collapses.

Adapting the classical fracture mechanics formulation, the delamination rate, dA/dN, on cyclically loaded laminates can be expressed by

$$\frac{dA}{dN} = k_1 \cdot f(\Delta G)^n = k_1 \cdot \varepsilon^p \cdot A^q, \tag{1}$$

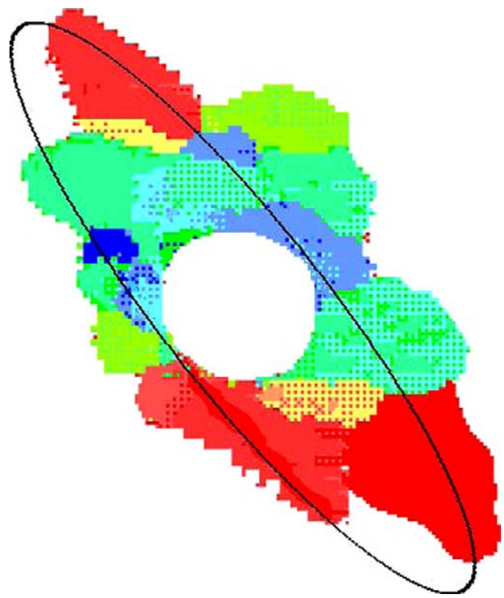

Fig. 3. Elliptical configuration of the delaminated area.

where ΔG is the maximum amplitude of the energy release rate and ε is the strain induced by the stress σ. k_1, p and q are experimentally evaluated constants.

In order to correlate the data from different laminated systems, a dimensionless parameter, λ is introduced, here referred as 'specific delaminated area'. The elliptical delaminated area, A_N, corresponding to a number of load cycles, N is defined by

$$A_N = a_N \cdot b_N,$$

where a_N and b_N are the major and minor axis of the ellipse, respectively.

In a similar way, the critical delaminated area, A_{cr} is defined by $A_{cr} = a_{cr} \cdot b_{cr}$, where a_{cr} and b_{cr} are the major and minor axis of the ellipse, respectively. Considering the low rate of growth of the minor axis, it will be assumed practically constant, or, $b_N = b_{cr} = b$.

Then,

$$\lambda = \frac{\mathrm{d}A_N}{\mathrm{d}A_{cr}} = \frac{\mathrm{d}a_N}{\mathrm{d}a_{cr}}. \tag{2}$$

Assuming that the critical buckling load is governed by

$$P_f = \frac{\pi^2 \phi}{a_{cr}^2} = \sigma_f \cdot t_d, \tag{3}$$

where P_f is the load intensity per unit width, ϕ is a buckling factor, σ_f is the stress intensity associated to the load and t_d is the width of the delaminated zone, from Eq. (3), it is possible to evaluate the size of the critical delaminated area in terms of σ_f

$$a_{cr} = \left(\frac{\phi_1 \pi^2}{\sigma_f}\right)^{\frac{1}{2}}, \tag{4}$$

where ϕ_1 is a buckling strength factor per unit of width of delaminated zone.

Generically, a delaminated area is defined in terms of the residual strength, σ_{res} by

$$a = \left(\frac{\phi_1 \pi^2}{\sigma_{res}}\right)^{\frac{1}{2}}. \tag{5}$$

Experimental data exhibit a correlation between λ and the number of load cycles through a potential function

$$\Delta = f\left(\frac{N}{N_{cr}}\right) = \left(1 - \frac{a}{a_{cr}}\right)^n = (1 - \lambda)^n, \tag{6}$$

where Δ is the damage index.

Upon integration of Eq. (1) and substitution of the limits for $N = 0$ with $a = a_0$, corresponding to the repaired area, and a cycle number N_{cr} for the critical delaminated area (residual strength equal zero) and introducing into Eqs. (4) and (5), the residual strength is

$$\sigma_0 = \left[\sigma_{cr}^{\frac{1-m}{2}} - \frac{N}{N_{cr}}\left(\sigma_{cr}^{\frac{1-m}{2}} - \sigma^{\frac{1-m}{2}}\right)\right]^{\frac{2}{1-m}}, \tag{7}$$

where σ_{cr} is the corresponding static stress for the critical delamination area, a_{cr}. Combining Eq. (7) with Eq. (6), the residual strength assumes the form

$$\sigma_{res} = (1-\lambda)^n \cdot \sigma_0$$
$$= (1-\lambda)^n \left[\sigma_{cr}^{\frac{1-m}{2}} - \frac{N}{N_{cr}}\left(\sigma_{cr}^{\frac{1-m}{2}} - \sigma^{\frac{1-m}{2}}\right)\right]^{\frac{2}{1-m}}. \tag{8}$$

Eq. (8) correlates the damage index, the number of load cycles, and the residual strength.

There is an ultimate damage size in the scanned area of the composite specimen corresponding to a critical delaminated area. The size of the critical area is stacking sequence dependent. Comparing the damage development of composites with different stacking sequences, delamination of the $(45_4/0_4/-45_4/90_4)_s$ specimens reached the critical delamination area size with fewer load cycles and lower load levels.

A good consistency between specific delaminated area distribution and the theoretical polynomial line described by Eq. (6) was observed (Fig. 4), when n assumes the value 1.54.

From test data it was possible to plot curves correlating the residual strength, the fatigue life and the specific area of delamination. These curves allow us to evaluate the m parameter and the critical values for the residual strength (corresponding to a zero fatigue life) and for the fatigue life (corresponding to a specific area of delamination, λ, equal 1).

These plots showed evidence of some stacking sequence dependence. But, the proximity of the values suggests that this dependence is negligible.

For $m = 0.13$ there are a good agreement between experimental data and predicted data from Eq. (8).

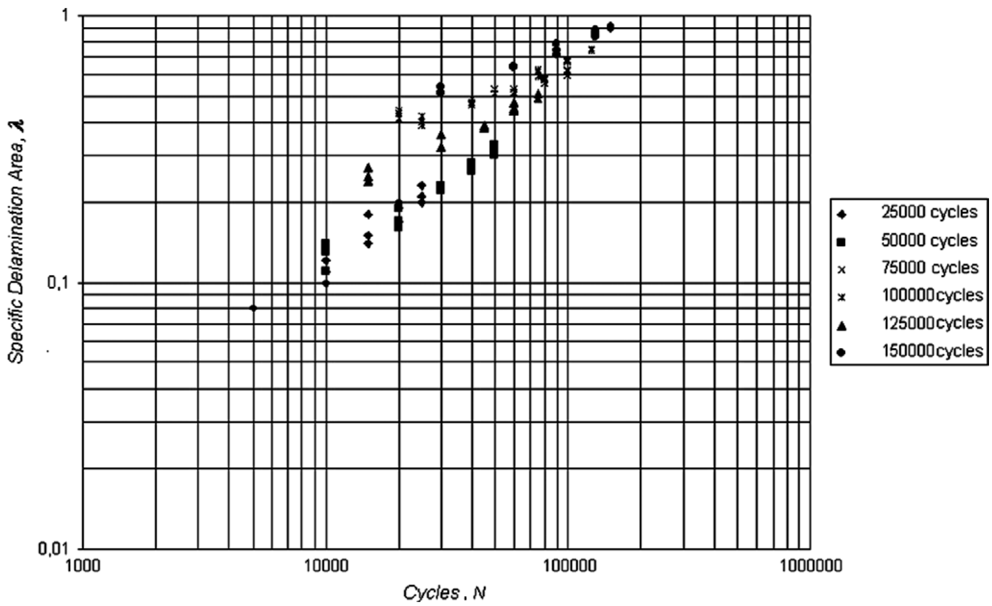

Fig. 4. Specific delamination area as a function of the fatigue life.

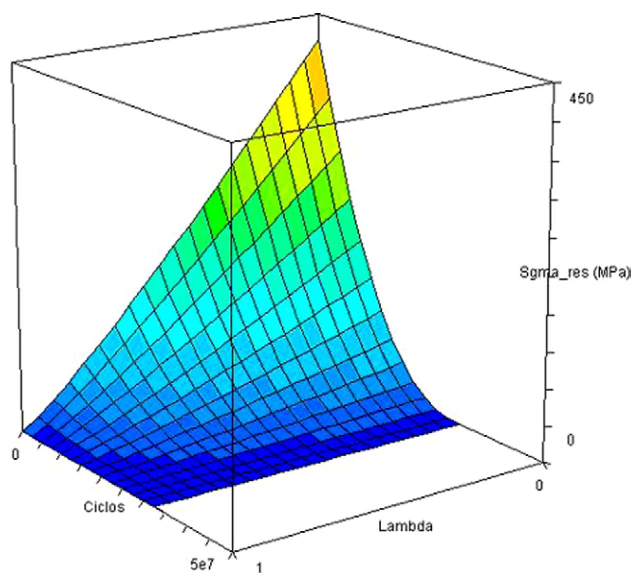

Fig. 5. Residual strength as function of the specific delamination area and the fatigue life.

The expectable values for the static residual strength, obtained from similar plots to the one shown in Fig. 5, are 418 MPa. The expectable fatigue life is 5×10^6 load cycles.

4. Conclusion

Laboratorial test data analysis indicated that:

- the composite residual strength can be predicted from a maximum accumulated compressive fatigue damage size, which can be evaluated from the normal projection of the different delaminated zones on a plane,
- it is possible to define a potential function correlating damage index, Δ, and residual strength,
- it can be established a correlation between the specific area of delamination, the fatigue life and the residual stress,
- the size of accumulated damage of the composite under certain stress level, and therefore, its residual strength, is dependent of stacking sequence,
- it exists a good agreement between experimental data and theoretical data obtained from a model proposed on this work. This model correlates the accumulated damage, fatigue life and static residual strength.

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