# Research on the fatigue behaviour of glass fiber reinforced composites

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## Abstract

Tensile fatigue behavior of tapered glass/epoxy laminates is investigated. The effect of nanoclay addition into the epoxy resin is examined. It is shown that the relative orientation between the adjacent belt layer and the cut layer has important influence on the fatigue life. The fatigue crack starts at the resin pocket and propagates along the interface between the belt layer and the core layer in the thicker section of the laminate. Crack propagation is mainly due to mode II crack failure. The addition of the clays enhances the resistance against this mode II crack propagation, and thus prolongs the fatigue life of the laminate.

## Keywords

A. Glass fibers; A. Nanoclays; A. Polymer matrix composites (PMCs); B. Fatigue; B. Matrix cracking.

## 1. Introduction

In the past few decades, composite materials have been used in more and more applications. This is more pronounced where reducing the structure non-useful weight becomes a crucial design criterion so as to maximize the weight of the useful payload of such structures. Examples of these applications include wings and fins of aircrafts, helicopter yoke and blades, robot arms, and satellites. In addition to removing unnecessary weights, tapering the structure, i.e., varying its thickness from one point to another is, in some applications, a design requirement to allow flexibility. One example of tapered designs is the flexbeam of the helicopter main rotor yoke. Material thickness variations are required to optimize the design of laminated composite structures. These thickness variations are accomplished by dropping layers of material (plies) along the structure to match the load carrying requirements. Tapered composites produced by terminating or dropping off some of the plies have received much attention from researchers since the 1980s[1-2]. Previous studies can be categorized into two groups. The first group investigated the various parameters influencing the properties of tapered composite structures. These parameters include: ply drop location, laminate thickness, number of plies dropped at one location, fabric type, loading condition, fiber content, and spacing between ply drops[2-8]. The other group focused on identifying failure mechanisms associated with tapered composite structures. A few studies[9-17]covered a variety of aspects such as predicting the onset and growth of delamination, the determination of the interlaminar stresses in the area of ply drop-offs, the estimation of strain-energy release rate related with delamination inside the tapered area, and the modeling of delamination development by using finite element analysis.

The idea of nanocomposites stems from that fact that interphase (with properties different from the constituent materials) with a considerable thickness is considered as a source of energy dissipation in composite structures. Another source of energy dissipation related to interphase is due to the friction and slippage of unbound region or delaminated area of clay platelet and matrix[18-19]. As a consequence, it can be expected that adding nano-particles (e.g. nano-clay) in polymer matrix would improve the ability of energy dissipation under dynamic loading thus enhance the damping property [20]. It is worth mentioning that, should vibration damping or dynamic properties be improved, the fatigue life of the structure must be enhanced. Nano particles such as nano layered silicate or nanoclay having thickness around 1 nm and lateral dimensions in the order of few microns, have very high aspect ratio and specific surface area (around 657 m2/g) [21]. Even at a very low concentration, these nanoclays can create a huge network of interfacial surface areas when well dispersed in polymer resin system. It is thus estimated that incorporating nano filler can improve fatigue life of composite structures. A number of research works have been carried out over last few years to examine the effect of nano fillers on fatigue life of composite materials. Many studies have been devoted to improving the mechanical properties of fiber-reinforced composites by adding nanoclay. In addition to mechanical properties, clay–epoxy nanocomposites have shown wide array of property improvements with only very low fractions of clay, including the improved thermal stability[22-23], decreased moisture and gas permittivity [24] and better flame retardation [25]. The nanoclay, in particular, exhibited ameliorating effects on fracture and fatigue resistance of carbon fiber composites: e.g. increased mode I delamination resistance [26], developed impact damage resistance and tolerance [27] and better static and impact fracture toughness[28-29]. It is clear from the literature review that nano clay reinforced polymers have better dynamic and fatigue behavior over the pristine matrix. The objective of the present study is to investigate the fatigue behavior of tapered composite beam structure made of glass fiber and epoxy resin modified with nanoclay.

## 2. Experimental

The tapered specimens are composed of three sublaminates as shown in Fig. 1: one internally dropped sublaminate, and two outer continuous sublaminates (belt sublaminates) that cover the dropped sublaminate. All of the laminates investigated are symmetric. The fiber orientations for all samples are summarized in Table 1. The laminates were tapered from 40 plies to 32 plies through a taper angle of approximately 10°. The dropped sublaminate contains 8 plies and terminates at the midplane of the laminates. The triangular section in Fig. 1 represents a resin rich region.

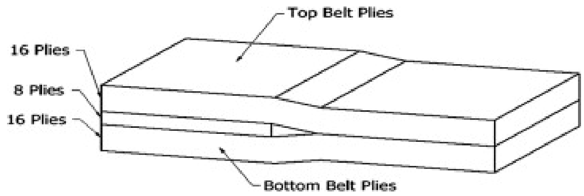


Fig. 1. View of the tapered laminate.

Hand lay-up and autoclave molding processes were used to fabricate all samples. At first, the fibers were cut from the fiber roll according to the orientation of lay-up using standard knives with replaceable blades into the appropriate lengths for hand lay-up. The laminate panels were made using a ply fill-in technique shown in Fig. 2 whereby an equivalent tapered section was built up on the other side of release plies.

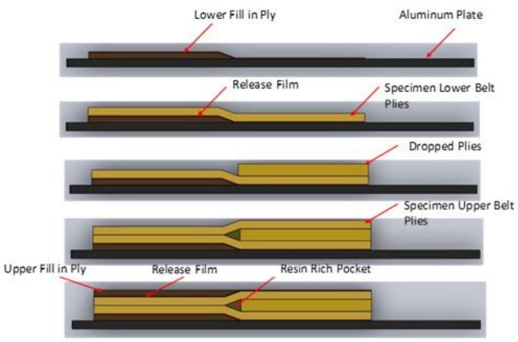


Fig. 2. Ply fill-in technique for manufacturing of the tapered panel.

The specimens were cut by high speed diamond wheel/water cooled cut-off saw in order to avoid any surface defect/damage within the dimensions shown in Fig. 3. The thin and the thick regions of the specimen are made of the same length; 101 mm whereas the length of the tapered region is 6 mm. Prior to conducting the tests, strain gages are bonded to the specimens. Gages of type Vishay CEA-06-125UW-350, manufactured by micro-Measurement of Measurements Group, Inc., are used and attached onto the specimens with M-Bond 200 adhesive as prescribed by Instruction Bulletin B-127-6.

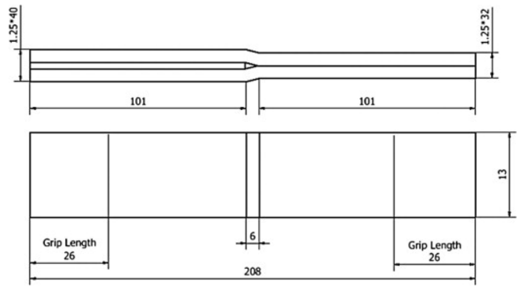


Fig. 3. Test specimen configuration and dimensions (in mm).

For all specimens, one strain gauge is bonded longitudinally at the center of one surface to monitor the axial strain. The strain gauge is located on the side of the thin section, 10 mm from the end of the thick section as shown in Fig. 4.

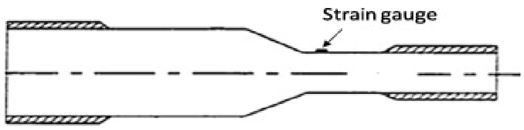


Fig. 4. Location of strain gauge on the specimen.

The cross sections of the samples were examined under Scanning Electron Microscope.Fig. 5 shows the micrographs for two samples, of the lay up sequence CPS. In Fig. 5a (no nanoclay), examining the central part of the figure, one can see the last belt plies (0° and 90° layers) before the cut plies (0° and 90° plies). It can be observed that the last 90° belt plies are not stable. A significant amount of fibers from these plies fall into the cavity created by the cut. As such the cavity is not just a “resin rich” area but it is also partially filled with fibers. InFig. 5b (with nanoclay) a similar situation is observed. The difference between the situations in Fig. 5a and b is that in the case of no nanoclay (Fig. 5a), there is more disorder in the fibers in the cavity area as compared to the case with nanoclay (Fig. 5b). The presence of the clay seems to dampen the flow of the 90° fibers into the cavity. Also, the cavity is filled more in the case with clay. This has a significant effect on the influence of the nanoclay on the fatigue life as presented later.

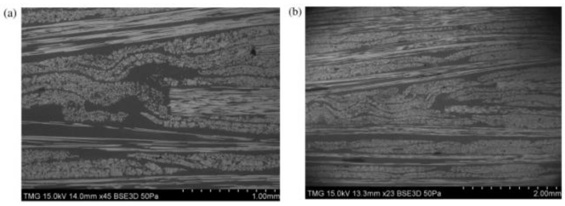


Fig. 5. Micrographs at the cut-off section of CPS samples. (a) Sample without nanoclay and (b) sample with nanoclay.

## 3. Results and discussion

Fig. 6 shows the tensile stress versus strain curves for the three stacking configurations, without (unfilled) and with (filled) clay addition. A small influence of the nanoclay filler on stiffness is evident. Both compositions exhibit linear behavior for the three stacking configurations. It can be concluded that nanoclay addition promotes more brittle-like behavior leading to a lower strain at failure.

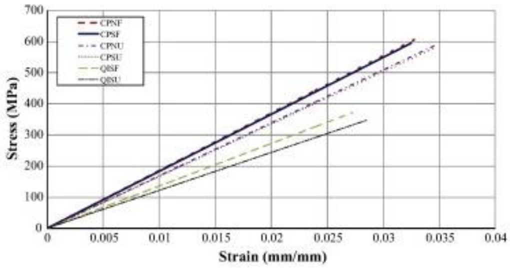


Fig. 6. Typical stress–strain curves for all tested samples.

Fig. 7 shows a typical image of fracture surface after the application of tensile tests on filled laminates. The failure modes in both laminates (filled and unfilled) are similar. It is observed that the failure is dominated by the fracture of longitudinal delamination between the 90°, for cross ply laminates, or -45°, for quasi isotropic laminates, (8th layer) and 0° (9th layer). This is due to high interlaminar stresses between layers with different orientations. Delamination is accompanied with crack between the dropped and continuous belt plies.

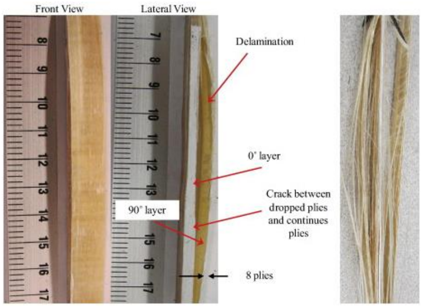


Fig. 7. Failure aspects in tensile tests of filled laminates.

Fig. 8 shows a typical photograph of a tested CPSF specimen after around 60,000 cycles at maximum stress level of 0.5*Sut* tensile fatigue. The photograph clearly shows the initial resin crack that is formed and the delamination growing along two interfaces between dropped and belt ply groups in the thick region. There is no evidence of delamination ahead of the resin crack, in the thin region. This failure pattern is observed consistently in all the tested specimens.

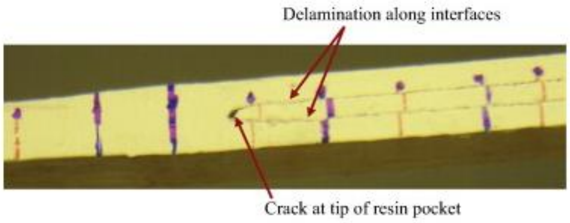


Fig. 8. Resin crack and delamination damage along two interfaces toward thick region in tapered beam.

Fig. 9 shows a representative photograph of delaminated tapered beam with delamination along length of thick and thin sections. In all cases, the delamination in the thin region is immediately followed by the final failure of the specimen as shown in Fig. 10. Evolution of failure modes of tapered beam is schematically summarized in Fig. 11.

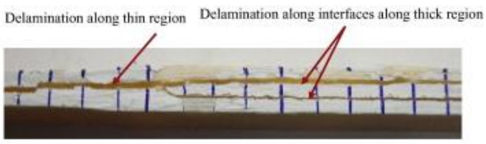


Fig. 9. Typical delamination damage before final failure.

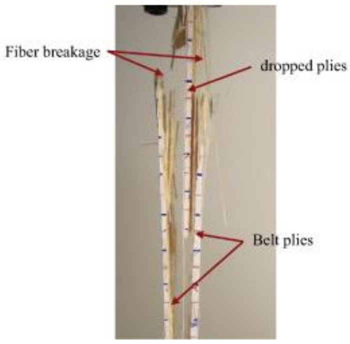


Fig. 10. Typical final fatigue failure.

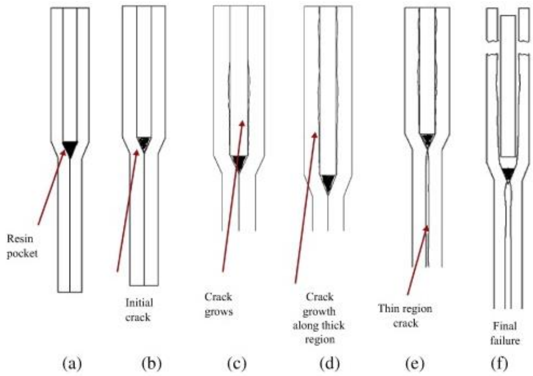


Fig. 11. Schematic for progression of failure of tapered beam under fatigue loading.

Fatigue strength depends significantly on the defined failure criterion. In the present study, the “final failure” criterion is adopted. According to this criterion, failure is defined when fibers break and total separation of the specimens is attained. The fatigue strength can be expressed in terms of maximum stress level versus logarithmic number of cycles to failure.Fig. 12 shows the fatigue behavior of the three stacking configurations for both filled and unfilled laminates.

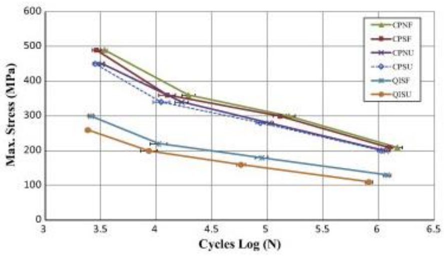


Fig. 12. Tensile fatigue strength, *S*–*N* curves, for all specimens.

Then, delamination seems to start always from this crack tip to the interface between the belt plies and the adjacent resin pocket as shown in Fig. 13(a). These cracks are faint but visible on the tapered beam surface during testing.Once a crack is formed, delaminations grow from the crack toward the thick region at both interfaces between dropped plies and belt plies simultaneously, Fig. 13(b). These delaminations grow in a stable and steady manner until they approach around 20 mm along the thick region.Finally, an unstable delamination occurs as delaminations grow faster along the entire length of the thick region as shown in Fig. 13(c).

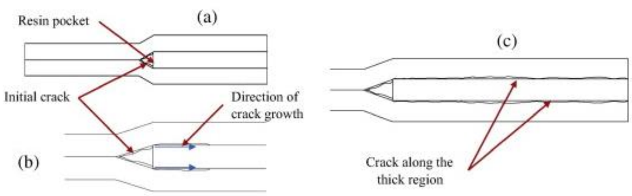


Fig. 13. Delamination starting at tip of dropped plies and growing in to interfaces.

Fig. 14(a) shows a photograph of a typical initial crack at point (T). Fig. 14(b) shows the crack as it grows to the thick region, whereas Fig. 14(c) shows delamination along the entire length of thick region (about 81 mm long). The mode of crack propagation in fatigue is similar to that in static loading.

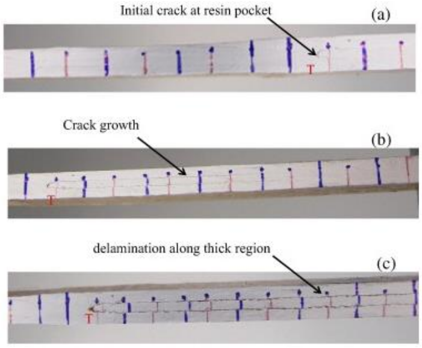


Fig. 14. Delamination evolution of tapered beam specimen.

Fig. 15 compares the crack propagation lengths in the thick region as a function of fatigue cycles for QISF and QISU specimens. The curves are plotted under two stress levels namely, high level at 0.8*Sut* and a low level at 0.5*Sut*. The delamination length is measured in the direction shown in the small insert.

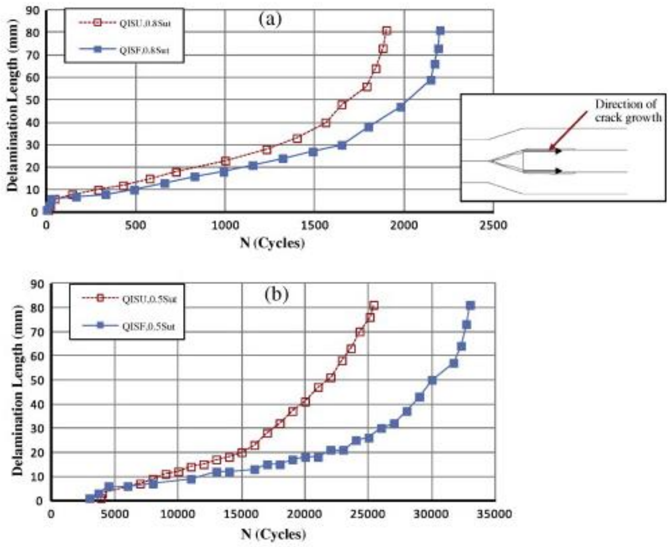


Fig. 15. Crack growth lengths for QIS of filled and unfilled laminates: (a) at 0.8*Sult* and (b) at 0.5*Sult*.

Fig. 16 ; Fig. 17 show the crack lengths for filled and unfilled CPS and CPN respectively. It is shown that CPS and CPN laminates have the same behavior of QIS laminates where adding the nanoclay improves the crack propagation rate in both low and high stresses. This improvement is more significant in low stress levels.

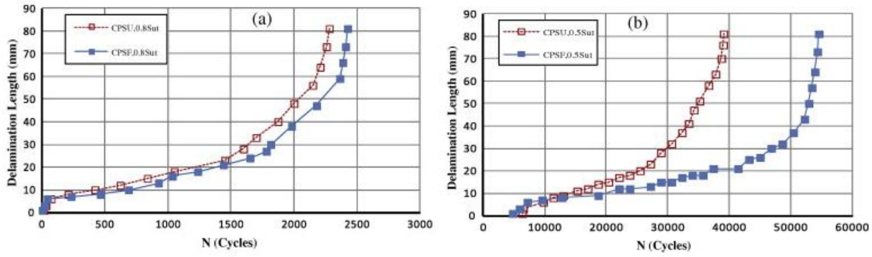


Fig. 16. Crack lengths for CPS of filled and unfilled laminates: (a) at 0.8*Sult* and (b)at 0.5*Sult*.

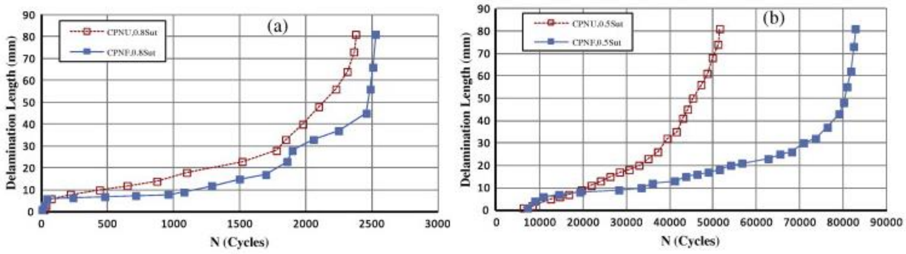


Fig. 17. Crack lengths for CPN of filled and unfilled laminates: (a) at 0.8*Sult* and (b) at 0.5*Sult*.

Fig. 18 shows a comparison of delamination length between three configurations at different stress levels. It is observed that CPS and CPN have crack growth rates less than QIS. The reason of this difference in crack growth rates may be related to the presence of the 45° layers in the QIS laminates, which give rise to shear stresses.

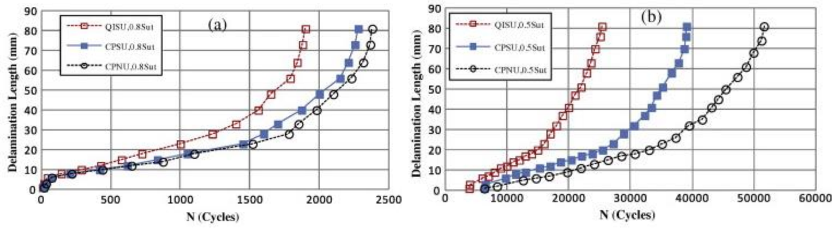


Fig. 18. Comparison between the three configurations at different stress levels.

Fig. 19 shows the damage index, *D*, plotted a function of fatigue cycles for QISF and QISU composites at 0.8 and 0.5 stress levels.It can be seen from Fig. 19(a) that in the early stage of fatigue (say, 0–400 cycles), the filled laminates exhibit more damage than the unfilled ones. After the initial damage period, the filled specimens sustain a relatively longer stable period with low damage indices for the rest of fatigue life. The final failure takes place much earlier in the unfilled composite than in the filled ones. It is also observed that at low stress level, the same behavior of filled and unfilled composite, Fig. 19(b).

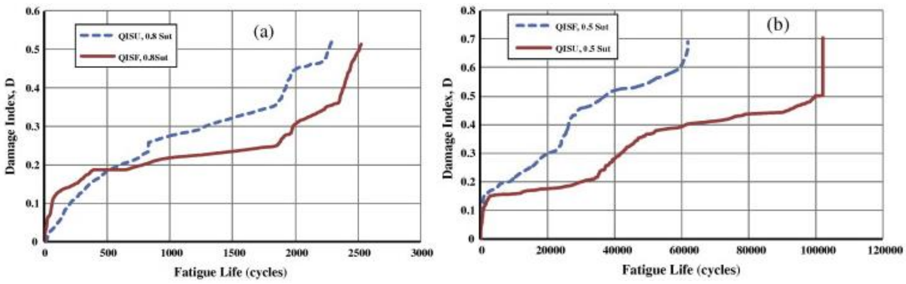


Fig. 19. Fatigue damage variable for QIS laminates, *D*, plotted as a function of fatigue life: (a) at 0.8*Sut*, and (b) at 0.5*Sut*.

The normalized stiffness variation with the number of cycles, evaluated for fatigue tests at stress level 0.5*Sut* for the QISU and QISF composites is shown in Fig. 20.

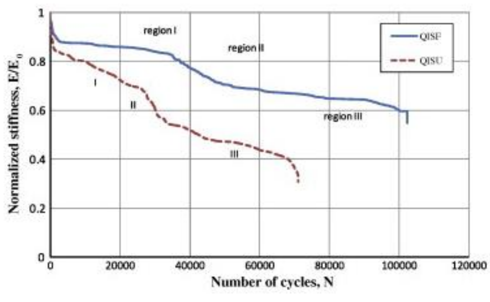


Fig. 20. The normalized stiffness variation with the number of cycles, evaluated for fatigue tests at $\sigma$max = 0.5*Sut* for QIS laminates.

## 4. Conclution

This paper presents the results of a study of tensile fatigue in glass/epoxy tapered beam composites with different stacking sequences, where nanoclay had been incorporated in the matrix. The main conclusions obtained are:

1.The static tensile strength and modulus of glass/epoxy tapered composites are slightly enhanced by the addition of nanoclay. The presence of nanoclay in the matrix increases the ultimate strength and decreases the strain to failure.

2.According to the failure criterion adopted, i.e. total separation of the specimens, tensile fatigue life was significantly extended with the incorporation of nanoclay to glass/epoxy tapered beam. The maximum improvement was about 54% with quasi isotropic laminates.

3.Nanoclay suppresses the fatigue damage growth in terms of damage index and crack growth rate over the whole fatigue life except the early stage of loading.

## Acknowledgements

This work is supported by the National Natural Science Foundation of China（No. 11602066） and the National Science Foundation of Heilongjiang Province of China (QC2015058 and 42400621-1-15047), the Fundamental Research Funds for the Central Universities.

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