

CRACK CLOSURE AND FIBRE BRIDGING CONTRIBUTION IN THE STRESS-RATIO EFFECT ON DELAMINATION GROWTH UNDER FATIGUE

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ABSTRACT

The objective of this paper is to investigate the contribution/role of the crack closure and the fibre bridging effects in stress-ratio influence in mode I delamination growth in carbon/epoxy composite laminates. The crack closure effect has been assessed by the identification of the non-linearity in the compliance curve of the double cantilever test specimen after the delamination extension. The effect of fibre bridging was investigated by cutting the bridging fibres during fatigue delamination. The fatigue test data was process using fracture mechanics principles. The delamination growth rate in laminates was characterized using approach of strain energy release rate. The results of the experiments of fatigue delamination growth with bridging fibres and un-bridged fibres have been compared for different fatigue stress-ratios. The results show that crack closure only occurs at lower stress ratios. Fibre bridging does not affect the stress ratio however the crack rate was decreased in this case.

KEY WORDS: *Stress ratio effect, Fibre bridging, Crack closure, Mode I fatigue delamination growth*

INTRODUCTION

Delamination is a threat to the composite structures that reduces strength and stiffness of composite structures which can lead towards failure of the structure. For the increased performance and reliability of composite laminates, the analysis of delamination growth behaviour in fatigue loading has gained wide attention from research community in recent past.

Fatigue stress ratio (ratio of minimum to maximum stress) is well known to affect the delamination growth in composite laminates. Hojo *et.al*¹ investigated the effect of stress ratio on delamination growth in composites laminates under mode I fatigue load. The crack closure was reported/observed for the lowest R-ratio in a series of tests. The stress ratio effect correction reduced the scatter in the delamination growth rate data. Hojo proposed an equivalent stress intensity factor for the delamination growth characterization to avoid effect of stress-ratio in the data. Tanaka and Tanaka² proposed semi empirical equations/models for the Paris law parameters to predict Mode II fatigue delamination growth behaviour under different stress ratios. The model bounds the delamination growth rate between a static delamination growth rate limit equal to 10^{-3} m/cycle and threshold delamination growth rate limit equal to 10^{-9} m/cycle. Schön³ followed a similar approach however the delamination growth prediction model was generalized for mode I fatigue load,

mode II fatigue load and mixed mode fatigue load. The schön model requires four material parameters to predict delamination growth rate. Anderson *et al.*⁴ proposed a semi empirical model/equation for the prediction of delamination growth behaviour adopting the concept of fatigue degradation of the damage zone (hypothetical zone ahead of delamination tip). It was assumed that fatigue loading degrades the damage zones, leading to its failure under monotonic loading, and results in the crack growth through a length equal to the damage zone length.

It is a fact that R-ratio effect emanates from physical mechanism during fracture. Ritchie⁵ has described various crack shielding mechanisms such as crack closure as well as fibre bridging that effect the cyclic R-ratio during fatigue loading of composites. The crack closure is widely considered and used as the mechanism that explains the stress ratio effect in metal fatigue crack growth (FCG)⁶. Fibre bridging is another mechanism that influences the stress ratio scatter in delamination growth data.

The roles of crack closure and fibre bridging (in reducing effective stress intensity factor) in the R-ratio effect are relatively less investigated. This paper experimentally investigates the crack closure effect and the effect of fibre bridging on the delamination growth rate. The contribution of the above effects on the R-ratio effect has been assessed. Fatigue tests have been performed on the carbon/epoxy specimens under different

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R-ratios. Crack closure was investigated using clip gage extensometer while the fibre bridging was investigated by cutting fibres during tests.

EXPERIMENTAL PROCEDURE

A series of experiments were performed to investigate the crack closure effect and the effect of fibre bridging on the mode I fatigue delamination growth. This section describes the test specimens, the fatigue tests procedure and experimental evaluation of crack closure and fibre bridging.

Mode I fatigue Test Specimens

Double cantilever beam (DCB) specimens were implied for the analysis of the fibre bridging and the crack closure effects respectively. The specimens were manufactured from of the M30SC/DT120 pre-pregs, which is a carbon/epoxy material. The elastic properties of the material are given as: longitudinal young/elastic modulus $E_1=150$ GPa, Transverse young/elastic modulus $E_2=7$ GPa, and in-plane Poisson's ratio $\nu_{12}=0.29$. A unidirectional laminate panel was made by stacking 40 prepreg plies of the material. During stacking process, a Teflon film with a thickness equal to $12 \mu\text{m}$ was placed between middle plies of the laminate to induce an artificial starter delamination in the test specimens. The laminate panel was cured in an autoclave according to the cure cycle approved by the material manufacturer.

DCB test specimens having width equal to 20 mm were cut from the panel using composite cutting wheel. The edges of the specimens were polished to remove the machining marks and aluminium tabs were attached to the specimens. The edges of the specimens were painted with white correction liquid to enhance delamination tip visualization. A marked millimetre scale was attached to the edge for delamination length measurements.

Fatigue test procedure

Fatigue tests were performed in a 10kN capacity MTS fatigue machine. The specimen was attached to the split hinges and clamped in the fatigue machine as shown in figure 1. Before starting the fatigue tests, the critical loads for static fracture of the specimens were determined by loading specimens to up-to crack

initiation. The delamination was extended by 2 mm ahead of artificial delamination to eliminate the effect of its trailing matrix pile up.

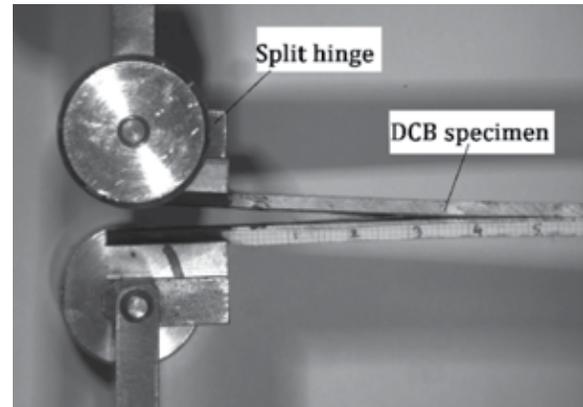


Figure 1: DCB specimen clamped in the machine

The fatigue tests were carried under cyclic R-ratios equal to 0.15 and 0.5 respectively. The cyclic frequency during the tests was 3Hz. The tests were performed using displacement control technique i.e. the maximum and minimum cyclic displacements were constant. The cyclic loads were automatically dropped with the delamination extension, thus automatic load shedding was achieved in this technique.

The load, displacement and the number of cycles during fatigue tests were recorded by the MTS machine controller computer. The delamination length during fatigue tests was monitored using a camera and computer system. The images of the delamination tip was taken after certain number of fatigue cycles and used for delamination length measurements.

Effect of Fibre Bridging on Delamination Growth

The difference between the delamination growth behaviour with the presence of fibre bridging and without fibre bridging was determined by performing two types of fatigue delamination tests. The first type of tests was performed according to same procedure as described previously. In second type of fatigue delamination tests, the bridging fibres were cut to remove its effect from the delamination growth rate. The fibre cutting was performed with a saw. The fibres were cut after every 0.5 mm extension of the delamination under fatigue. The specimen was held open under maximum cyclic

displacement during fibre cutting.

Crack closure effect on delamination growth rate

The crack closure effect on Mode I delamination growth in composites was investigated using a clip gauge extensometer. The closure load was determined after each 2 mm delamination extension in the fatigue test under R-ratio 0.15. The gauge was mounted at the open end of the DCB specimen as shown in figure 2. The specimen was statically loaded to the maximum cyclic load and then unloaded to zero. The crack tip opening displacement was measured by clip gauge extensometer in this process. After test the displacement was plotted against load. The load at which the displacement-load curve became non-linear was the crack closure load.

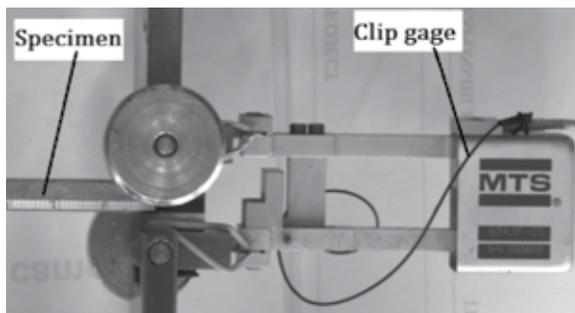


Figure 2: Clip gauge extensometer attached to the DCB specimen

DATA ANALYSIS

Compliance technique was used for the calculation of SERR G . The relation is given as follows⁷:

$$G = \frac{P^2}{2b} \frac{dc}{da} \quad (1)$$

Where P , a , C and b are the load, delamination length, compliance and specimen width respectively.

Delamination growth rate was characterized in terms of SERR range ΔG that was defined as⁸:

$$\Delta G = (\sqrt{G_{max}} - \sqrt{G_{min}})^2 \quad (2)$$

In above equation G_{max} and G_{min} are the maximum and minimum SERR respectively.

RESULTS AND DISCUSSION

Effect of Crack closure on Mode I fatigue delamination growth

Figures 3a and 3b presents the comparison of the minimum cyclic and crack closure loads respectively. In both figures the crack closure loads are less than minimum cyclic loads. In figure 3a bridging fibres were cut while in figure 3b bridging fibres were not cut. The difference between crack closure and minimum loads is more in figure 3b. This indicates that the bridging fibres contribute to the crack closure in figure 3b as compared to 3a. Since the crack closure loads are less than minimum cyclic loads, implying the closure was not occurring during fatigue delamination.

Lowering the R-ratio (less than 0.15), due to decreased minimum cyclic load will lead to crack closure. In this case the closure load will become more than minimum load. Literature reports similar evidence of crack closure for lower R-ratios. Hojo et al. [1] performed similar tests for the crack closure load measurements. Hojo observed crack closure for the lowest R-ratio i.e. 0.1.

From figure 3, it can be also observed that minimum load is decreasing along delamination length while crack closure loads remain approximately same. As the tests were executed on DCB specimens under displacement control, the R-ratio remains constants while maximum and minimum loads were decreased as delamination extended. For long delaminations under same constant displacements, load range was thus continuously decreasing during tests that resulted in slow delamination growth. Although in this study the crack closure level does not crossed minimum cyclic loads, it could be fairly assumed that delamination growth under lower load ranges will result in crack closure. Such load ranges are lower enough to be termed as threshold level with nearly ceased delamination growth. The work of Hojo et al. [9] basically represents threshold delamination behaviour where crack closure was occurring at R-ratio equal to 0.1 as mentioned earlier.

Crack closure in metal fatigue growth is mainly attributed to the plasticity at the crack tip¹⁰. Other mechanisms of crack closure like oxidation induced closure,

roughness and asperity induced closure may be also present to some extent in metal fatigue crack growth.

Contrary to this, the crack closure in composites delamination may be attributed to the roughness of the mating fracture surfaces. The possibility of plasticity induced closure is less in composites as the matrix layer between adjacent plies is very thin to have enough plastically deformed material for crack closure¹¹. In fact the nature of crack closure in composites will be merely dependent on the matrix. Thermo-sets (epoxies etc) are relatively brittle as compared to thermoplastics (PEEK etc). In case of thermoplastic PEEK as matrix, significant evidence of plasticity has been reported in literature¹².

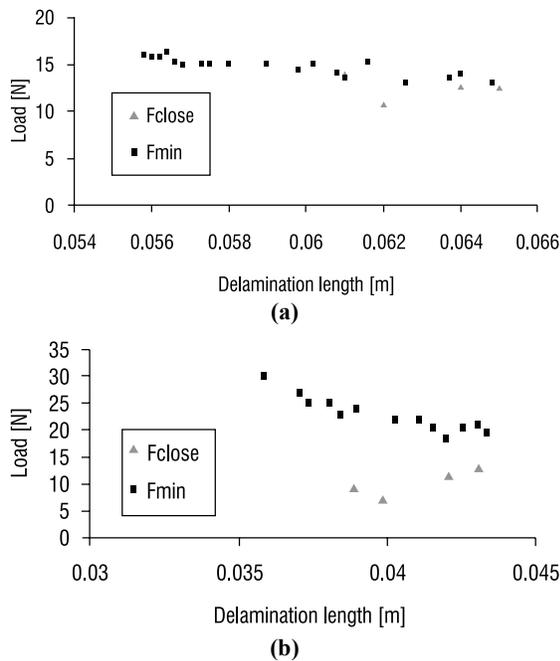


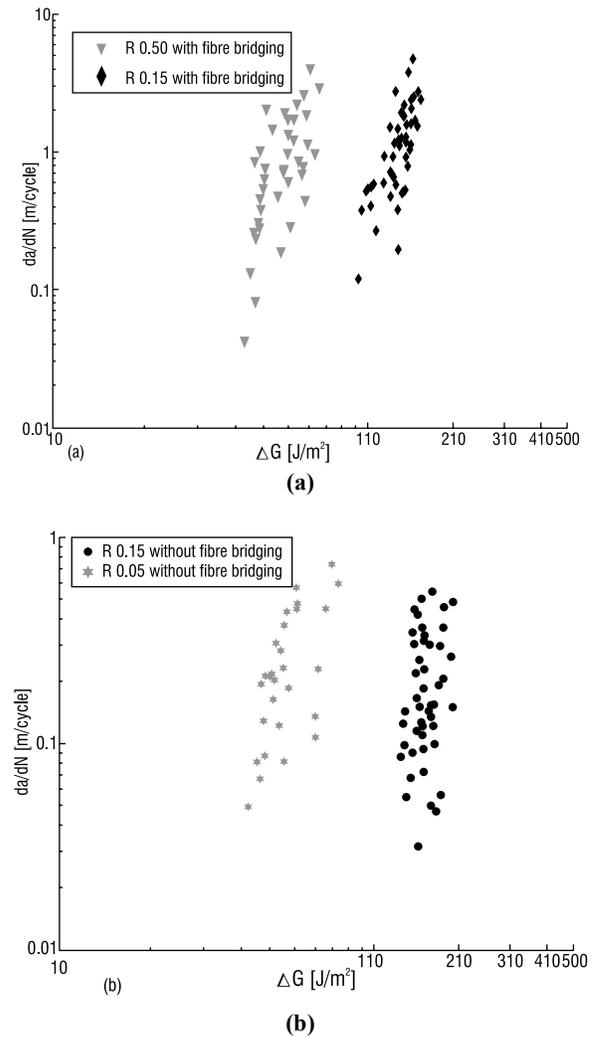
Figure 3: Comparison of crack closure load and minimum cyclic loads in fatigue tests under R-ratios 0.15 (a) and 0.5 (b)

The Effects of the fibre bridging on the delamination growth rate behaviour

Delamination growth rate da/dN is plotted against ΔG in figures 4a and 4b for the tests with and without bridging fibres respectively. The R-ratio effect is clearly present in both cases. Delamination growth rate for same ΔG is higher for higher R-ratio value in both cases as shown in the figures. In figure 5, delamination growth results from both types of tests are plotted on the same

graph. The figure shows that delamination growth rate is negligibly affected by cutting of the bridging fibres with respect to R-ratio and both curves falls in the same scatter bands as shown.

In fact the fibre bridging will decrease the SERR range that will ultimately decrease the delamination growth. However the R-ratio will be almost same in both cases i.e. in presence of bridging and without bridging. The R-ratio remains constant because the bridging affects both minimum and maximum cyclic loads as shown schematically in figure 6. This hypothesis was also experimentally verified in the present study. The maximum and minimum loads during fatigue delamination test were recorded prior and afterward of cutting of the bridging fibres. The test experimentally proved that the values of the loads at minimum and maximum



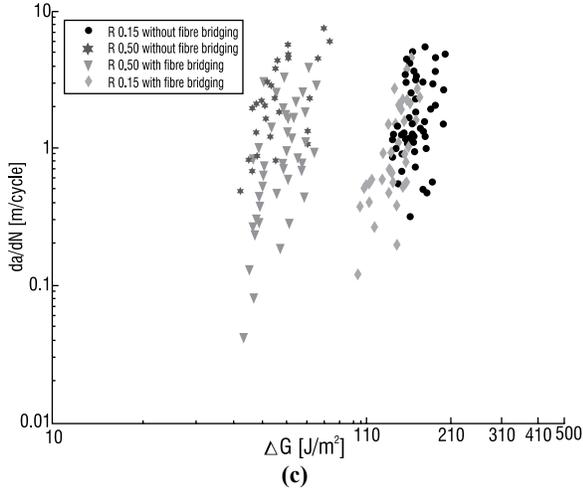


Figure 5: Plotting delamination growth rate da/dN versus ΔG for the Mode I fatigue tests with bridging fibres and without bridging fibres on one chart

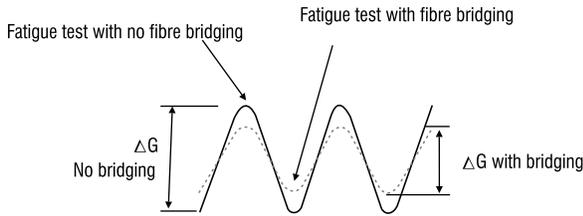


Figure 6: schematic illustration of change in SERR range due to fibre bridging

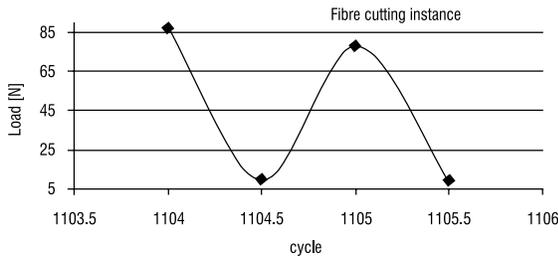


Figure 7: Constant displacement fatigue Load cycle showing decrease in maximum and minimum cyclic loads after fibre cutting

cyclic displacements were decreased due to cutting of the fibres as shown in figure 7. The cyclic R-ratio was 0.089 and 0.087 (i.e. ~ 0) before and afterward of the fibre cutting respectively. This disproves the reporting of Ritchie⁵ where fibre bridging has been presented as the crack shielding mechanism that decreases the crack driving force while increasing the R-ratio

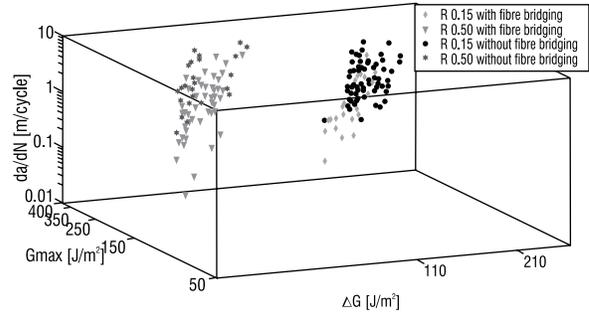


Figure 8: 3D plot of delamination growth rate vs. G_{max} vs. ΔG for the present fatigue delamination tests with and without fibre bridging

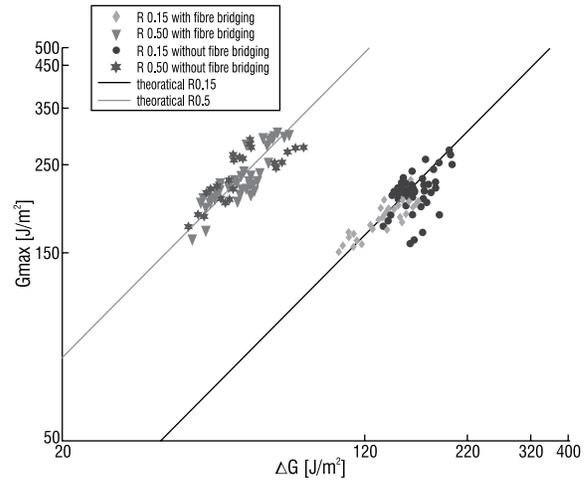


Figure 9: Maximum cyclic SERR vs. SERR range for the fatigue tests with and without fibre bridging and its comparison with the lines for R-ratios 0.15 and 0.5

The effects of the fibre bridging on the delamination growth rate and stress-ratio can be characterized by plotting the delamination growth against G_{max} and ΔG for both types of tests in a 3D plot as shown in figure 8. Fibre bridging decreases G_{max} and ΔG and delamination growth simultaneously in such a manner that data points shift in all three coordinates while keeping R-ratio constant. The projection of the data points of figure 8 on the G_{max} - ΔG plane are shown in figure 9. In this figure constant R-ratio lines are drawn. These lines pass through the data points for both tests implying negligible effect of the fibre bridging on the R-ratio.

The results for the present investigations of the fibre bridging effect can be extended to explain the effect of micro cracking in front of delamination on

the delamination growth rate. Researchers^{5,13-19} have considered frontal micro cracking as the unbroken ligaments that bridge the crack in a similar fashion as fibre bridging does. However further experiments are required to verify that frontal micro cracks enhances fibre bridging which further effect the actual R-ratio of the delamination growth.

CONCLUSIONS

The roles of the crack closure and fibre bridging on the R-ratio effect was investigated for the mode I fatigue delamination growth in carbon/epoxy composites. From the results following conclusions were drawn.

1. The crack closure mechanism will effect delamination growth and the R-ratio in the threshold delamination growth region only.
2. Bridging fibres has significant effect on the crack closure during delamination growth.
3. Fibre bridging decreases delamination growth by decreasing the range of effective driving force.
4. Effective R-ratio remains constant due to fibre bridging.

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