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Propagation of delamination zones in bonded joints

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Abstract. Delamination is one of the main failure mechanisms in bonded composite joints. Owing to a considerable spatial scatter in adhesion over the interface in such joints, initiation of a delamination zone and propagation of its front are highly random processes. The main delamination front is rather tortuous, and many small delamination spots are formed in its immediate vicinity. These processes can be additionally complicated in the case of loading types such as fatigue and/or multiple impacting. This paper deals with experimental methods of analysing delamination zones at various stages of their evolution. X-radiographs of delamination zones are digitalized and scaling analyses based on fractal and multifractal approaches are performed in order to quantify the morphology as well as the damage distribution in the immediate vicinity of delamination fronts.

Key words: delamination, bonded joints, scaling, roughness exponent, multifractal spectrum.

1. INTRODUCTION

Recent years have seen an increased use of bonded composite joints in various applications (e.g. aerospace industry). This can be attributed to several factors, such as the high strength-to-weight ratio and low stress concentration of bonded joints compared to bolted or riveted joints. Such development presupposes a detailed analysis of reliability and failure of such joints. It has been shown that composite joints demonstrate a variety of failure modes depending on the manufacturing processes [1]. This situation can become more complex with the transition from (quasi)static loading to conditions that more adequately reflect the in-service loads, namely, fatigue and impact fatigue [2,3]. The effect of repetitive loading in an adhesive joint is more complicated than that in a homogeneous material and the adhesive itself is usually a composite material [4]. The most dangerous failure mode is linked with propagation of a delamination crack, resulting in functionality deterioration of the joint and its eventual fracture.

The propagation of delamination zones is a nontrivial process that cannot be easily measured and quantified. Carbon fibre-reinforced (CFRP) composites lack the transparency of glass-fibre reinforced composites, making any in-situ measurements a cumbersome task. A number of techniques are used to study the evolution of delamination in bonded composite joints subjected to various forms of loading. These techniques include X-ray radiography, sectioning, and electronic speckle pattern shearing interferometry (ESPSI) [1]. In contrast to the first two methods, ESPSI provides an in-situ capability but at a price – currently – of reduced detail in characterization of the delamination front's features.

This paper examines various aspects of the evolution of delamination zones in bonded CFRP lap-strap joints tested under various loading conditions and suggests several parameters, including scaling ones, to characterize such zones.

2. EXPERIMENTAL STUDY

Specimens for experimental studies were manufactured by adhesive bonding cured panels of T800/5245C CFRP. The composite panels were formed from unidirectional prepreg with a volume fraction of fibres of 0.6 and layer thickness of 0.125 mm. The adhesive used was Hysol Dexter's EA9628, which was supplied as a 0.2 mm thick film. Lap-strap joints (Fig. 1) were manufactured using pre-cured CFRP laminate sheets. Assembled joints of adhesive and CFRP were cured in an autoclave for 60 min at 120 °C. Specimens were cut from the bonded panels using a diamond saw. End tabs were bonded to the samples to aid grip in the fatigue tests and to provide load alignment.

A servo-hydraulic fatigue testing machine with digital control and data logging was used in the standard fatigue tests. Testing was under displacement control conditions using a sinusoidal wave with the stress ratio

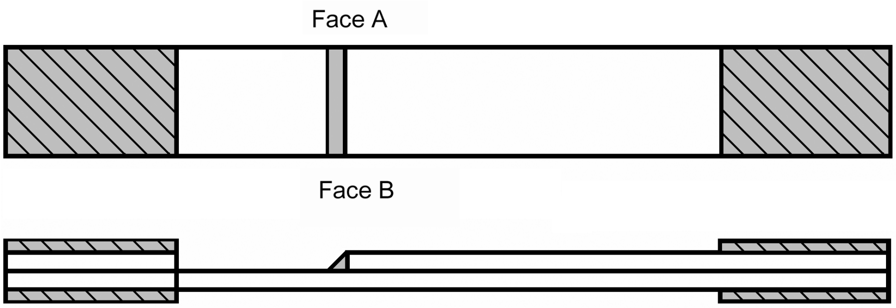

Fig. 1. Bonded composite joint (plan and side views).

$R = \sigma_{\min} / \sigma_{\max} = 0.1$ and frequency 5 Hz. The maximum displacement was selected to generate an initial force that was 56% of the quasi-static failure load [2]. Axial impact fatigue was implemented using a modified CEAST RESIL impactor, as described in detail in [3]. In these tests a specimen is fixed at one end (the right-hand end in Fig. 1) to an instrumented vice whilst a hammer strikes an impact block attached to the other (free) end.

The process of delamination crack initiation and propagation between two bonded plates was monitored during the tests by observation of opposite edges of the specimen. The tests were interrupted before the final failure, and a specimen with a well-developed delamination crack was studied, using penetrant-enhanced X-radiography (PEXR) to visualize the shape of the crack/delamination front and the nature of damage in the process zone ahead of the main crack in such joints. After testing, both edges and fracture surfaces were examined with an optical microscope. Selected fracture surfaces were extracted using a diamond saw and gold coated. These were then examined in greater detail using scanning electron microscopy (SEM).

3. EXPERIMENTAL RESULTS AND DISCUSSION

Our test results vividly demonstrate [2,3] that the level of energy associated with damage in impact fatigue is significantly lower than that for similar damage in standard fatigue. Though for both types of loading delamination initiates in the adhesive layer and then propagates into the ply of the composite adjacent to it, the mechanisms of failure are very different. Analysis by SEM shows that the failure surfaces observed in impact fatigue are in fact very different to those in standard fatigue: they are generally less uniform and exhibit more signs of high-rate/brittle fracture than fracture surfaces after standard fatigue testing.

Analysis of delamination propagation also demonstrates differences in response to the two regimes of loading. Standard fatigue shows an initiation period followed by an acceleration phase. After this there is a stage of propagation with a nearly constant rate until a second acceleration phase is reached. Impact-fatigue is characterized by two principal tendencies: fast crack growth in the early fatigue life, i.e. below 10 000 cycles, followed by slow crack propagation. Initial measurements indicate a crack growth rate at the early stages of impact-fatigue in excess of 2.4×10^{-3} mm/cycle. In contrast, the maximum rate measured for the initial 20 mm of crack growth in standard fatigue was approximately 1.4×10^{-3} mm/cycle.

Multiplicity and the difference in mechanisms, responsible for the evolution of a delamination zone, as well as their realization at different stages of loading cause, together with a mixed-mode character of fracture, a complex type of delamination front. Even without a detailed analysis of its shape, which is impossible with the only available in-situ technique, ESPSI, it is clear that it is not a straight line, parallel to a position of the fillet (see Fig. 1). Measurements of crack length from both specimen’s edges during the loading history (Fig. 2)

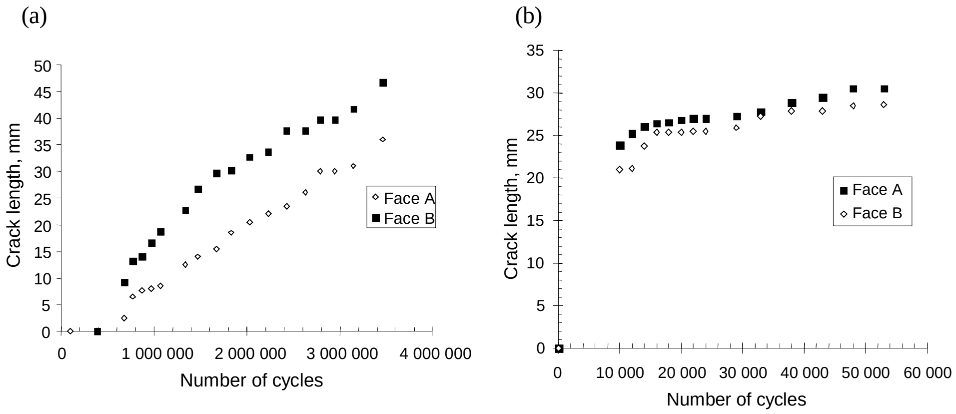

Fig. 2. Evolution of delamination in standard fatigue (a) and impact fatigue (b). Measurements were performed on two opposite edges of the specimen – Face A and Face B.

vividly demonstrate differences in its propagation in various parts of the specimen. Not only does the crack at one edge show an accelerated delamination, but also the respective rates change at various stages, resulting in phases of relative 'catching up' or 'slowing down'.

To get a better understanding of the real geometry of delamination fronts, penetrant enhanced low-kV X-radiography was performed to observe the delamination front across the sample width and to assess damage ahead of the crack front after a specific number of impacts. The X-radiographs of the delamination zones were digitalized in order to perform the scaling analysis based on fractal and multifractal approaches [5–7] used to quantify the morphology as well as distribution of damage in the immediate vicinity of the delamination fronts.

4. SCALING ANALYSIS

A typical result of a digitalized delamination zone from an X-radiograph is shown in Fig. 3a. As in Fig. 2, one of the edges (the top one in Fig. 3a) propagates quicker than the other one. It is also seen that the highest delamination length is not at the edges but somewhere in the middle of the specimen. Obviously, this cannot be registered by observing only the edges. However, such a convex shape of the delamination front is not a universal feature of the process as in some specimens a concave shape is observed. This, together with the change in the in-plane slope of the delamination front as well as our SEM analysis, proves that the shape of the delamination front is a result of the interaction of multiple failure mechanisms at various spatial and temporal scales.

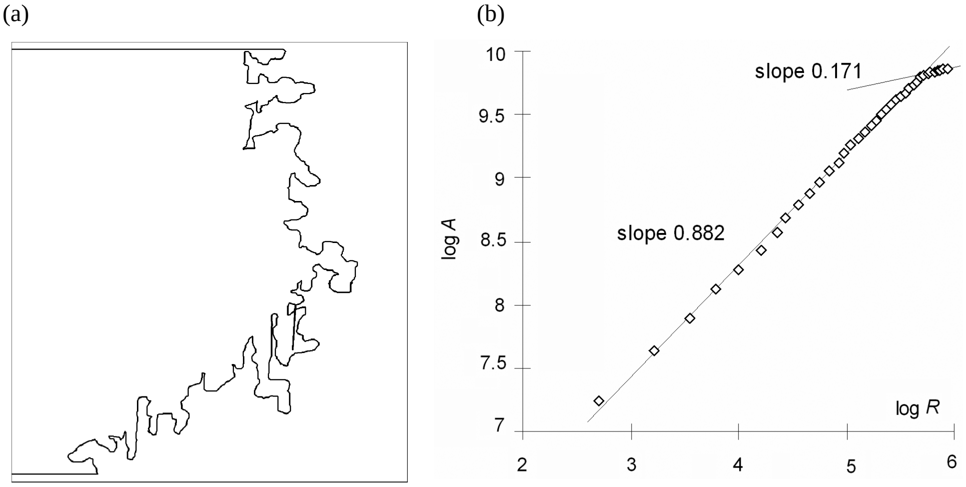

Fig. 3. The delamination zone (growing from left to right) (a) after 6×10^4 cycles of standard fatigue and scaling of its area (b).

The resulting delamination front is highly tortuous, and so the ideas of scaling analysis can be applied to characterize it. Study of the distribution of the damaged area A with the changing distance R along the propagation direction (Fig. 3b) demonstrates the presence of two areas with significantly different scaling exponents: the farthest part has an exponent that is five times lower than that for the part close to the delamination occupying the entire width of the specimen (left part of Fig. 3a). In-plane roughness of the delamination front can be studied by the method developed in [7] and used for an in-plane roughness analysis of the crack front, e.g. in [6]. The respective scaling law $y_{\max}(r) \propto r^{\zeta}$ contains the scaling exponent ζ that characterizes in-plane roughness, linking the maximum variation in the delamination length $y_{\max}(r) = \left\langle \max y(r')|_{x<r'<x+r} - \min y(r')|_{x<r'<x+r} \right\rangle|_x$ (x is the coordinate along the crack front) and a given window size r, for which this difference is determined. The calculated magnitude for the roughness exponent is $\zeta = 0.37$ (Fig. 4a).

Another tool to quantify the scaling character of the delamination zone is the multifractal analysis [8] that has been used to analyse, e.g. load distributions near crack fronts and is applied here to a distribution of damage (delamination length) along the front. According to this method, a stochastic distribution can be described in terms of a function, $f(\alpha)$, linking scaling exponents α from the finite interval $[\alpha_{\min}, \alpha_{\max}]$ with the (Hausdorff) dimension of the support of a particular measure, in our case – probability of delamination n_j in box (j):

$$\alpha = \lim_{l \to 0} \frac{1}{\log l} \sum_{j=1}^{N} \mu_j \log n_j, \qquad f = \lim_{l \to 0} \frac{1}{\log l} \sum_{j=1}^{N} \mu_j \log \mu_j, \tag{1}$$

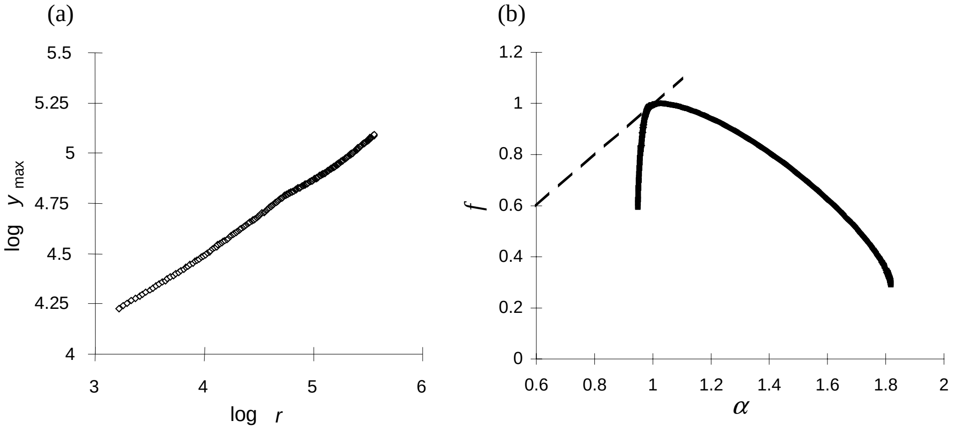

Fig. 4. Scaling analysis of the delamination front in Fig. 3a: in-plane roughness (a) and multifractal spectrum (b).

where $\mu_j = n_j^q \left(\sum_{m=1}^{N} n_m^q\right)^{-1}$; N is the number of boxes of size l, necessary to cover a delamination zone. The obtained results are presented in Fig. 4b in the form of a multifractal spectrum (as function $f(\alpha)$ is known). The curve vividly confirms the multifractal character of the damage distribution since it possesses all the features of the multifractal spectrum: (a) it is a cup convex curve that lies under the bisector $f=\alpha$ (dashed line in Fig. 4b); (b) it has a single connection point with this bisector, and (c) its maximum value is the box-counting dimension of the geometric support of the measure D ($D=1$ for a distribution along a line).

5. CONCLUSIONS

Experimental studies of delamination zones in adhesive composite joints demonstrate that the propagation process is a result of the interaction of multiple fracture mechanisms at various spatial and temporal scales. The level and, subsequently, result of this interaction is significantly affected by the type of the applied load. The impact-fatigue regime, i.e. low-energy multiple impacting, is considerably more damaging one that that of the standard (non-impact fatigue). Additional parameters, based on scaling analysis, are shown to be suitable to characterize the complex shape of the delamination zone, obtained as a result of multimechanism failure process.

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Ülekattega ühenduste defektsete piirkondade levi

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Ülekattega ühenduste lahtikihistumine on selliste sõlmedega juhtunud avariide peamine põhjus. Lahtikihistumispiirkonna tekke asukoht ja selle frondi levi on kirjeldatavad kui juhuslikud protsessid, mis sõltuvad koormuse liigist. Artiklis on kirjeldatud eksperimentaalset meetodit, mis võimaldab jälgida ja analüüsida lahtikihistumispiirkondi nende erinevates arengustaadiumides. X-radiograafilised kujutised defektsetest piirkondadest digitaliseeritakse ja teostatakse fraktaalsel ja multifraktaalsel lähenemisel põhinev mastaabi analüüs eesmärgiga määrata defekti suurus ning kuju ja selle jaotus kihistumisfrondi vahetus läheduses.