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EFFECTS OF INDUCED DAMAGES ON THE FLEXURAL FATIGUE BEHAVIOR OF GLASS FIBER REINFORCED PLASTIC (GFRP)

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ABSTRACT

The paper presents the flexural fatigue loading of single lap with single and multiple bolted joints made from 3mm thick Glass Fiber Reinforced Plastic (GFRP) flat sheet. This is accomplished by creating an accurate finite element model in three-dimensional and analyze the stress distribution for various bolted joints. In this aspect, the geometry and different joint configurations were altered in order to determine their effects on the overall behavior of the joint. Physical flexural fatigue tests by three-points bending were carried out using universal testing machine at specified frequency and stroke mode. Any internal activities that leads to failures such as the propagation of crack and the ultimate failures subjected to flexural loading were investigated using real-time acoustic emission monitoring equipment. Both physical and microstructure observation of specimens were done to determine the characteristic and extent of the damages in specimens after experiments. It is found that special specimen that designed to fail under well-defined modes, micro-cracks generate in the matrix before any effect was noticeable in the macroscopic mechanical behavior. These micro-cracks included matrix cracking, interface fracture, debonding and fiber breakage. Simulation showed that stresses were not evenly distributed throughout the bolted joints but rather concentrate on specific location. The damages initiated at the first few cycles were due to the porosity and defect during manufacture and the cumulative number of AE events does not exhibit a linear increase with time for all the configurations but exhibited their own characteristic of damage development. Increasing number of fasteners did not show significant improvement in joints strength but their arrangement play more important role.

INTRODUCTION

It is rarely possible to produce a structure without joints because of the limitations on material size, convenience and economy in manufacture or transportation, and the need for accessibility. The necessity for some components to be dismantled has led to mechanically fastened joints being incorporated in most structures. One of the most commonly used mechanical fasteners is the simple bolt and nut. Unfortunately bolt holes, generally regarded as induced damages, are sources of stress concentrations which can influence the fatigue life [3]. Analysis of stress distribution are mostly studied by using stress concentration factor [6], which is defined as:

$$K = \frac{\text{Highest value of stress at a discontinuity}}{\text{Nominal stress at the minimum cross - section}}$$

(Equation 1)

The highest stress around the hole was found to be 3 times the nominal stress in non-homogenous composite materials [1]. With the introduction of fastener under the action of flexural loading, the material cannot penetrate each other at the contact surface and the contact traction is always compressive. Since the domain of contact area and the distribution of contact traction are unknown, the contact problem is essentially a highly nonlinear problem with unknown boundary conditions [5]. Finite element analysis is the most recent technique used to evaluate the distribution of stress for complicated model by imposing contact conditions by means of the Penalty Method and the Coulomb friction law. A good agreement was found between simulation approach with experimental results when necessary precautions were taken.

Research on the failures of micro-mechanical scale in bolted joints during service has become a very interesting subject in recent year. Acoustic Emission (AE) monitoring has been shown to be a useful technique for real-time detection of internal activities during loading. The damage mechanism analyses with AE amplitude identified the main damage mechanism [4]:

(i) from 40 dB to 55 dB → matrix cracking,
(ii) from 60 dB to 65 dB → interface fracture,
(iii) from 65 dB to 80 dB→ fiber pull-out phenomena,
(iv) from 80 dB to 100 dB → fiber fracture.

There is little research on the effects of bolted joints in GFRP under the flexural cyclic loading. Therefore it is the aim of this study to investigate effects of induced damages on the flexural fatigue behavior of GFRP.

EXPERIMENTAL PROCEDURES

The material used in the present work was FR-4 G10 Glass Fiber Reinforced Epoxy 3mm in thick laminate of 20 plies. The lay-up used was $[0/90]_{20}$ and the flexural strength and bending modulus were 350-450 Mpa and 23.6 Gpa respectively. Six configurations of joints were investigated. Table 1 shows the dimensions of these different configurations.

Table 1: Dimensions of Six Different Configurations

Configuration	**Test specimen**	**Width b (mm)**	**Length L (mm)**	**Thickness h (mm)**
1	Single coupon without hole	30	300	3.0
2	Single coupon with single hole but without fastener	30	300	3.0
3	Single lap with single fastener at the center	30	300	3.0
4	Single lap with two bolts arranged in row	30	300	3.0
5	Single lap with two bolts arranged in column	48	300	3.0
6	Single lap with four bolts;	48	300	3.0

In order to determine the stress distribution of test specimens, suitable models were created by using ANSYS finite element package in full three-dimensional in order to reflect the physics of damage mechanisms and to obtain a realistic simulation of the structural behavior of composite joints. The models take into account of all the necessary inputs such as frictional contact problem between fasteners and GFRP, the material properties, element types and non-linearity behavior of bolted joints. The development of the 3D FEM model is needed in order to determine the non-uniform stress distribution through the thickness of the laminate in bolted composite joints.

Figure 1: *CONFIGURATION 1*

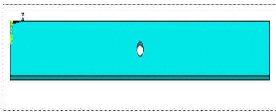

Figure 2: *CONFIGURATION 2*

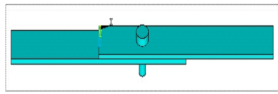

Figure 3: *CONFIGURATION 3*

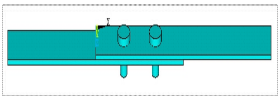

Figure 4: *CONFIGURATION 4*

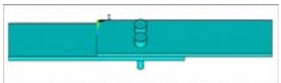

Figure 5: *CONFIGURATION 5*

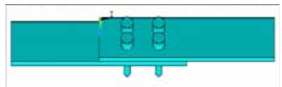

Figure 6: *CONFIGURATION 6*

Drilling was performed using 7.7 mm Tungsten carbide drill and water was used as the lubricant and coolant and also prevented the formation of glass fiber dust. The speed of drilling was 250 RPM and the feed rate was 0.05mm/sec. The quality of the bore surfaces was found to be good with little damages. Figure 7 below showed a microscopic view around the hole after being mounted and polished.

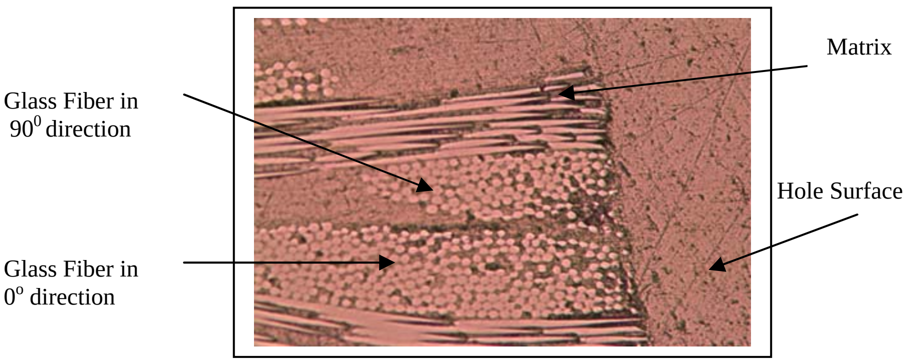

Figure 7: Microscopic View of GFRP G-10 around the Hole (magnification of 200 times)

The fasteners used in this research were of stainless steel, 7.69mm (5/16 in) in diameter. The fasteners were installed in the coupon and tightened to a torque of 10Nm. The fasteners were constrained from rotating during the test and using this method of fastener installation it was found that there was no reduction of torque during fatigue testing. The

holes drilled at the desired location in which the configurations will be estimated to fail under tension mode failure when subjected to cyclic loading. This is done when the ratios of the plate width (w) to hole diameter (2a) is 3.9 and the ratios of edge distance (e) to hole diameter varied between 3.6 to 6. The laminate thickness (h) to hole diameter remains constant with ratio of 0.39.
Standard 3-point flexure tests with test frequency of 2Hz and deflection of 35 mm with cyclic loading ± 5mm were carried out in the experiment. A total number of 81000 cycles divided into three stages, namely initial stage, intermediate stage and final stage were imposed upon the configurations respectively. Any internal activities were detected by real-time Acoustic Emission monitoring equipment. The high sensitivity piezoelectric AE transducer was placed on the material to record AE events throughout the experiment. After the test, specimens from all the configurations were mounted using cold mounting resin to determine the extend of the damage.

RESULTS AND DISCUSSIONS

Under the three-point bending up to 40 mm, all the configurations behave elastically (below yield strength) or nearly 50% of maximum displacement allowed. *CONFIGURATION 1* exhibited nominal stress, around 175.94 Mpa at the center after deflection that still below its flexural strength. Unlike *CONFIGURATION 1*, the hole-induced at *CONFIGURATION 2* resulted in extremely high stress (520.55 Mpa) at upper compressive surface near the hole that exceeds the given compressive strength. A very good agreement between experimental data and simulation results with only differences of 1-5 % have been observed. Table 2 showed the both the maximum values for surfaces under tension and compression obtained from ANSYS.

Table 2:Stress Distribution by Simulation

Configuration	Maximum compression Stress (Mpa)	Maximum tension Stress (Mpa)
CONFIGURATION 1	215	192
CONFIGURATION 2	528	307
CONFIGURATION 3	247	252
CONFIGURATION 4	216	225
CONFIGURATION 5	322	233
CONFIGURATION 6	286	254

Among all the configurations with bolted joints (*CONFIGURATION 3-6*), they exhibit relatively low stress distribution compare to *CONFIGURATION 2* where the fastener redistribute the stress at the hole bore. The highest compression stress mostly occurred at the distance equal to the radius of bolt from hole while maximum tension stress took place at the front-face of lower piece correspond to the edge of upper coupon.

CONFIGURATION 5 and *CONFIGURATION 6* indicated at higher stress concentration because of additional factor, which was the interaction of stress between the holes.

Table 3 displays the AE signal distribution under flexural cyclic loading. The shape of the amplitude distribution gave a crucial indication the source and mechanisms which produced these signals.

Table 3: Amplitude Distribution (dB) over cycles

Cycles ($X10^3$) Configuration	0-1	1-3	3-9	9-18	18-27	27-54	54-81
1	40-58	40-62	40-70	40-74	40-74	40-85	40-88
2	40-98	40-90	40-85	40-98	40-98	40-98	NIL
3	40-60	40-74	40-74	40-80	40-80	40-70	40-74
4	40-60	40-65	40-80	40-72	40-70	40-78	40-82
5	40-60	40-58	40-61	40-66	40-70	40-85	40-92
6	40-60	40-65	40-75	40-75	40-78	40-82	40-82

It is clearly seen that for the first 0-1000 cycles, the progression of AE amplitude distributions for all the configurations ranged from 40 dB until nearly 60 dB except for *CONFIGURATION 2*. The voids, porosity or defect in the specimen during manufacture could have resulted in these AE events since they showed nearly the same amplitude. *CONFIGURATION 2* showed much higher amplitude at first 1000 cycles because the hole creates a higher stress concentration above its flexural strength. Thus, with the amplitude as high as 98 dB, all the main damage mechanisms such as matrix cracking, interface fracture and fiber fracture might have occurred from the initial stages until final failure of the material. After the first 1000 cycles, most of the configurations showed their own characteristics in amplitude distributions but all these configurations experienced signal strength up to 80 dB or above. *CONFIGURATION 1* generated least AE events at the end of the experiment although it showed the trend of exponential increment of AE signal over cycles. This configuration without any induced damage experienced first the matrix micro-cracks, followed by a saturation crack density and finally the occurrence of fiber fractures. All the configurations with mechanically fastened showed an inconsistency in amplitude distribution. For example, fiber fractures took place in the *CONFIGURATION 3* at intermediate stage while for *CONFIGURATION 5*, fiber breakage occurred at final stage besides other lower amplitude damages. The phenomena can be seen clearly by plotting AE events over time as shown in Figure 8 and Figure 9. At the end of the experiment, *CONFIGURATION 3* and 4 emitted nearly an equal total number of AE events. The cumulative number of emissions for *CONFIGURATION 5* and *6* were much higher than other configuration but that doesn't mean that they suffered more severe damages. It is because the areas for these configurations are bigger than other due to wider specimen's width.

One can see that most of the internal activities inside the material generally heavier at the final stage due to the occurrence of new damages. For example, for *CONFIGURATION 5* at the cycles of 18001-27000 cycles, there was no sign of signal above 80 dB but a clear region of AE signal with amplitude 80 dB and above in cycles of 27001-54000 that indicated the fiber fractures.

The region can be described as sudden increase of AE signal collected during fatigue loading (Figure 12 and 13).

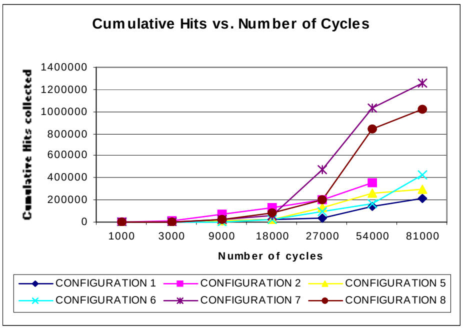

Figure 8: Cumulative Hits recorded over number of Cycles

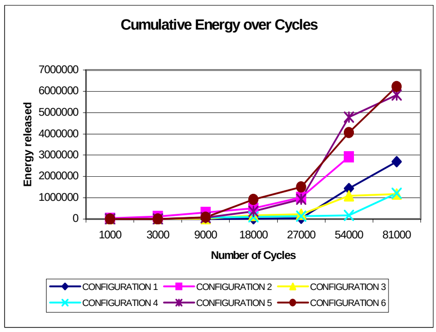

Figure 9: Cumulative Energy collected over number of Cycles

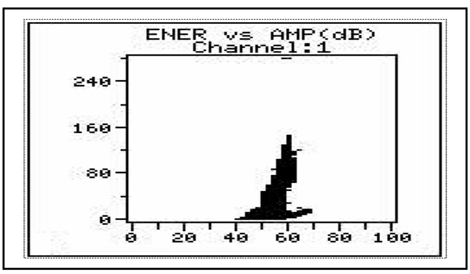

Figure 10: Energy Recorded between 18001-27000 Cycles for *CONFIGURATION 5*

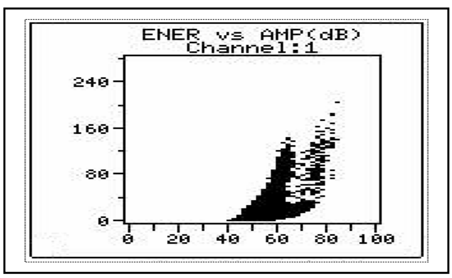

Figure 11: Energy Recorded between 27001-54000 Cycles for *CONFIGURATION 5*

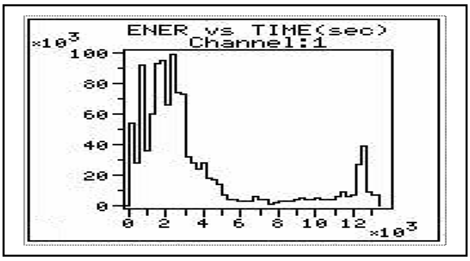

Figure 12: Energy Emitted over Time at 27001-54000 Cycles for *CONFIGURATION 5*

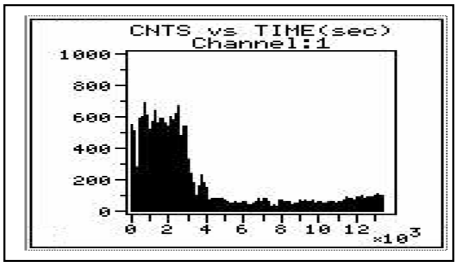

Figure 13: Counts recorded over Time at 27001-54000 Cycles for *CONFIGURATION 5*

From all the results discussed above, it seen that all the configurations encountered all type of micro-mechanisms damage during cyclic loading with different level of damage sustained by the composite laminates. *CONFIGURATION 2* was the worst design among the configurations to which it failed only after 52000 cycles. Damages were initiated around the hole (Figure 14) and propagates toward the laminates (Figure 15). Little fiber pull-out damage had been observed due to the long fiber length used in the material.

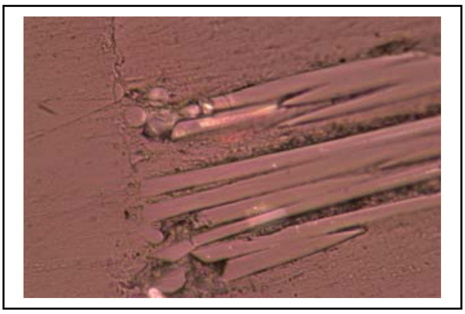

Figure 14: Damage around the hole for (magnification of 500 times) *CONFIGURATION 2*

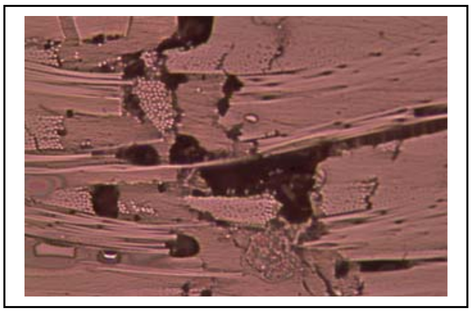

Figure 15: Severe damages at (magnification of 200 times) CONFIGURATION 2

All configurations with bolted joints showed more localized defects around the hole but severe damages at the distance equal to the radius of washer. This show that the clamping effects of mechanically joint can to some extend prevents the crack from propagating from hole. Three main types of fatigue damage around fastener holes have been observed. The nucleation and growth of delamination around fastener holes that acted as stress raiser were found. Under cyclic loading, the laminates with an open hole experienced an initial increase in residual strength but decrease in residual stiffness. The joints were very sensitive to flexural fatigue loading and suffered reductions in residual strength and stiffness. Besides delamination, the shape and dimensions of the hole changed slightly caused by the erosion and re-deposition of material around the fastener hole. This hole wear resulted in changing the condition of friction and the occurrence of plastic deformation. There were also some damages near the faying surface and at the countersink that may be produced by rocking of fastener during cyclic loading. The situation happened mostly in *CONFIGURATION 4* and *6*. The load distribution along the length of fastener is therefore not uniform and this produces accentuated wear at the faying surface that lead to highly localized region.

CONCLUSIONS

The paper has presented in some detail aspects of mechanically fastened Glass Fiber Reinforced Epoxy behavior under flexural cyclic loading. The experimental programs carried out in this paper given a general view of internal activities developed by using non-destructive technique. A well-designed model using ANSYS simulation package displayed a very informative stress distribution in the configuration under transverse loading. Combination of these results, the following conclusions can be made.

(1) Although the transverse loading imposed below its yield strength (nearly 50%), but the configurations suffered remarkable damages under fatigue as the number of cycles increased. Configuration with an open hole gave a most severe damages and configuration without any induced damage respond well under cyclic loading.

(2) Specimens with bolted joints showed a highly complex nature of damage development under fatigue loading. Simulations indicated that stress distributions were uneven and damages initiated at whose location with high stress concentration. Under the well-designed configurations to fail under tension mode, single lap with single fastener and two fasteners arranged in row showed quite similar effect and respond but damages developed more rapidly in configuration with two fasteners in column. It is because the stress interaction between fastener holes lead to re-establishment of a new damage state of a higher damage density, which means less fatigue resistant. Configuration with four fasteners did not show any great improvement in joint strength.

(3) The clamping of fastener can somehow prevent the propagation of crack from fastener hole but there were few types of fatigue damages observed around fasteners hole. For example, the damage near the faying surface and at the countersink that produced by rocking of fasteners during loading and hole wear caused by the erosion at the fastener holes.

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