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# Tensile fatigue behavior of tapered glass fiber reinforced epoxy composites containing nanoclay

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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.



## 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 nanoparticles (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 $m^2/g$) [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

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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.

It is noted that in a real engineering structure, the lay up sequence is more complicated and there are more drop-off regions. However in order to understand the mechanisms for the crack propagation and fatigue behavior, a simple tapered arrangement such as that in Fig. 1 can provide better insight without the burden of complexity.

Table 1 shows three different lay up sequences, all with the same number of plies. In the first lay up sequence (CPS), the fiber orientation in the last belt plies is 90° whereas that of the first cut plies is 0°. In the second lay up sequence (CPN), the fiber orientation of the last belt plies is 90° and that of the first cut plies is also 90°. In the third lay up sequence (QIS), 45° layers are added in addition to the 0° and 90° layers. Also, the last belt plies have orientation of −45° while that of the first cut plies is at 0°. These features have important influence on the fatigue performance of the samples.

### 2.1. Materials and fabrication of composite laminates

The laminates were fabricated from the following materials. Unidirectional S-glass fibers were manufactured by AGY World Headquarters and supplied by Aerospace Composites Products Inc. Organoclay Nanomer I.30E was supplied from Nanocor Inc. The resin and hardener are EPON 828 and EPICURE 3046, respectively, both supplied by Hexion Specialty Chemicals. A high-speed stirring method is used to disperse the clay in resin.

The procedure for dispersing nanoclay in the resin is as follows: The resin was first preheated to 45 °C to reduce the viscosity. Then 2 wt.% of nanoclay was added to the resin. The clay was mixed in

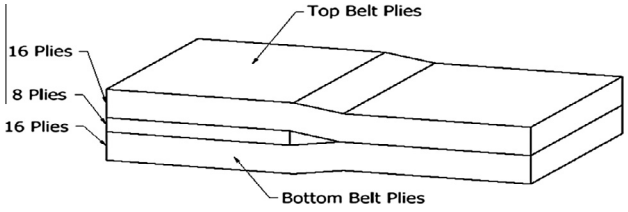


**Fig. 1.** View of the tapered laminate.

**Table 1**
Different sample configurations.

| Fiber orientation | Sample configuration |
|---|---|
| Cross-ply (CPS) | $[0_2/90_2/0_2/90_2/0_2/90_2/0_2/90_2/0_2^a/90_2^a]_s$ |
| Cross-ply (CPN) | $[0_2/90_2/0_2/90_2/0_2/90_2/0_2/90_2/90_2^a/0_2^a]_s$ |
| Quasi-isotropic (QIS) | $[0_2/90_2/+45_2/-45_2/0_2/90_2/+45_2/-45_2/0_2^a/90_2^a]_s$ |

[a] Orientation of the dropped ply.

resin by hand with a spatula. Next, the high speed homogenizer up to a maximum rotational speed of 25,000 rpm for 20 min was used to disperse the clay. Temperature of the suspension was closely monitored using a thermometer and was kept below 100 °C throughout the process to avoid self-polymerization.

The resin was prepared by the following procedure: The exact amount of hardener (35 phr) was first added to neat epoxy or epoxy–clay mixture (after dispersion with high speed homogenizer) at room temperature. The mixture and hardener were then mixed slowly with a stirrer for 5 min to avoid air entrapment. To remove air bubble, the mixture was then degassed in a vacuum oven at a vacuum of 25 mmHg for 25 min at room temperature.

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. Formation of laminate panel (for 40–32 layers) was done following the steps below:

1. The lower fill-in plies were placed on the mold (4 cured layers of the same composite material).
2. The lower belt plies (16 layers) were laid-up.
3. The dropped plies (8 layers) were laid-up.
4. The upper belt plies (16 layers) were laid-up.
5. The upper fill-in plies (4 cured layers of the material) were finally placed.

This technique allows tapered panels to be made between flat plates and produces good consolidation without the need for special tooling. All of the full length plies for the laminates have in-plane dimensions of approximately 210 mm long, and 15 mm wide. The internally dropped plies that make up the ply-drop step are also 15 mm wide and 100 mm long.

### 2.2. Specimen preparation

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.

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.

### 2.3. Microscopic observation

The cross sections of the samples were examined under Scanning Electron Microscope. Fig. 5 shows the micrographs for two