SHORT FIBER INTERFACIAL TOUGHENING FOR COMPOSITE-FOAM SANDWICH

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Abstract: Interfacial toughness, critical bending load and energy absorption of carbon-fiber/aluminum-foam sandwich beams with low-density short aramid-fiber interfacial toughening are investigated in this study. Short aramid fibers of different lengths and densities were inserted at the interface between carbon-fiber face sheets and aluminum-foam core during the sandwich fabrication process, to improve the interfacial bonding of the sandwich structures. With less than 1 wt% of short aramid fibers, over 80% improvement in the interfacial toughness, over 30% improvement in the peak bending load and over 80% in the energy absorption were achieved, showing the interleave using low-density short aramid fibers is effective in promoting the key toughening mechanism of fiber-bridging against cracking along the interface between carbon-fiber face sheets and aluminum foam core. The interfacial strengthening, toughening, and underlying mechanisms were discussed and analyzed, together with the observations from scanning electron microscopy.

1. Introduction

Strong and light weight carbon-fiber aluminum-foam sandwich structures, consisting of an aluminum-foam core with two carbon-fiber/epoxy composite face sheets, can be used in a wide range of applications, including automotive, marine, aerospace, and other transportation applications [1] due to their high specific stiffness and strength, high energy-absorption and large plastic deformation capacities. However, studies [2] showed that both the collapsing load and energy absorption of carbon-fiber aluminum-foam sandwich structures were decreased significantly if debonding or delamination occurred at the face-core interface. Failures frequently occur at the interface, not only because of the weak adhesion of brittle epoxy [3, 4], but also due to the stress concentration at the interface zone. Therefore, the interfacial toughness controlling delamination at the face-core interface has been identified as the key factor for the carbon-fiber aluminum-foam sandwich structures, and the focus of the present study.

In this study, a low-density short-aramid-fiber interleave method, initially proposed and studied by Sohn, Walker and Hu [5, 6] for laminar carbon-fiber/epoxy composites, is adopted for interfacial toughening in the carbon-fiber aluminum-foam sandwich structures. This simple and cost-effective interleave method has been proven both experimentally [5, 6] and analytically [7] that the in-plane distributed low-density short aramid fibers can actually provide “Z-directional” toughening against delamination. More importantly, recent
independent studies by Bond et al. [8, 9] on comparisons between various
interleave methods show that the short aramid-fiber interfacial toughening is
among the best in both Mode-I and Mode-II delamination toughness
measurements, as shown in Figure 1. Furthermore, the low-density short
aramid-fiber interleave technique can be easily applied to the interface between
the carbon-fiber face-sheet and aluminum-foam core. Finally, it has been
proven recently that the method is effective against interfacial de-bonding
in carbon-fiber aluminum-foam sandwich structures [10]. The key
toughening mechanism of crack-bridging has been well-documented in various
composite systems [11 - 13].

Therefore, the objective of this study is to adopt the simple and cost-
effective interfacial toughening method using low-density short aramid fibers to
prevent interfacial de-bonding between the aluminum-foam core and carbon-
fiber face sheets so that the energy absorption and critical bending load of
the sandwich structures can be enhanced.

2. Short aramid fiber mat

Short aramid fibers employed in this study were prepared from Kevlar 49
TM. The Kevlar 49 TM fiber was chopped into various lengths from 6 mm
to 14 mm at the interval of 2 mm. The initially chopped aramid fiber strands
were next stirred in a blender with a

Figure 1. Mode-II strain energy release rate (G_{II-C}) of carbon-fiber/epoxy composites [9].

Figure 2. Surface view of a thin mat of short aramid fibers.

3. Reinforcing effect of short aramid-fiber interfacial toughening

3.1. Interfacial toughness of sandwich with aramid fiber interleave

The double cantilever beam (DCB) test was chosen to measure the
interfacial toughness quantified as the energy release rate for interfacial crack
growth between the aluminum-foam core and carbon-fiber face sheet. An
interfacial pre-crack of 50 mm in length and 23.6 μm in thickness was introduced
during composite processing, which is between 10-ply 1.5 mm thick carbon-
fiber face sheet and 15mm-thick Alporas TM aluminum-foam core. The total
length and width of the specimen were 178.4 mm and 20.0 mm respectively.
The density of aramid fibers was kept constant at 12 g/m² for all DCB tests.

The average toughness values and standard deviations of G_C of carbon-fiber
aluminum-foam sandwich samples between two different crack extensions,
2-3 mm and 10-15 mm, are shown in Figure 3 for short aramid fibers of
different lengths. G_C for initial crack growth around 2-3 mm in Figure 3 (a)
showed slight increase as crack-bridging
due to short aramid fibers was still to be established. $G_C$ for crack growth between 10-15 mm in Figure 3 (b) showed a strong effect of aramid fiber bridging and a clear trend of aramid-fiber length influence. $G_C$ could not be measured for further crack growth due to shear failure of the aluminum-foam core.

Figure 3. Critical energy release rate of sandwich samples with and without short aramid fiber interfacial toughening; (a) initial $G_C$ for 2-3mm crack extension, (b) $G_C$ for 10-15mm crack extension (error bars mark the standard deviation, minimum of four specimens per group) [10].

The average $G_C$ of plain carbon-fiber aluminum-foam sandwich samples without short aramid-fiber interleave is only 1,518 J/m$^2$, but the average $G_C$ of the carbon-fiber aluminum-foam sandwich samples with the low-density interleave for 6 and 8 mm aramid fibers is 2,753 J/m$^2$ and 2,709 J/m$^2$ respectively, or increase of 80% and 78%.

### 3.2 Properties of carbon-fiber aluminum-foam sandwich under 3PB test

Quasi-static three-point bending (3PB) test is chosen to measure the effect of short aramid fiber interfacial toughening on the energy absorption and critical bending/crushing load of the sandwich structures. Both the top and bottom face sheets over the Alporas TM aluminum-foam core are made of 6 carbon-fiber plies with the final thickness of around 1 mm. The span $L$ and width $b$ of 3PB specimens are 112.0 mm and 14.0 mm, respectively, and the diameter of the three loading pins is 10 mm. Short aramid fiber mats of three typical densities close to those in the previous studies were used in the present study: 3 g/m$^2$ [5, 6], 12 g/m$^2$ [10], and 50 g/m$^2$ [8, 9].

Average values and standard deviations of the peak bending load and energy absorption of carbon-fiber aluminum-foam sandwich samples, and the influence of aramid-fiber length and density are shown in Figure 4. The average peak load in Figure 4 (a) has been increased from 0.47 kN (without the aramid-fiber interleave) to over 0.65 kN (with the 14 mm aramid-fiber interleave), or 38% improvement. Moreover, the average energy absorption of the plain carbon-fiber aluminum-foam sandwich samples without short aramid fiber interleave is only 8.70 J, but the average energy absorption of the carbon-fiber aluminum-foam sandwich samples with 50 g/m$^2$ of short aramid fibers has been increased to 15.68 J and 14.32 J for 14mm and 6mm aramid fibers respectively, or 80 % and 65 % higher than the original energy absorption. The 14 mm and 6 mm aramid-fiber toughening have similar trends that the effect of interfacial toughening is gradually increased with increasing aramid fiber density and stabilized when the density reaches around 12 g/m$^2$. The
improvement from 12 to 50 g/m² is marginal. 6 mm aramid fibers are slightly less effective than 14 mm aramid fiber, due partially to the fact that fiber pull-out during Mode-II interfacial shearing may be easier in the case of shorter fibers.

3. Interlaminar toughening effect of short glass fibers

The double cantilever beam (DCB) test was also used to measure the Gc and toughening effects for glass-fiber interleaved interface between the polymer-foam core and glass-fiber/epoxy composite face-sheet. A pre-crack of 22 mm in length and 26 μm in thickness was created between 8-ply 2 mm thick glass fiber face-sheet and 30 mm-thick PMI polymer foam core. The total length and width of the specimen were 152.4 mm and 25.4 mm respectively.

As shown in Table 1, average interfacial toughness for the toughened specimens is higher than that for the specimens without enhancement, and the average improvement in Gc is about 75%. The results indicate the validity of glass-fiber interlaminar toughening technique as well.

4. Underlying interfacial toughening mechanism

To understand the underlying toughening mechanisms of low-density short aramid-fiber interleave, Scanning Electron Microscope (SEM) observations of the fracture surfaces were conducted. Both the top and bottom fracture surfaces from various samples were examined using a Phillips XL30 SEM at magnification of 500-1000 times and voltage accelerations of 15 kV.

Figure 5 shows a resin-rich section of fracture surface on the carbon-fiber face-sheet of a sandwich sample have
been filled by resin with distributed low density aramid fibers. The fracture surface clearly shows tensile fracture and pull-out of short aramid fibers, which is the evidence of aramid fiber bridging and crucial to the interfacial toughening. Without those short aramid fibers, the interfacial fracture would be controlled by the bond strength of brittle epoxy only.

A fracture surface on the carbon-fiber face sheet contacted with a thin wall between two aluminum-foam pores is shown in Figure 6 (a), and the section of the sandwich structure before failure was illustrated in Figure 6 (b). The presence of short aramid fibers together with resin effectively increased the connecting areas between the carbon-fiber face sheet and the thin aluminum-foam wall, and the in-situ formed “filler reinforcement” was strengthened by the short aramid fiber. The composite nature of the filler reinforcement is clearly evident as shown in Figure 6 (a). This toughening mechanism is equally applicable to carbon-fiber aluminum-honeycomb sandwich structures. Also, the thin aramid fiber layer between carbon fiber and aluminium foam can be beneficial if corrosion is a concern.

5. Conclusion

The interfacial toughness, energy absorption and critical 3PB crushing load of carbon-fiber face-sheet and aluminum-foam core sandwich beams with and without the low-density short aramid-fiber interleave at the interface have been measured and compared under various interfacial conditions. Based on those experimental results, the interfacial toughness [10], the energy absorption and critical bending crashing load [11] have all been enhanced effectively. From the results obtained so far, the density of 12 g/m² of short aramid fibers is sufficient and is a good compromise for less weight gain and effective toughening. Scanning Electron Microscope observations have confirmed the bridging effect of short aramid fibers, and in-situ formed aramid-fiber “fillet reinforcement” at the edge of large opening.

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References


