Experimental Analysis of Debonding of Skin/Stringer Interfaces under Cyclic Loading and Ageing

Ahmed Abbadi, Laurent Michel, Bruno Castanié

EXPERIMENTAL ANALYSIS OF DEBONDING OF SKIN/STRINGER INTERFACES UNDER CYCLIC LOADING AND AGEING

Ahmed Abbadi[1], Laurent Michel[1] and Bruno Castanié[2]

Université de Toulouse; INSA, UPS, Mines Albi, ISAE; ICA (Institut Clément Ader);
[1]ISAE, 10, avenue Edouard Belin, F-31055 Toulouse, France
[2]INSA, 135 Avenue de Rangueil, 31077 Toulouse, France

ABSTRACT

An experimental investigation aiming to characterize the fatigue failure mechanisms and effect of ageing of skin/stringer interfaces is presented. A simplified specimen known as a "stringer foot specimen" is used. The effects of local design, of the angle of plies located at the interface and of moisture ageing are studied. Among other results, it is shown that a quasi-infinite fatigue life can be obtained under 33% of the static damage initiation load for all designs. In the framework of multi-level analysis, this study is a preliminary investigation to study cyclic buckling of composite stiffened structures.

Keywords: Interface, fatigue, Skin/stringer debonding, moisture ageing, Postbuckling.

1. INTRODUCTION

The present study aims to analyse the skin/stiffener behaviour of aeronautic structures under fatigue loadings. A simplified specimen known as "stringer foot specimen" is used. A recent material (T700/M21) is considered and the influence of some design details and ageing are studied. The experiments were conducted to focus on the influence of two types of interfaces, ((0°/0°) or oriented (+45°/-45°)), local design effects (straight edges and tapered edges) and moisture ageing on the onset of fatigue and speed of crack propagation. Globally, these tests demonstrate that the response to cyclic debonding for lower loads is acceptable for stringer foot specimens. The onset of delamination may occur after millions of cycles and the propagation of cracks is stable and slow for loads equal to 50% of Limit Loads.

This analysis falls within the framework of multi-level analysis already developed to analyse skin /stiffener debonding [1, 2] or other problems, such as pinned junctions [3] under static loading (see Fig. 1). Although, in practice, the ultimate goal is the analysis of the separation of stiffeners on full-scale panels, the implementation of testing and modelling at these large scales is difficult, even under static loads. So, simplified tests must be conducted on a less complex structure. The choice of the level of analysis using "non-specific" specimens is illustrated in Fig. 1. Such specimens are representative of a technology (materials, design and manufacturing methods) but independent of any particular programme or aircraft zone. Here, the specimen is composed of a laminate (the skin) where an over-thickness (the flange) has been added, as initially proposed by Minguet et al [4] (see Fig. 2). It is known as a "stringer foot specimen". These specimens are subjected to four-point bending, which leads to interface failure between the flange and the skin. Thus, the phenomenon of skin/stringer debonding can be studied first by means of non-specific specimens. This scale of analysis also gives results closer to the reality of the substructure than DCB or ENF tests. It also allows different design configurations to be analysed more easily and economically.

Composite structures are now widely used in aerospace applications due to their good fatigue resistance when subjected to in-plane loads and their light weight. According to the manufacturers' policy, skin/stiffener interfaces are not designed with fatigue loading in mind and the interface only has to sustain static loads up to ultimate loads [1-3]. However, optimizing the mass of this kind of structure will require postbuckling to occur under limit loads as in the case of a metallic fuselage. So, buckling and unbuckling should occur many times, thus creating cyclic out-of-plane loading of the interface and requiring fatigue of the interface to become a design basis.

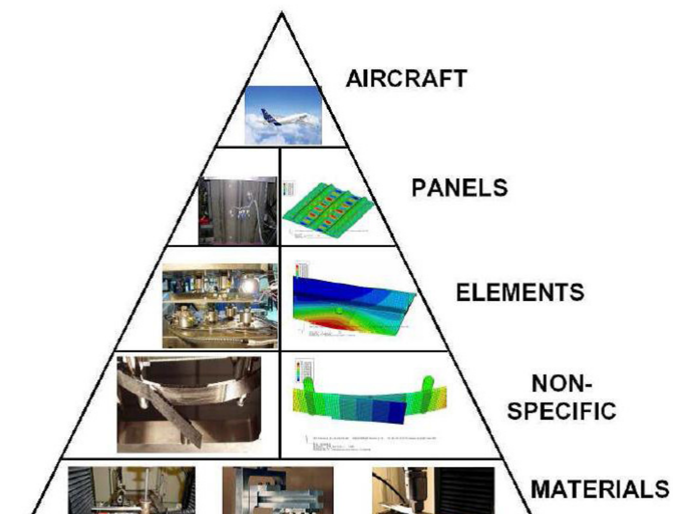

Fig. 1: Multi-level analysis applied to skin/stringer debonding (reproduced from ref [1]).

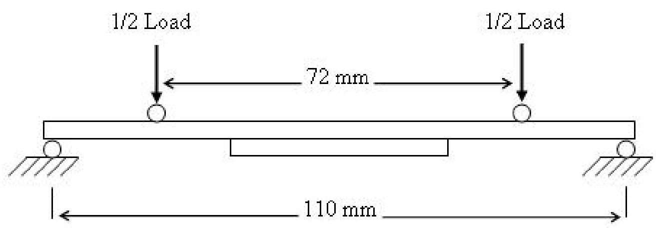

Fig. 2: Specimen geometry and configuration, unit: mm and Four-point bending test principle

Numerous studies have been devoted to the fatigue of composites over several decades [5, 6]. However, the authors focused essentially on in-plane responses (for example, single lap shear joints [7-8]). Many studies have also been directly concerned with modes I [9, 10] with DCB specimens, II [11,12] with an ENF specimen or even III [13]. So far, few data exist on the fatigue debonding of skin/stiffener interfaces. Researchers have mainly focused on the difficult modelling of static postbuckling and the debonding of stiffeners by various global/local techniques [1-2, 14-17], on pre-sizing methods based on analytical models [18, 19] or, more recently, on advanced computational techniques [20]. At the scale of the panel (see Fig. 1), very few results are reported in the literature for cyclic buckling. Weller and Singer [21] in the early 90's reported favourable behaviour of stiffened composite panels subjected to repeated buckling under shear and compression. In the E-U COCOMAT programme, tests conducted under fatigue [22, 23] showed very good behaviour of panels in fatigue even after postbuckling. Cyclic tests up to 50,000 cycles were performed without significant damage. Non-specific specimens have also been used to analyse design effects or environmental effects on static debonding loads [1] or to validate computational methods [24-26] for static loads. Some investigations have also been carried out on these specimens for fatigue analysis. Cvitkovich et al. [27] investigated the fatigue damage mechanisms and identified the influence of skin lay-up in carbon epoxy composite bonded skin/stringers. In this investigation, four-point-bending fatigue tests were performed. Microscopic observation was used to document the initiation of matrix cracking, delamination and fatigue delamination growth. The location of the 90° skin and flange plies relative to the bondline was identified as the dominant lay-up feature controlling the location and onset of matrix cracking and subsequent delamination for the two stacking sequences studied. The study was limited to one material (IM6/3501-6 graphite/epoxy prepreg tape) at room temperature. Krueger et al. [28] developed a new methodology to determine the fatigue life of bonded composite skin/stringer for a tapered configuration based on the same test method.

This short analysis of the literature shows a lack of knowledge in this field. This paper therefore aims to provide additional, recent results on the fatigue debonding of stringer foot specimens which, a priori, should give valuable results for cyclic buckling of larger structures. The next subsection of this paper will describe the experimental study and its objectives. Then the results will be discussed and some conclusions drawn.

2. EXPERIMENTAL STUDY

2.1. Description of specimens and test matrix

The geometry of the specimens is illustrated in Fig.2. Specimens were manufactured by hand lay-up of a unidirectional, 134 g/m^2, T700/M21 pre-impregnated laminate. Both the skin and the flange laminates had a multidirectional lay-up, containing 0°, 90°, +45° and -45° plies. Skin and flange thicknesses were 2.08 mm (16 plies) and 1.82 mm (14 plies) respectively. The stacking sequences are given Table 1. In the case of tapered edges, only one type of interface was used, 0°/0°. One objective of the study was to analyse the local design effects by using two kinds of local stacking: straight edges (easy to manufacture and cheap) and tapered edges (more complicated to stack but better under static loading [1]). For these two configurations, the effect of ageing was analysed. The ageing was carried out at 70°C and 85% humidity for 120 days. These conditions of humidity and temperature were assumed sufficient to saturate the specimens with respect to their thickness. Two ways of assembling the flange were also analysed: co-cured (flange laid up at the same time as the skin) and co-bonded. In the case of co-bonding, the skin was polymerized first and the flange was laid up and placed on the skin with an FM300K.05 adhesive film between the two parts. A second polymerization was thus necessary for these specimens. The 0°/0° interface was chosen to enable comparison for ageing and design effects. The behaviour of two types of interface, 0°/0° and 45°/-45°, was also analysed but only for straight edges. Thus 6 different configurations were analysed. The experiment matrix and the number of specimens tested are given Table 2.

Table 1: Stacking sequences of the flanges and skins

Interfaces		Stacking Sequence	Thickness(mm)
0°/0°	Skin	$[90/+45/0/-45/-45/0/45/0]_S$	2.08
	Flange	$[90/+45/0/0/-45/0/0]_S$	1.82
45°/-45°	Skin	$[+45/90/-45/0/-45/0/45/0]_S$	2.08
	Flange	$[-45/0/-45/0/90/0/0]_S$	1.82

Three load levels were fixed: 66%, 47% and 33% of the 1st static damage initiation load (F_{ini}) found by Bertolini et al. [1] under static four point bending. These values represent respectively 1.LL, 0.7.LL and 0.5 LL. The limit loads (LL) are the maximum loads that any aircraft can be subjected to during its life. Below the limit loads (LL), the structure must be calculated for use under fatigue loading and this is the reason why absence of crack growth is mandatory for composite parts. The ultimate loads (UL) are equal to 1.5

Table 2: Test Matrix

	Straight Edges 0°/0°	Straight Edges 0°/0° + Co-Bonding	Straight Edges 45°/-45°	Straight Edges 0°/0° + Ageing	Tapered edges 0°/0°	Tapered edges 0°/0° + Ageing
100% (static)	3 Specimens (F1=567 N)	3 Specimens (F1=884 N)	3 Specimens (F=505 N)	2 Specimens (F=481 N)	2 Specimens (F=932 N)	2 Specimens (F=1055 N)
66%	2 Specimens (F2=378 N)	2 Specimens (F2=589 N)	4 Specimens (378N and 313 N)	4 Specimens (378 N)	3 Specimens (620 N)	3 Specimens (620 N)
47%	2 Specimens (F3=264 N)	2 Specimens (F3=413 N)	3 Specimens (264 N)	3 Specimens (264 N)	3 Specimens (440 N)	3 Specimens (440 N)
33%	1 Specimen (F4=189 N)	2 Specimen (F4=294 N)	1 Specimen (189 N)	3 Specimens (189 N)	3 Specimens (310 N)	2 Specimens (310 N)

LL and the structure must sustain these loads only statically. This ability is validated by static certification tests, which are required before the aircraft is allowed to fly. The average value of Fini for the static tests was found to be 567 N and 932 N for the straight and tapered edge configurations respectively, for 0°/0° interfaces at room temperature without ageing. For +45°/-45 interfaces, the static value was lower (505 N, [1]) but the same fatigue load levels were applied to enable a direct comparison. Two more tests at 333 N (i.e. 0.66 x 505 N) were also integrated in the test results. The static strengths for aged specimens were found to be slightly different [1] but, for practical reasons and also to enable a direct comparison, the same fatigue load values were applied. A total of 61 specimens were tested.

2.2. Description of tests and monitoring conditions

A four-point bending fatigue test was preferred to three-point bending in order to limit the risk of breaking the skin as done in the static study [1]. Moreover, no transverse shear occurred at the debonding location. The upper supports were mobile and placed 72 mm apart, and the lower supports were fixed 110 mm apart (see Fig. 2).

For each configuration, fatigue tests were run under a sinusoidal waveform. The test frequency was set at only 4 Hz (to avoid temperature effects and due to the flexibility of the specimen under bending, which affects the PID of the machine) with a load ratio, R = F_{min}/F_{max}, of 0.1 (F_{min} and F_{max} are, respectively, the minimum and maximum loads applied during a fatigue cycle). 4 Hz is very slow and is the reason why some experiments that required a long testing time were limited to only one specimen (see Table 2). The minimum and maximum displacements during fatigue tests were recorded as a function of the number of cycles. The cyclic loading was stopped depending on the load level and a camera was used every 100, 1000 and 10000 cycles to document the occurrence, delamination onset and propagation of cracks.

At the higher load levels (66% and 47% of the static damage initiation load) the start of cracking was detected visually by taking a photograph of the side of the specimen, locally painted white. At lower load levels (33% of the static damage initiation load) the test was stopped and the specimen was placed in a three-point bending rig as shown in Fig. 3. Then a small load was applied to open the crack delaminations slightly, by hand tightening a screw, to increase the visibility of the damage and the crack length with the specimen and rig placed under a microscope. This procedure was almost the same as in Cvitkovich et al. [27].

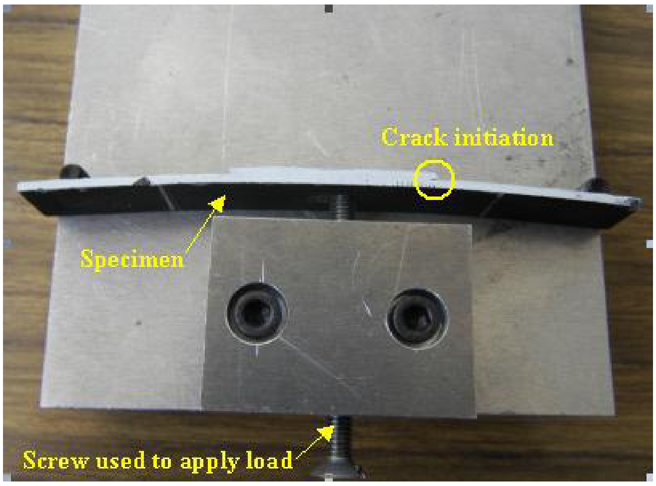

Fig. 3: Three-point-bending rig with specimen in place

3.1. Interface effect (straight edges)

In Fig. 4, the number of cycles to the onset of delamination is given versus the applied load. Tentative curve fitting is also provided to highlight the difference between the three interfaces. In the case of static behaviour, the onset of delamination is globally the same for 0°/0° and 45°/-45° interfaces despite discrepancies in the results [1]. In fatigue, the curve fitting shows that the 45°/-45° interfaces seem to delay the onset of delamination. This phenomenon is clearly visible at ratios of 47% and 33%. For the 66% ratio, the onset of delamination occurred at a low number of cycles, about one thousand, although, for lower loads, it started after more than one million. These results demonstrate the possibility of cyclic out-of plane loading for such structures. In the case of co-bonded 0°/0° interface, the gain is significant in static loading (+56%) but the results show

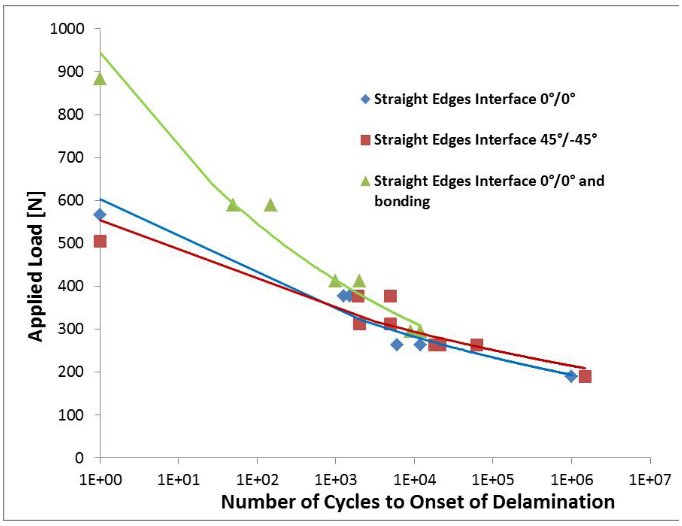

Fig. 4: Maximum cyclic load as a function of the number of cycles to delamination onset for straight edges

clearly that this gain is lost under cyclic loadings.

Even though it was not a key feature of the analysis, the speed of propagation was also monitored. For the first two interfaces (not bonded), the crack propagated very slowly with the number of cycles (see Fig. 5). The same observation was made for the 33% ratio. This figure shows that, for a number of cycles six times greater, the 45°/-45° interface had slower crack propagation speed than the 0°/0° interface. Furthermore, the tests showed that this interface

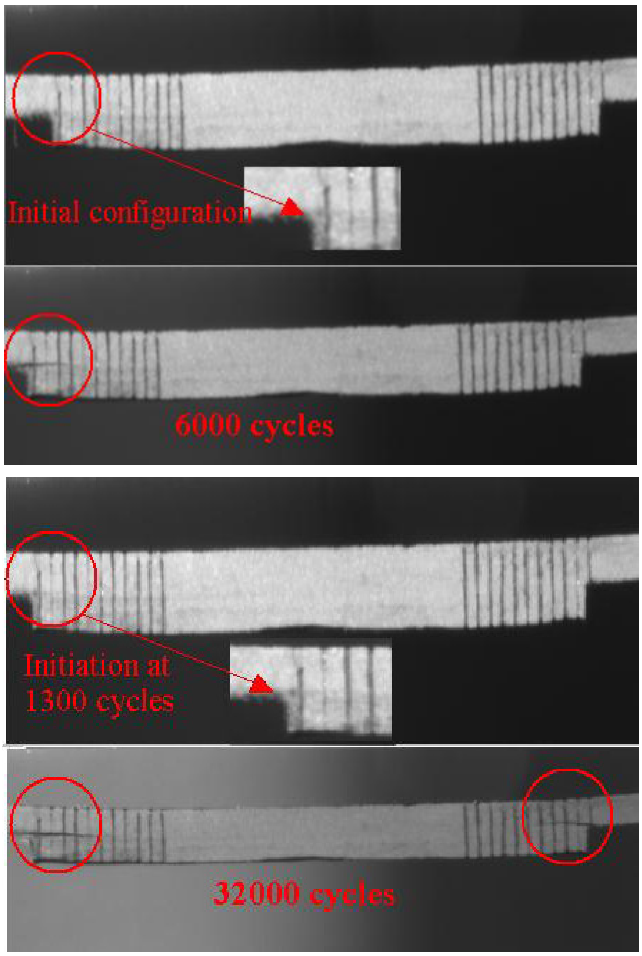

Fig. 5: Behaviour of co-cured specimens with straight edged configuration, interface 45°/-45°, at load level of 66%.

slowed down the crack propagation significantly. This observation is consistent with static DCB experiments [29] reported in the literature.

3.2. Geometry effect (comparison between straight and tapered edges)

For this analysis, the interfaces were the same (0°/0°) for all specimens. The tapered edged specimens were cycled under a high load condition, of the order of 620 N (representing 66% of the monotonic static tests, see Table 2) compared to the cyclic loading of 378 N used for straight edged specimens (which also represented the same percentage, 66%, of the monotonic static tests). It was confirmed that in fatigue also, the tapered edges significantly delayed the initiation of delamination compared to straight edges (Fig. 6). For the second test at 33%, the test was stopped at 2.2 million cycles, i.e. after more than one week of testing. Nevertheless, this configuration (tapered edges), exhibited faster crack propagation speed than the straight one. Fig. 7 gives some pictures of the fast crack propagation for 66% of the static load. In Fig. 8, for a load of 440 N, corresponding to 47% of the monotonic load, the delamination lengths are plotted versus the number of cycles. The positive role of tapered edges in delaying the initiation of delamination seems to be reduced by this faster, and thus more critical, crack propagation. However, it is important to note that the load level is always significantly higher in comparison to straight edges (378 N) and, since the length of the crack does not increase the critical energy release rate as shown in [29] for this interface, it is not surprising that the crack propagation is very quick at this load level.

3.3. Effect of ageing (straight and tapered edges)

The onsets of delamination of pristine and aged specimens are shown in Figures 9 and 10 for straight and tapered edges respectively. Fatigue tests on aged specimens showed that the crack was initiated earlier than in unaged specimens, for both configurations. This result is in good

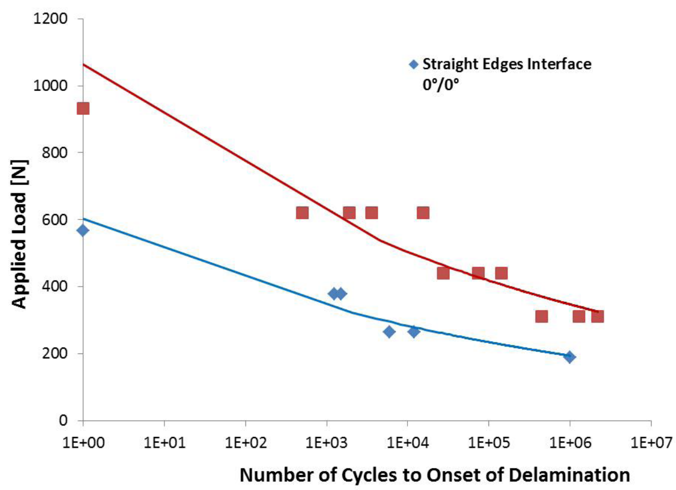

Fig. 6: Comparison to onset delamination between straight and tapered configuration

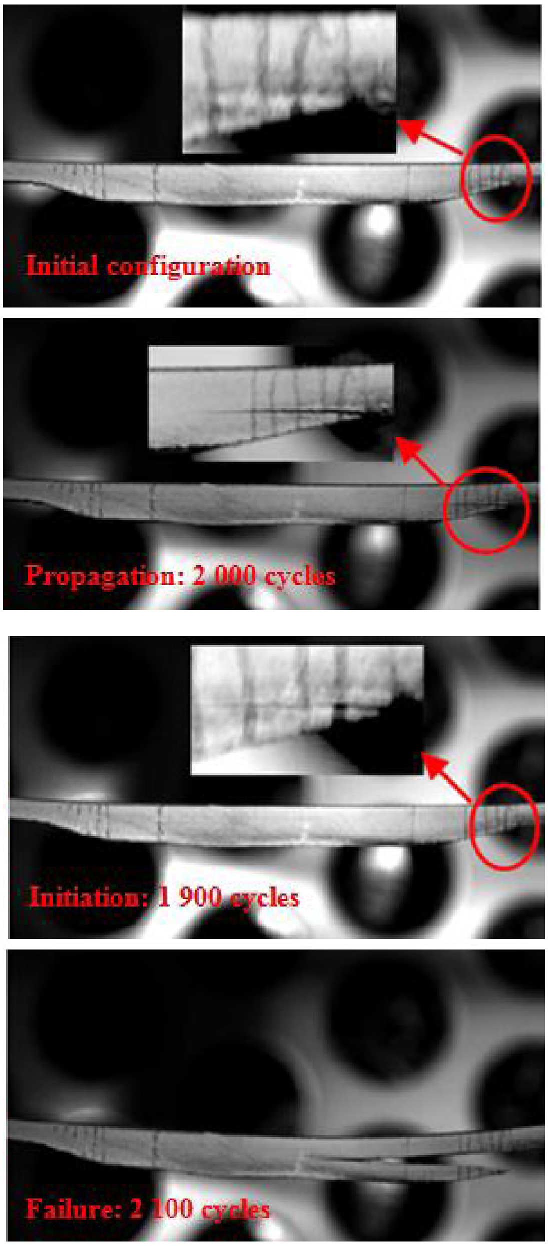

Fig. 7: Behaviour of co-cured specimens with tapered edge configuration, interface 0°/0°, at load level of 66%

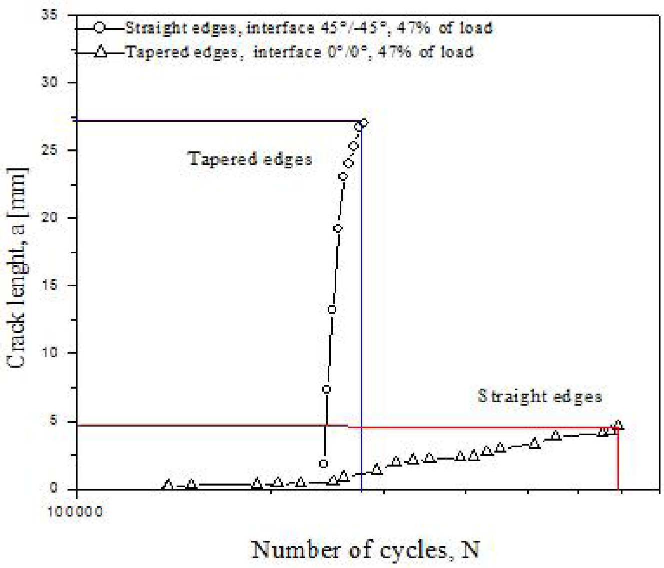

Fig. 8: Delamination length versus number of cycles for both configurations at 47% of static load

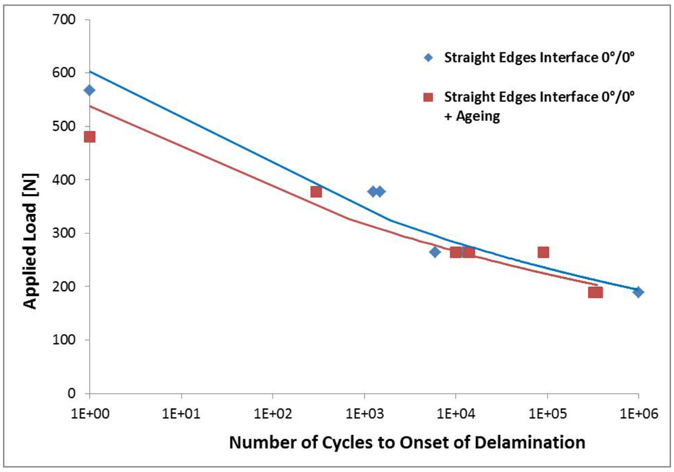

Fig. 9: Number of cycles to delamination onset for aged and unaged specimens (straight edges)

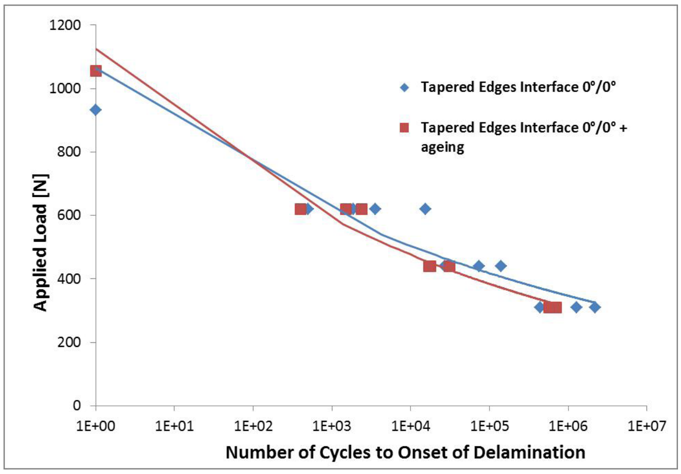

Fig. 10: Number of cycles to delamination onset for aged and unaged specimens (tapered edges)

agreement with static test data obtained by [1]. Ageing of samples has little influence on the propagation of the crack once initiated but, in the case of straight edges, the fatigue onset threshold of aged samples showed a decrease of 33% compared to unaged specimens (for a load of 400 N). In the case of tapered edges, this decrease was about 34% for the same load (400 N). This shows that the ageing phenomenon should be taken into account when sizing composite structures subject to repeated out-of-plane loading.

4. CONCLUSIONS

Fatigue tests were performed on stringer foot specimens with two design options (straight edges and tapered edges), two manufacturing procedures (co-cured and co-bonded) and two other parameters: the orientation of the plies located at the interface, and ageing. The fatigue test results were presented in standard S/N diagrams. The onset of delamination occurred between the skin and the flange for all configurations thus also validating the use of the stringer foot specimen to analyse skin/stiffener debonding in fatigue. The design with tapered edges significantly delayed delamination initiation compared to straight edges. For 33% of the Ultimate Load, representing 50% of the Limit Load, the onset of delamination occurred only after 106 cycles and one test had to be stopped after 2.2 million cycles. It is also noteworthy that these results were obtained for applied loads significantly higher than those used with straight edges (310 N vs 189 N). The only drawback of this design is that crack propagation was significantly faster because of the higher loads. For the analysis of straight edges with different interfaces (0°/0°, 45°/-45° or 0°/0°bonded), unlike in static conditions, it seems that the 45/-45° delays the onset of delamination. Then, with straight edges, the crack propagates slowly with the number of cycles but crack propagation is slower for the 45°/-45° interface than the 0°/0° interface. For co-bonded specimens, the marked gain under static conditions is not found in fatigue tests. Thus this manufacturing procedure has to be avoided in cases of cyclic buckling. The fatigue test results on aged specimens for both configurations (straight and tapered edges) showed that the crack was initiated earlier than in unaged specimens, while ageing had little influence on the propagation of the crack once initiated. Tests should also be performed at low (-50° C) and high (70° C) temperatures to check the response of the structure. Nevertheless, some preliminary but incomplete results show that the temperature has little influence on debonding in this case [29]. Globally, these tests demonstrate that the response to cyclic debonding for lower loads is acceptable for stringer foot specimens. The onset of delamination may occur after millions of cycles and the propagation of cracks is stable and slow for loads equal to 50% of limit loads. So the preliminary results presented in this paper should encourage the design and testing of large stiffened composite structures under repeated buckling to validate the conclusions and trends at larger scales.

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