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Fatigue Studies of Polyurethane Sandwich Structures

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The fatigue characteristics of polyurethane foam-cored (PUF) composite sandwich structures were investigated using three-point bending tests carried out according to ASTM C 393. Three types of specimens (epoxy/glass-PUF-epoxy/glass, polyester/glass-PUF-polyester/glass, and epoxy/glass-PUF-polyester/glass) were considered for investigation. Experimental results indicate that degradation of stiffness occurs due to debonding and sliding between the skin and the foam during fatigue cycles. Epoxy/glass-PUF-epoxy/glass sandwich structures exhibit higher bending strength along with higher stiffness degradation than the other two types of sandwich panels, due to higher initial fatigue loading. The lowest fatigue properties have been obtained for the polyester/glass-PUF-polyester/glass sandwich panel specimens. Better performance of the epoxy/glass-PUF-epoxy/glass sandwich panels is most likely due to the superior properties of the outer thin skins. Most of the specimens fail within the foam region and not at the skin level. This situation is possibly due to debonding between the foam and the skin. The fatigue damage development in the foam and skin has been investigated using scanning electron microscopy.

Keywords failure mechanism, fatigue, polyurethane, scanning electron microscopy

1. Introduction

In recent years, there has been an increasing level of interest in sandwich composites, which have become very popular thanks to their lighter weight, cost effectiveness, and durability of the resulting structures. Traditionally, sandwich structures have two thin metal faces forming the skins and a rigid foam core in between them. Currently, research[1-3] has concentrated on replacing the metal plates with fiber-reinforced plastics (FRP), such as glass/epoxy and glass/polyester, which confer greater interfacial bonding strength between the foam and the outer shell.

Polyurethane (PU) sandwich constructions enable cost-effective manufacturing of stiff and lightweight structures, as well as decorative parts, in a single processing step. Albus and Stefan[4] have used PU rigid foam for thermal insulation in building materials (such as walls, roofs, and floors). Textron Automotive Company has demonstrated two bumper beam designs made from glass fiber that were tailored to meet the 8 km/h impact velocity requirements of the Federal Motor Vehicle Safety Standard 581.[5]

Palle[6] has studied heat-transfer behavior of a PU sandwich construction of bonded pipe in a pipe system with a steel jacket pipe. PU sandwich plate systems have been introduced in shipbuilding, claiming significant benefits in performance, cost, and safety compared with conventionally stiffened steel plate structures.[7] In all cases, the sandwich structures help realize the best combination of thermal resistance, mechanical properties,[8] creep,[9] and buckling strength.[10]

Shenoi et al.[11] have investigated the static and flexural fatigue characteristics of foam-core polymer-composite sandwich beams. Burmen et al.[12] have tested the fatigue characteristics of two cellular foam-core materials used in load-carrying sandwich structures. However, little research has been focused on the fatigue behavior of sandwich structures, which are very important in dynamic loading.

In this paper, the bending strength, bending fatigue strength, and stiffness degradations are evaluated on foam-cored sandwich structures. Three types of specimens with glass fabric-reinforced plastic faces and polyurethane foam core are used. The fatigue failure mechanism is explained using scanning electron microscopy (SEM).

2. Experimental

2.1 Materials Selection

Sandwich specimens were fabricated according to standard specifications. They consisted of a glass fabric (woven type) and polyurethane foam core. Table 1 shows the properties of the material used for these specimens. The primary chemicals used to produce the PU foam (thermoset) are methylene diisocynate (MDI) and polyether polyol.

2.2 Preparation of Sandwich Panels

The major steps in manufacturing a sandwich specimen are:

1. Take an equal amount (50 mL) of MDI and polyether polyol liquids into separate, clean, and dry glass cups;
2. Cover an area of the wooden die about 700 × 700 × 20 mm^2 with a Teflon sheet;
3. Mix the MDI and polyether polyol with a stirring rod in a separate glass vessel;

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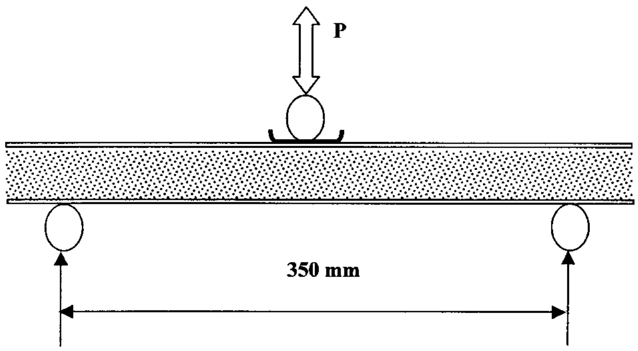

Fig. 1 Three-point bending fatigue test setup

Table 1 Material Details of the Specimen

Construction	Material	Specification
Skin	Glass fabric	E glass roving cloth
Resin	Epoxy	LY556
	Polyester	…
Foam	PU foam	Density 0.4–0.6 g/cm^3

Table 2 Basic Static Bending Strengths of All Panels

No.	Sandwich Panels	Bending Strength, MPa
1	Epoxy/glass-PUF-epoxy/glass	0.54
2	epoxy/glass-PUF-polyester/glass	0.43
3	Polyester/glass-PUF-polyester/glass	0.35

4. Pour the mixture into the die, cover the die, and apply a pressure of 5 tons;
5. Leave it for 20 min and take out the PU rigid foam from the die;
6. Lay up a woven glass fabric on a polyurethane foam core;
7. Lay up a resin on each face of the glass fabrics;
8. Lay up reinforcement fibers on each side of the rigid foam; and
9. Cure at ambient temperature for 24 h.

2.3 Static Bending Test

The static bending test was conducted according to ASTM Standard C 393 on a fatigue-testing machine (Shimadzu, 10 tons) (Shade Inc., Lincoln, NE) at a constant crosshead speed of 0.5 mm/min. The span length was chosen as 250 mm. Strain gauges were attached to the outer skin to measure strain caused by the bending load.

2.4 Fatigue Tests

Fatigue testing was carried out according to ASTM C 393 by using a three-point bend (3PB) setup with a span length of 250 mm (Fig. 1). To prevent any degradation of the matrix, frequencies of only 1, 3, and 5 Hz were chosen. The test was load controlled, while the displacement was allowed to vary. Different load levels, based on the 3PB static ultimate load (65% of 3PB of bending load), were chosen to determine the stress versus number of cycles (S-N) curve and to get an idea of the fatigue life of the sandwich panels. The tests were performed to failure or to 10^6 cycles. The fatigue test was set to stop automatically if the displacement exceeded 20 mm, either due to specimen failure or stiffness degradation. The displacement was monitored at constant load to obtain the stiffness degradation.

The following formula was used to determine the stiffness degradation (*SD*) of sandwich panels:[13]

$$SD = \frac{\text{slope at first cycle} - \text{slope at maximum cycle}}{\text{slope at first cycle}} \times 100\%$$

$$= \frac{\dfrac{\Delta P}{\Delta\delta_{\text{First cycle}}} - \dfrac{\Delta P}{\Delta\delta_{N\,\text{cycle}}}}{\dfrac{\Delta P}{\Delta\delta_{\text{First cycle}}}} \times 100\%$$

where ΔP is the difference between the maximum and minimum loads (*N*) and $\Delta\delta$ is the specimen displacement in mm due to ΔP.

3. Results

3.1 Bending Strength

Results of the bend tests are given in Table 2 (to be consistent with the other number). The bend strengths of the polyester/glass-PUF-polyester/glass and epoxy/glass-PUF-polyester/glass sandwich panel are 35% and 18% lower, respectively, than that of the epoxy/glass-PUF-epoxy/glass sandwich panel.

3.2 Fatigue Strength

The *S-N* curves of the three panels at the three test frequencies are plotted in Fig. 2. The plots of fatigue-bending stress versus number of cycles at fatigue frequencies of 1, 3, and 5 Hz are also obtained. At a 1 Hz frequency, the three panels did not completely fail when the machine was stopped. Due to their very high resistance against fatigue at this frequency, the test was stopped because the maximum deflection limit of 20 mm was exceeded. At 3 Hz, the epoxy/glass-PUF-epoxy/glass partially failed due to debonding between the skin and the foam. The other two specimens completely failed due to debonding and cracks in the foam, which could be visually observed. At 5 Hz, all of the specimens completely failed due to debonding and cracks in the foam. However, there was no damage noticeable in the outer skins.

The fatigue responses of all three types of sandwich exhibit two distinct regions: a steady-state region (SR) and a deteriorating region (DR). In SR, there is a marginal decrease in the fatigue stress. The debonding between skin and foam does not significantly affect the fatigue life behavior of PU sandwich panels. The rate of strain is almost constant. The *S-N* curves for the three types of sandwich panels are nearly identical in shape in this region for all frequencies. Few, if any, cracks are seen in between the skin and the foam.

It is clearly evident from the graph that there exists a transition point (TP) between SR and DR at which there is a sudden

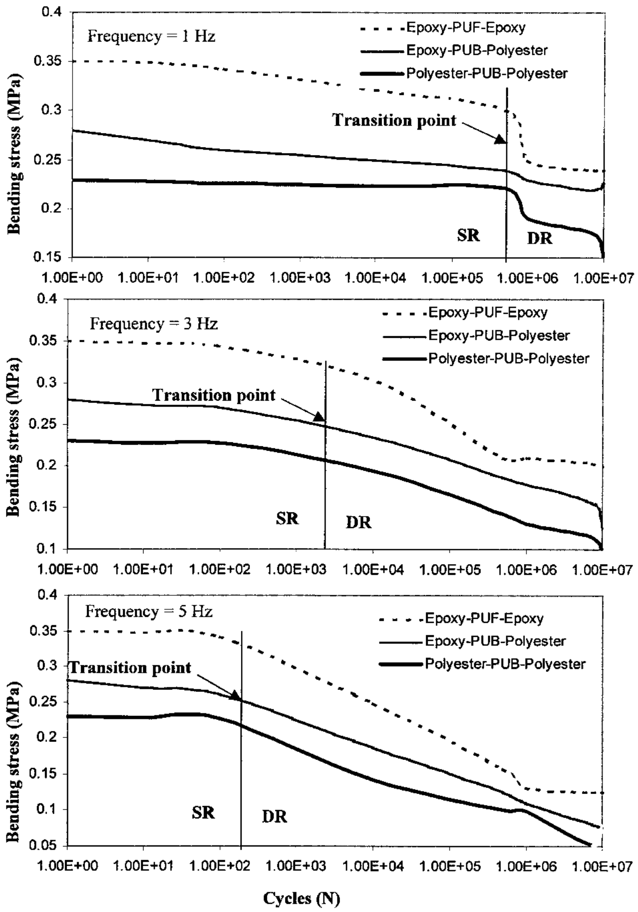

Fig. 2 *S-N* curve of two-directional woven glass sandwich panels at various frequencies

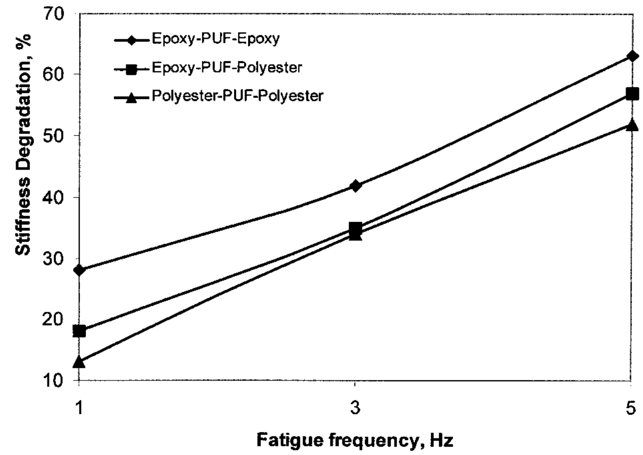

Fig. 3 The stiffness degradation of PUF sandwich panel at frequencies of 1, 3, and 5 Hz

increase in the slope for specimens. Beyond TP, the slope of the curve changes drastically. However, the TP for all specimens is approximately the same. At 1 Hz, the transition point for each sandwich specimen is observed at 7.5×10^5 cycles. At higher fatigue frequencies, the transition point is observed at earlier cycles, e.g., 1.76×10^3 and 1.5×10^3 cycles for 3 and 5 Hz fatigue frequencies, respectively. Above TP, the sandwich specimen possesses numerous cracks between the foam and the skin.

In the DR portion, debonding between the skin and the foam plays a major role, with the strain rate changing in an unnatural way. When in the DR, there is a rubbing noise that increases in intensity thereafter. This problem suggests that crack propagation or delamination occurs progressively until failure.

3.3 Stiffness Degradation

Epoxy/glass-PUF-epoxy/glass sandwich panel shows superior bending properties, but large stiffness degradation (SD) is observed at the end of the fatigue limit. Epoxy-glass skins can accommodate higher fatigue stresses, due to their superior properties when compared with polyester-glass composites. Because epoxy/glass-PUF-epoxy/glass possesses the highest bending strength, as shown by the three-point bend test results, these specimens prevent the skin from buckling on the compression side and also resist the high compressive stresses occurring during cyclic loading. In other words, the superior performance of the epoxy/glass sandwich panels may be attributed to the combination of high shear and compression properties of the interface in the sandwich composite.

As the composite deteriorates, cracks are nucleated between the skins and the foam; hence the skins see a smaller load while the foam takes the major portion of the load. Due to the imbalance in the load sharing, the foam loses its stiffness, thereby increasing the stiffness degradation steeply. The polyester/glass-PUF-polyester/glass sandwich panel has the lowest fatigue strength due to its inferior bending strength.

At a higher fatigue frequency, the fatigue behavior of both side epoxy/glass-PUF-epoxy/glass specimens are found to be having high stiffness degradation. It seems that the fatigue load and frequency are major parameters that affect degradation. This situation may be due to failure in the adhesive at the skin/foam interface. Sorensen and Bent[13] have explained that the cyclic stress increases with increasing separation of the foam and the skin.

It can be observed from Fig. 3 that stiffness degradation increases with the increase in fatigue frequency. Furthermore, with an increase in fatigue cycle number, the strain value also increases. For a higher number of fatigue cycles, the skin/foam interfacial damage occurs very rapidly and becomes the main cause of stiffness degradation.

3.4 SEM Studies on Fatigue Damage Analysis

An analysis of the fatigue behavior facilitates understanding of failure and damage mechanisms generated during fatigue. SEM observations (Fig. 4a-c) show an important influence of the interface on the specimen failure.

In epoxy/glass-PU-epoxy/glass specimens, the fatigue damage was confined to the skin. The damages consist of shear cracking between the fiberglass plies, as shown in Fig. 4(a). There is no appreciable interfacial cracking between the skin and the foam core.

Polyester/glass-PU-polyester/glass specimens completely broke in some locations. With cracking spreading across the

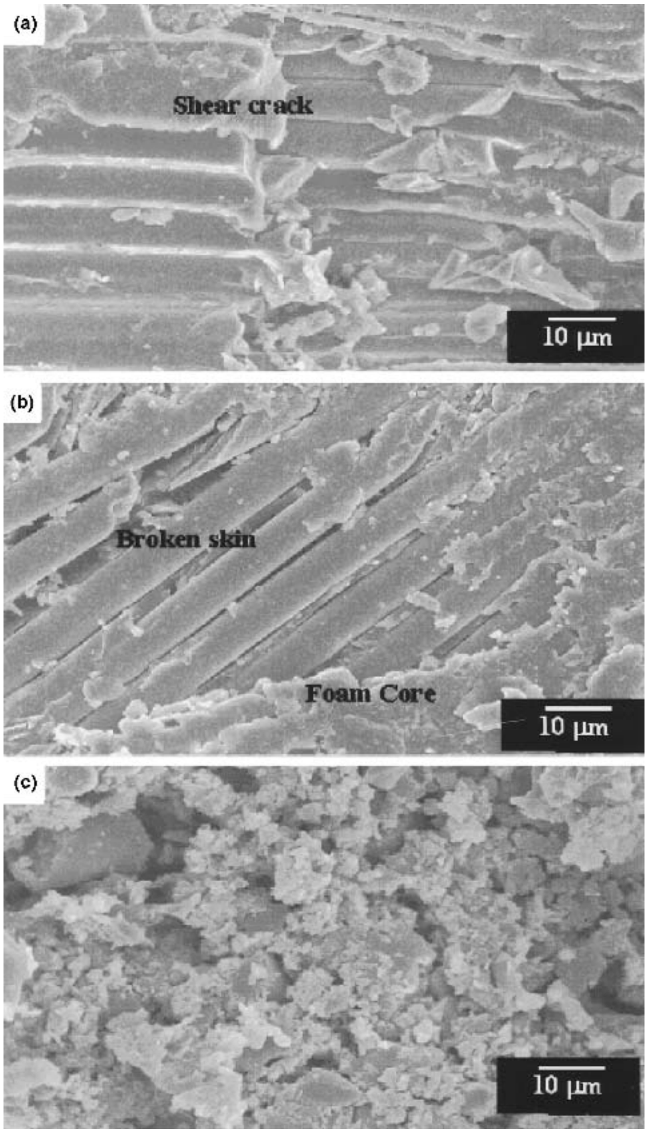

Fig. 4 Fatigue damage in **(a)** epoxy/glass skin, **(b)** polyester/glass skin, and **(c)** polyurethane foam core at 5 Hz

skin, the foam core is torn and foam cells are partially compressed immediately beneath the broken skin (Fig. 4b).

The damage to the foam consisted of tearing and cell compression. The bonding between this damaged region and the underlying undamaged core is shown in Fig. 4(c). Three modes of failure are caused by shear stresses, namely, skin failure by fiber breakage, core failure by crushing, and skin/foam interfacial failure due to debonding.

4. Discussion

The bending fatigue strength of sandwich structures depends upon the strengths of the outer skins, the foam core, and the adhesive bonding between the skin and the foam. Failure of any of these would cause complete failure of the sandwich structures. Judawisastra et al.[14] have reported that the fatigue strength of sandwich panels is influenced by the skin strength and thickness, as skin buckling is an important failure phenomenon. The failure of sandwich structures occurs not only due to fatigue stress, but it is also due to the shear stresses between the layers. It appears that the failure in fatigue is due to the combination of tension, compression, and shear stresses.

The skin/foam interfacial bond strength in sandwich panels depends upon the stiffness of the sandwich structure which is likely to be reduced even by partial delamination of the foam core and the skins.[15] During compression and tension cycles, the outer skin and foam core rub against each other, leading to an increase in temperature at the mating surfaces. The interface temperature increases with increase in the frequency of fatigue cycles due to less time for heat dissipation. The stiffness (adhesive bond strength between the skin and foam) decreases with this increase in temperature at the interface; hence, stiffness degradation of all the specimens increases with increasing fatigue-cycle frequency. This degradation leads to premature failure of the sandwich as a result of debonding of the skin and the core in the form of long cracks between them. Triantafillou and Gibson[16] have reported that a comparison of the load for debonding with other failure modes shows that debonding occurs only if relatively large cracks exist at the interface between the face and the core.

5. Conclusion

A simple fabrication procedure to make consistent quality, polyurethane foam cored composite sandwich structures was established, and a detailed bending fatigue characterization of the sandwich structure was performed. The results of the characterization indicate:

- Epoxy/glass-PUF-epoxy/glass exhibited highest fatigue strength along with highest stiffness degradation, while the polyester/glass-PUF-polyester/glass specimens exhibited lowest fatigue strength and lowest stiffness degradation.
- At 1 Hz frequency, none of the specimens completely failed; but at 3 Hz and 5 Hz, all specimens failed due to delamination at the interface between the skin and the foam.
- Three failure modes were prevalent, namely, skin failure due to delamination, shear failure in the core, and skin/core interface, and core failure due to crushing stresses.

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