DAMAGE AND FRACTURE IN CFRP ADHESIVE JOINTS UNDER IMPACT FATIGUE

Juan Pablo Casas-Rodriguez, Ian A. Ashcroft, and Vadim V. Silberschmidt

Wolfson School of Mechanical and Manufacturing Engineering, Loughborough University,
Loughborough, Leicestershire, LE11 3TU, UK

ABSTRACT

In recent decades the use of adhesive joints in the aerospace industry has increased considerably thanks to their high strength-to-weight ratio, low stress concentration and capacity to join different adherends. However, these joints are subjected to complex load spectra and one form of possible loading is that of repetitive low-velocity impacting, also known as impact fatigue. In this paper impact fatigue (IF) is compared to standard fatigue (SF) and combined impact and standard fatigue (CISF) for bonded CFRP lap-strap joints. The back-face strain technique is investigated as a means of in-situ monitoring of damage in the joints and was found to be a suitable method of monitoring crack growth in both IF and SF. The back-face strain output was related to crack size via FEA models, although, this was more difficult for the dynamic case.

It was seen that crack propagation was faster in IF than in SF for similar maximum loads and that the fracture surfaces in IF exhibited more features of brittle fracture. It was also seen that the incorporation of small blocks of IF in a predominantly SF load spectrum significantly increased the rate of failure of the joints. Finally, it was seen that the dynamic strain energy release rate was a suitable fracture parameter for characterising crack growth in impact fatigue.

1. INTRODUCTION

In recent years the use of structural adhesive joints in the aerospace and other industries has increased considerably owing to their high strength-to-weight ratio, relatively low stress concentrations and ability to join different adherends. In service, structural joints are usually subjected to cyclic loading and hence the study of fatigue in the joint materials is of importance in predicting the service life. In laboratory tests, fatigue is generally approximated as sinusoidal loading, characterized by the force ratio (R) i.e. the ratio between the minimum and maximum force, frequency and maximum force. This type of loading is termed “standard fatigue” (SF) in this report. However, studies of real loading histories identify that aerospace structures generate vibrating loads than can propagate into structural elements as cyclic impacts. This phenomenon is known as “impact-fatigue” (IF).

In contrast to the relatively large body of research on single impact loading in adhesive joints, IF has received little attention to date. In [1] the IF behaviour of bonded GFRP single lap joints was investigated using a drop-weight test. The results showed that the impact-fatigue strength of the joints was dependent on the magnitude of stress and the loading time.

Various empirical relations have been used to characterize impact fatigue. The most popular approach is to relate the cumulative time, $N_{\mathrm{f}}T$, to the maximum stress amplitude in the impact, $\sigma_{\max}$, [2-4]:

$$\sigma_{\max}\left(N_{\mathrm{f}}T\right)^{m}=C$$

where N_{f} is the number of cycle to failure and T is the loading time, C and m are empirical impact-fatigue parameters.

The main aim of this paper is to investigate damage evolution in CFRP adhesive joints subjected to impact fatigue and to compare this with damage evolution in standard fatigue (i.e. non-impacting, constant amplitude, sinusoidal fatigue). A series of tests with multiple tensile impacts applied to adhesively bonded lap joints have been performed and the microstructure of the fracture surfaces studied. The results of these tests are compared with finite-elements simulations of the joints for various stages of crack propagation.

2. EXPERIMENTAL

2.1 Sample preparation

Samples were manufactured by adhesively bonding cured carbon fibre reinforced polymer (CFRP) panels. This is known as secondary bonding and is distinguished from co-bonding and co-curing in which the adhesive and CFRP are cured together. The CFRP pre-preg used in this work was nominally 0.125mm thick and was comprised of 0.6 volume fraction of unidirectional T800 fibres in a Rigidite 5245C matrix from Cytec Ltd. A multidirectional (MD) lay-up scheme of $[(0/-45/+45/0)_2]_S$ was used to manufacture panels 2mm thick that were cured for 2 hours at 182ºC with an initial autoclave pressure of approximately 600 KN/m^2. The adhesive used was Hysol Dexter's EA9628, which is a rubber toughened single part epoxy film adhesive of 0.2 mm nominal thickness.

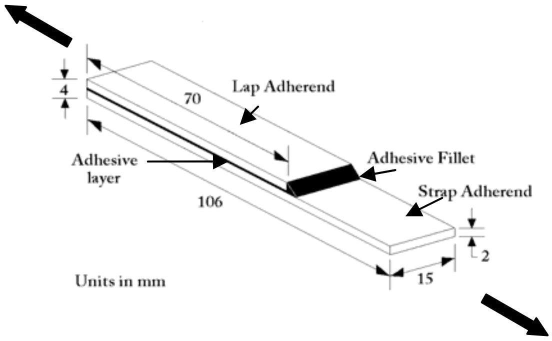


Figure 1: Dimensions of the lap-strap joint

The dimensions of the lap-strap joints (LSJs) used in this investigation are shown in Fig. 1. This type of joint consists of a strap adherend which spans the two loading points and a lap adherend which terminates at a point along the strap. This geometry behaves very differently to the more commonly used single and double lap joints and is more representative of the joints seen in many structural applications. The CFRP panels were grit blasted and acetone cleaned prior to bonding. Assembled joints of adhesive and CFRP were cured under pressure in an autoclave for 60 min at 120ºC. The fatigue samples 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.

2.2 Quasi-static and standard fatigue testing

A servo-hydraulic fatigue testing machine with digital control and computer data logging was used in the quasi-static and SF testing. The quasi-static failure load was calculated as the average of the maximum force reached by two specimens tested at a displacement rate of 0.05 mm/s. SF testing was in load control with a maximum load of 8.5kN, which was approximately 60 % of the average quasi-static failure load. A sinusoidal waveform was used with an R-ratio (minimum-to-maximum load) of 0.1 and frequency of 5 Hz. All testing was in ambient laboratory environmental conditions where temperature and relative humidity varied between 18-25ºC and 50-60%, respectively. Thermocouples were placed at various points on the surfaces of the samples in order to investigate any thermo-elastic heating during testing, however, no change in temperature was observed.

2.3 Impact fatigue testing

The IF test used in this work was based on repetitive pendulum impacts, as previously described in [5]. The pendulum was released from a pre-selected initial angle, which corresponded to a potential energy of 1.07 J and the pendulum impacted the striking anvil at a velocity of 1.5 m/s. This resulted in a tensile force in the sample similar to that seen in the SF tests, although the boundary conditions were slightly different in that there was more allowable rotation at the loaded end of the sample in the IF. After each impact the pendulum was automatically caught and returned to the loading position, with the time between impacts being approximately 15 seconds. Measurements of force as a function of time were used to calculate velocity and energy. Measurement of crack growth was made using the methods described in 2.4

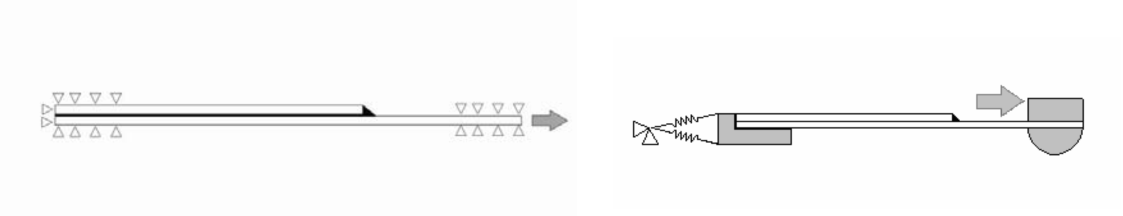
2.4 Crack growth measurement

Two techniques were used to measure crack growth during fatigue testing. The first consisted of measuring the crack at the edges of the specimen using optical microscopy. The second was based on back-face strain measurements [6, 7]. In this technique changes in the measured strains from carefully positioned strain gauges are related to damage in the sample to enable the monitored strain output to provide an in-situ measurement of crack growth during the fatigue tests. In this paper the results from strain gauges bonded to the strap adherend at 15 mm from end of the lap adherend are presented.

2.5 Finite element analysis (FEA)

The commercial FEA software MARC 2007 r1 was used to develop non-linear models of the bonded joints using four noded plane strain isoparametric elements with assumed strain interpolation. Material properties were obtained from previous work [8, 9]. The strain energy release rate, G, was calculated using the virtual crack close (VCC) technique [10].

The first model was a quasi static analysis of the LSJ using the boundary conditions shown in Fig. 3(a). The second model was an implicit, transient, dynamic analysis of impact in the LSJ using the boundary conditions shown in Fig. 3(b). In this case the support includes calibrated springs that are used to represent the dynamic response of the supporting vice. Calibration of the springs was carried out using a single aluminium bar of similar dimensions to the LSJ.



(a) **(b)**

Figure 3: FEA Boundary conditions (a) Standard fatigue (b) Impact fatigue.

3. EXPERIMENTAL RESULTS

3.1 Fatigue crack growth in impact and standard fatigue

A comparison of the fatigue crack growth (FCG) under IF and SF conditions can be seen in Fig. 4. This shows the severity of damage evolution under cyclic impact conditions. In general, an initial crack growth rate of approximately 10^{-2} mm/cycle was observed in IF that decreased until a crack length of approximately 27 mm was reached, after which the rate plateaued or, in the case of specimen IF1 where the failure included delamination between 0º and 45º plies at the specimen edges, started to increase. The sample tested in SF showed a steady decrease in FCG with crack growth, with rates significantly below those seen in IF.

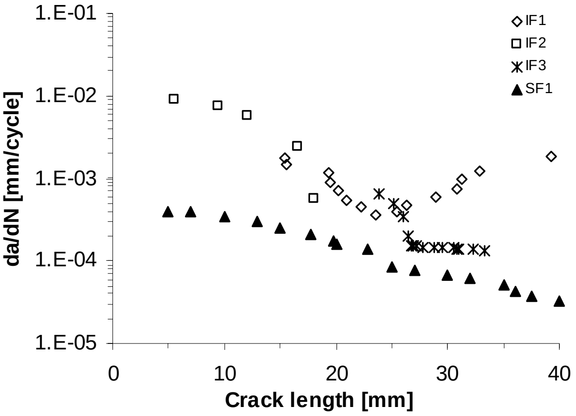
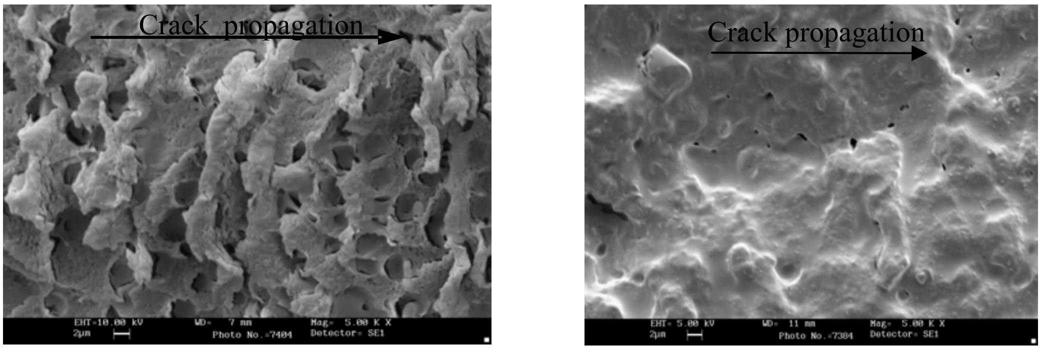


Figure 4: Fatigue crack behaviour in LSJ tested in standard fatigue and impact fatigue

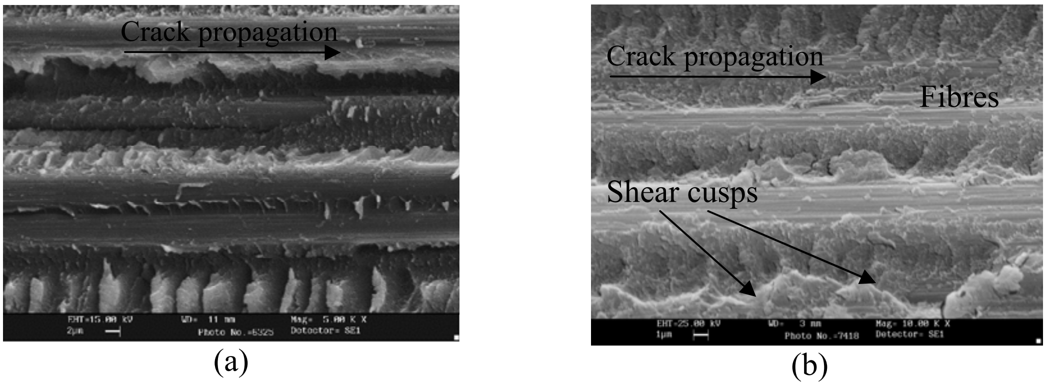
Initial optical examination of failure surfaces for specimens tested under IF conditions showed patterns of failure similar to those observed in SF [8]. Initial crack growth was predominantly cohesive failure in the adhesive layer. This was followed by a transition region with a mixture of adhesive and CFRP fracture before progressing to a third region in which crack growth was predominantly in the 0º CFRP ply in the strap adherend adjacent to the adhesive. However, a more detailed analysis shows distinct differences between the fracture surfaces in IF and SF. Comparison between corresponding facture regions between IF and SF showed specific differences. It was seen in the cohesive failure region for the sample tested in SF, that the fracture surface exhibited ductile tearing with void formation by the cavitation of rubber particles and a 'wavy' fracture surface, as seen in Fig. 5 (a). The cohesive failure region in IF, however, is characterized by a lack of cavitating rubber particles and brittle cleavage fracture, as seen in Fig 5 (b).



(a) (b)

Figure 5: SEM of cohesive failure in LSJs (a) tested in SF, (b) tested in IF

A comparison of the fracture surfaces in the CFRP failure regions also shows differences in the fracture under SF and IF conditions. Failure in SF is characterized by the presence of matrix rollers and deformed shear cusps, as shown in Fig. 6(a). Shear cusps are related to mode II fracture and during the continuous fretting of surfaces in fatigue can be transformed into matrix rollers. In IF more brittle behaviour is observed, with the shear cusps being less well developed and an absence of matrix rollers, as seen in Fig. 6(b).



(a) (b)

Figure 6: SEM of Lap failure in LSJ’s (a) tested in SF, (b) tested in IF

3.2 Combined impact and standard fatigue (CISF)

In these experiments blocks of 100 impacts were alternated with blocks of 5000 SF cycles. The results are presented in Fig. 7, with results from a SF test included for comparison. It can be seen that crack growth increases in the IF blocks and this affects the subsequent crack propagation in SF. The overall result is increased and more variable crack growth than that seen in SF. It is thus seen that the inclusion of relatively small periods of cyclic impact in a load spectrum can have a significant, deleterious effect on the evolution of damage in bonded joints.

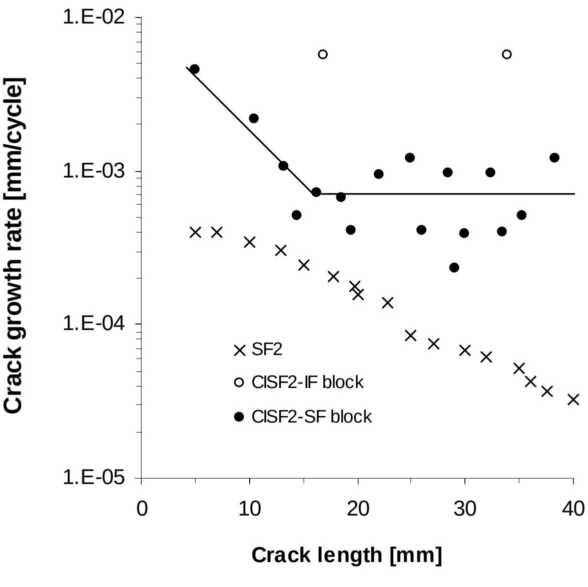
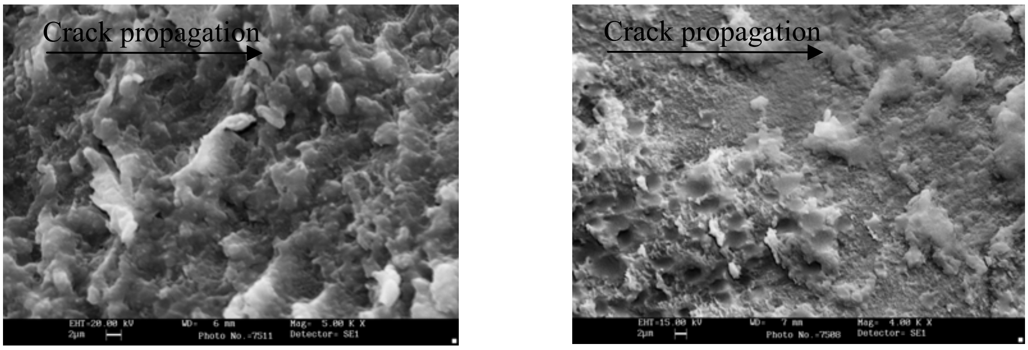


Figure 7: Comparison of crack growth rates in CISF and SF specimens

The IF blocks also affect the uniformity of the fracture surfaces, as illustrated in Fig. 8. The IF crack growth regions are characterized by valleys where no cavitating rubber particles are present. The toughening mechanism characterised by rubber cavitation is active during the SF blocks of the test, but a more irregular distribution of cavities is seen than in pure SF. This may be because the crack growth depends on the loading history, being affected by the damage zone ahead of the crack front, where micro-damage can exist [11].



(a) (b)

Figure 8: SEM of fracture surfaces in specimens tested in CISF with cohesive failure: (a) SF region, (b) IF region.

3.3 Back-face strain results

The results from FEA simulations and experiments with a strain gauge on the strap adherend back-face in a SF test are shown in Fig. 9. Strain gauge location has a strong effect on crack monitoring, with the greatest change in gradient seen at the location of the strain gauge. Strain decreases as the crack approaches the location of the gauge and then starts to increase again once the strain gauge location has been passed. The gauge is thus effective at monitoring crack position over a range of approximately 20mm. The experimental results can be seen to be in excellent agreement to the FEA simulation.

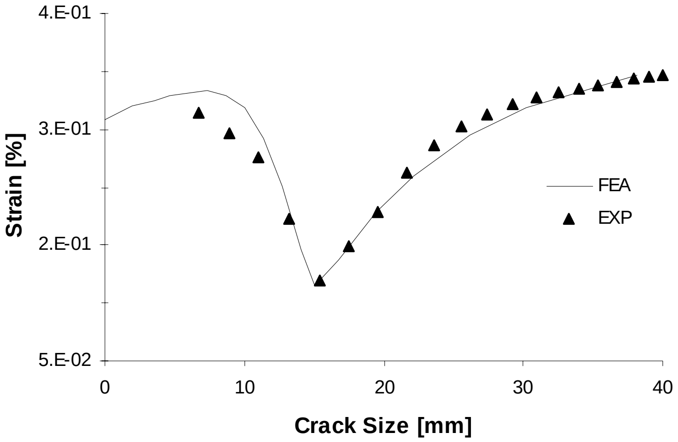


Figure 9: Comparison of experimental and FEA back-face strains in SF

Comparisons of experimental and FEA simulated back-face strain results during an impact for different crack sizes are plotted in Fig. 10. There is still a reasonable agreement between the experimental and FEA results, although the difference is greater than for the static analysis. This is not surprising because there is more scatter in the experimental results and the modelling is considerably more difficult for the dynamic case. In addition to the added complexity of including dynamic effects it was also seen that small misalignments between the hammer and the impact block during the test could have a significant effect on the simulated dynamic response of the sample. It should also be noted that the models reported here are from 2D analyses which cannot fully represent the complex crack fronts and process zones seen in practice.

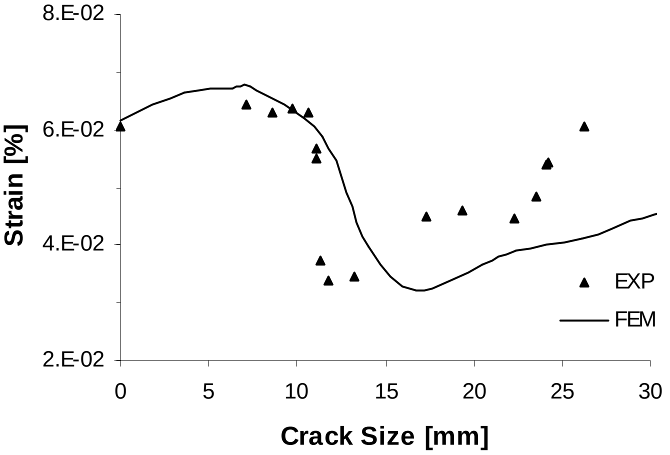


Figure 10: Comparison of experimental and FEA back-face strains in IF

3.4 Fracture mechanics characterisation of crack growth

Previous work on fatigue crack growth in adhesive joints has shown that the maximum strain energy release rate (G_{max}) or strain energy release rate range ($\Delta G = G_{max} - G_{min}$) are useful parameters to characterise the fatigue crack growth rate (FCGR or da/dN) [12-13]. It is often seen that a plot of G_{max} or ΔG has three distinct regions [14], a threshold region at low values of G, a region in which there is a power law relationship between G and da/dn and a region of accelerating crack growth as G_{max} approaches the critical strain energy release rate G_c. In most cases this relationship has been established using simple sample geometries, such as the double cantilever beam. The LSJ is also suitable for this purpose but caution should be paid to changing mode mixity and changing fracture path as the crack propagates in this test as these will affect the crack growth rate. A plot of FCGR against G_{max} for SF is shown in Fig. 11. The plot demonstrates increasing FCGR with increasing G_{max}, as expected.

The dynamic strain energy release rate (G_{dyn}) can be used to characterise FCG for impact fatigue. It was seen that under impact conditions higher maximum values of force and strain energy release rate were seen than under quasi-static conditions for similar levels of applied load. Figure 12 shows a plot of fatigue crack growth rate as a function of maximum dynamic strain energy release rate in impact fatigue. Comparison of Figs. 11 and 12 illustrates that crack growth in IF is at significantly lower values of strain energy release rate than in SF. An anomalous FCG plot can be seen for sample IF1. At high values of G_{dyn} the results compare well with the other samples, however, below approximately 50 J/m^2 the crack growth rates begins to increase as G_{dyn}

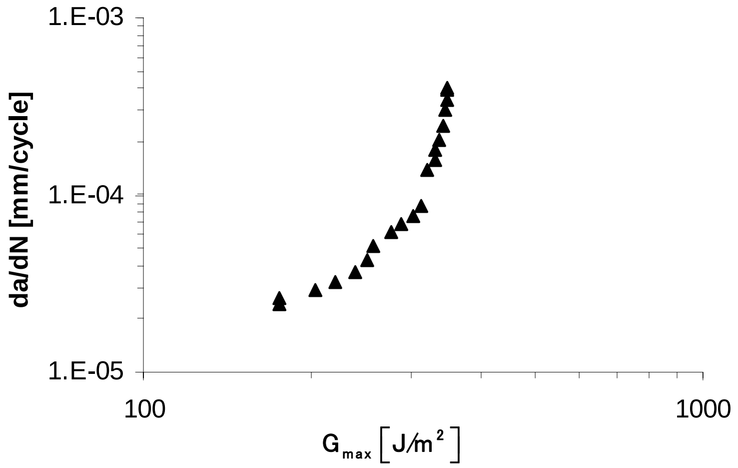


Figure 11: Fatigue crack growth in standard fatigue for lap strap joints

decreases. This can be attributed to a change from crack propagation predominantly in the adhesive layer to crack propagation predominantly in the CFRP. This is discussed further in [15].

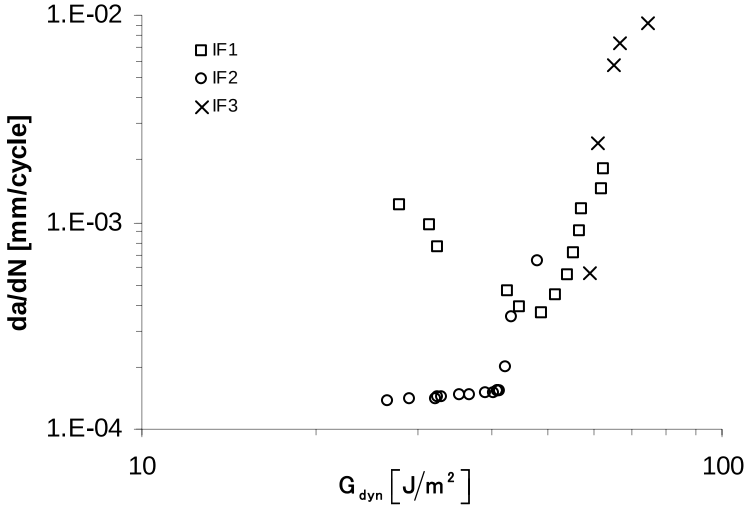


Figure 12: Fatigue crack growth in impact fatigue for lap strap joints

4. CONCLUSIONS

It can be concluded from this work that the back strain face technique is a suitable method of monitoring crack growth in both IF and SF and that the strain output can be related to crack size via FEA models. Although, this is more difficult for the dynamic case.

It is seen that crack propagation is faster in IF than in SF for similar maximum loads and that the fracture surfaces in IF exhibit more brittle fracture features. It is also seen that incorporation of small blocks of IF in a load spectrum can significantly increase the rate of failure of a bonded composite joint. Finally it is shown that the dynamic strain energy release rate is a suitable fracture parameter for characterising crack growth in impact fatigue.

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