IMPACT RESISTANT FIBER REINFORCED ELASTOMER COMPOSITE MATERIALS

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ABSTRACT

There is a continuing need for better fracture and impact-resistant materials in civil and military applications. This work characterizes the impact resistance and fracture toughness of several fiber-reinforced polyurethane composites.

A series of Charpy impact tests were conducted to measure the impact strength and specific impact strength for five combinations of fiber reinforced elastomer composites, and epoxy matrix composites. The elastomers covered a range of durometers (hardness). Impact strength and specific impact strength of the composites were also compared to results from aluminum and steel specimens. For the same fiber type, all elastomer composites had greater impact strength than the epoxy composite. When specific impact energies are considered, the intermediate and rigid elastomer composite specimens have greater impact resistance than the baseline metal specimens and compared favorably with hot rolled 4140 steel. The fiberglass and intermediate hardness elastomer specimens resisted multiple Charpy impact tests with gradual loss of strength.

Compact tension specimens of fiberglass using the same intermediate and rigid elastomer matrices and epoxy resin were fabricated and tested to acquire preliminary trends in fracture toughness. The rigid elastomer composites performed better than the semi-rigid elastomer, and were comparable or slightly less than fracture toughness values for fiberglass/epoxy.

KEY WORDS: Impact resistance/Behavior, Composite Materials, Elastomers/Rubber

1. INTRODUCTION

Impact resistant materials remain a concern to all types of military and civilian equipment manufacturers. To a large extent traditional composites and metals are currently used in impact resistance applications. Metals are considered tough or impact resistant when they have high

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strengths and deform significantly (plastically) before fracture. Polymer resins used in composites typically have rubber (elastomer) particles added to reduce brittleness [1]. For example flexible vinylester plastic has about 6.5 times the impact resistance of a rigid vinylester, however it has lower strength and stiffness [2]. Considerable data on fracture toughness has been accumulated in the field of traditional carbon epoxy composites [3]. The Navy is also investigating fiberglass composite/elastomer sandwich structures that can endure sudden impact and natural seawater flows [4].

Instead of using elastomer particles as additives in a rigid epoxy or vinylester, it is proposed to use an elastomer directly as the matrix in the composite material. The intent is to show that when rigid and semi-rigid elastomers with high resilience are used with high strength fibers they will produce light, tough impact resistant strong structures. Previous research work on flexible or elastomer composites at Texas A&M University–Kingsville provided extra impetus for the current work. For a previous project, very compliant “rubber muscles” were fabricated, and attached to artificial “legs”. So that they could be bonded to the “polyurethane rubber muscle,” the “legs” were fabricated from filament wound graphite/fiberglass and a rigid polyurethane elastomer. The leg tubes proved to be very impact resistant [5].

The current work characterizes the impact resistance and fracture toughness properties of several fiber reinforced elastomer combinations and compares them with baseline metals and traditional epoxy composites. These lightweight fiber-reinforced elastomer composites have the capability to replace metals and traditional composites for high impact strength and vibration damping while providing good in-plane stiffness.

2. EXPERIMENTAL

Charpy Impact and Compact Tension Fracture Toughness tests were conducted in order to characterize the properties of fiber reinforced elastomer composites. V-notch Charpy specimen and Compact tension specimens were machined from composite laminates that were fabricated by a hand-lay-up process.

2.1 Material and Fabrication Typical graphite and fiberglass types were selected for the fiber reinforcements. Graphite is commonly used in the aerospace industry, but fiberglass tends to be less brittle and is cheaper, hence it was used as well. The mechanical properties of baseline metals and fiber reinforcements used in the laminates are given in Table 1. Designations or “nicknames” are given for all reinforcements, metals and resin systems.

The elastomer matrices used range from intermediate to rigid in durometer hardness. RP6442 and RP 6444, from Vantico, are commonly used in casting. RP6442 is an intermediate stiffness elastomer with good vibration damping, has a high elongation to failure, has adequate mixed viscosities before cure, and is considered tough for it’s durometer. RP6444 is a rigid elastomer with high Izod impact values [6]. The rigid elastomer Version G from RSI [7] is a new system with a high strength and was expected to have very high impact strength and fracture toughness. The epoxy system used was suitable for hand lay-up process and has same general durometer as the rigid elastomers. In Table 2 is shown all the elastomers in ascending order of their hardness.

The fabrication of the flexible composite laminates used a hand lay-up process modified by Peel for two-part elastomer resins [8]. Two batches of impact specimens were fabricated. In batch one, IM-7 graphite cloth was stacked in alternate [0/90] sequence 24 times to get the required

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thickness of the laminate. RP 6442, RP 6444 and Epoxy resin systems were used with the above graphite cloth stacking sequence.

In batch two, 48 layers of fiberglass cloth were stacked in a quasi-isotropic \([(0/90)(45/-45)]_6\) lay-up. The \((0/90)\) direction fibers used unidirectional E-glass cloth. The \((45/-45)\) oriented fibers used 8 layers of the unidirectional E-glass cloth and 16 layers bi-directional E glass cloth in a symmetric manner. All of the elastomer and epoxy resins in Table 2 were used with the fiberglass stacking sequence.

Both batches were allowed to cure at room temperature, and post-cure for several weeks before testing.

It was determined after initial hand lay-ups that the Version G resin system is highly sensitive to humidity and temperature. The high South Texas humidity likely caused it to out-gas during cure and caused considerable porosity. The impact energies and strengths obtained are likely lower than ideal. Future Version G specimens will be fabricated in a humidity and temperature-controlled environment.

2.2 Mechanical Tests and Standards  The Charpy impact test were performed using all of the five fiber reinforced elastomer, two fiber/epoxy, aluminum 6061-T651, cold rolled 1018 steel and highly impact and fracture-resistant hot rolled 4140 steel specimens. The test method adopted was consistent with ASTM Standard E 23. A total of five specimens for each fiber resin combination and metals were tested. The impact strengths were recorded and averaged.

The Compact Tension Test specimens evaluated in this investigation are based on ASTM test method E-399-90. Small Compact Tension fracture toughness tests were fabricated from the E-glass lay-up listed above and epoxy, RP6442, RP6444 as listed in Table 2. The selection of these materials were made on the basis of impact test results, and availability of reinforcements. Processing difficulties precluded testing the Version G polyurethane/ fiberglass fracture toughness specimens. The fracture toughness tests were intended to compare the relative effects of each resin system, rather than obtain the highest fracture toughness values. There were 5 specimens for each resin fiber combination with \(a/W\) ratios ranging from 0.45 to 0.55.

3. DISCUSSION OF EXPERIMENTAL RESULTS

3.1 Impact Resistance  The average Charpy impact energy of each material combination is tabulated in Table 3. Due to differences in resin and fiber types, the cross sectional area of the Charpy specimens varies. The average impact energy of each material combination was normalized based on a thickness of 10 mm, and are shown in Figure 1.

Impact strength of the specimens as shown in Figure 2 was calculated by dividing each impact energy by the cross sectional area under the notch. For the same fiber reinforcement, the elastomer composites showed higher impact strengths than the epoxy composites. The stiffer graphite fiber, even when combined with the very tough RP 6444 urethane, was little different from the graphite/epoxy. Of all the flexible composite combinations, the fiberglass/RP6444 performed the best, approximately 33% better than the fiberglass/epoxy. As noted above, the fiberglass/Version G combination was expected to perform better. Fiberglass fibers are considered to be less brittle than graphite fibers, so perhaps it should not be surprising that the

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fiberglass specimens performed better than their graphite counterparts. When compared with the aluminum and steel baseline specimens, the metal specimens still had better impact strength.

Using specific impact strength (dividing the Charpy Impact strength by density) may help in comparing the flexible composites with their much heavier metal counterparts. Figure 3 shows that all the fiber reinforced elastomer combinations have better specific impact strength than the low toughness baseline metals and the epoxy composites. The three flexible composites with specific impact strengths greater than 0.150 KJ-m/kg are compared with a high toughness hot rolled 4140 steel in figure 4. The hot rolled 4140 steel can be considered as an upper limit or goal to reach with the flexible composites. Note that the fiberglass/ RP6444 combination almost meets that goal.

In Figure 5 is shown a number of the aluminum and flexible composite specimens after the impact tests had been completed. Note that the aluminum specimens fractured in two pieces. All of the CR 1018 and one of the HR 4140 also fractured into two pieces. The reinforced epoxy specimens tended to delaminate and fracture at the notch as well. The more rigid RP 6444 and Version G specimens tended to delaminate but did not fracture completely. Most interestingly, the E-glass/RP 6442 composite showed very little physical damage (minimum delamination) after impact. The Charpy tests were repeated four times each on the five test specimens of fiberglass/RP 6442 with the results depicted in Figure 6. Surface spall marks on the specimen were predominantly behind the notch (point of contact of Charpy test hammer and specimen) and at the ends of the specimen (held by the fixture), but the specimens remained in essentially their original shape. Note that there is about a 35% decrease in impact energy absorbed after the first impact, but consecutive impacts show less than 10% change.

3.2 Fracture Toughness The fracture toughness, $K_{IC}$, for the fiberglass and epoxy, RP6442 and RP6444 combinations are compared with published values for aluminum 6061-T651 and the highly fracture resistant 4140 steel in Figure 7. Below each material combination is its $(a/W)$ ratio where $a$ is the crack length and $W$ is the width of the specimen. The traditional epoxy fiberglass composite compared well with the 6061-T651 aluminum. There was no conclusive correlation between the $a/W$ ratio and fracture toughness across the three material combinations. The fiberglass / RP 6444 fared better than the fiberglass / RP 6442 combination, most likely because of increased strength and reduced elongation before failure. Further work is being performed that will enable a better understanding between the matrix stiffness, elongation to failure, and fiber type on fracture toughness.

5. SUMMARY

The flexible composite materials considered in this study, performed better than their epoxy-matrix baseline, and performed as well as high impact resistant steel, when specific values are compared. For the same fiber type, all elastomer composites had higher impact strength than the epoxy composite. For the same resin type, the fiberglass specimens performed better than the graphite specimens. The rigid elastomer composites performed better than the intermediate stiffness composites, but the intermediate elastomer composites showed less tendency to fracture or delaminate. When density (specific impact energies) is considered, the intermediate and rigid elastomer composites specimens had greater impact resistance than the baseline metal specimens as well as the traditional composite specimens. V-notch Charpy specimen of E-glass/RP6442
showed a unique property of withstanding multiple impacts with minimum structural damage. The fracture toughness test showed that traditional fiber glass/epoxy composite showed fracture toughness close to that of 6061-T651 aluminum. More fracture toughness work is needed if one is to obtain general trends of fiber reinforced elastomer composites.

6. REFERENCES


7. ACKNOWLEDGEMENTS

The authors wish to thank RSI, Graco Supply Company and Vantico (Now Huntsman Advanced Materials) for the donation of the polyurethane resin systems, and the College of Engineering at Texas A & M University – Kingsville for the purchase of the fiberglass.
Table 1. Approximate Physical Properties of Reinforcements and Baseline Metals

<table>
<thead>
<tr>
<th>Material Type (Designation)</th>
<th>Tensile strength, GPa (ksi)</th>
<th>Modulus of Elasticity GPa (Million psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IM 7 Graphite cloth (Gr)</td>
<td>2.93 (425)</td>
<td>276 (40.0)</td>
</tr>
<tr>
<td>Unidirectional E-Glass (FG)</td>
<td>3.45 (500)</td>
<td>72.4 (10.5)</td>
</tr>
<tr>
<td>Bi-directional E-Glass (FG)</td>
<td>3.45 (500)</td>
<td>72.4 (10.5)</td>
</tr>
<tr>
<td>Aluminum 6061-T651 (Al6061)</td>
<td>0.29 (42.1)</td>
<td>70 (10.2)</td>
</tr>
<tr>
<td>Cold rolled 1018 Steel (CR1018)</td>
<td>0.44 (63.8)</td>
<td>205 (29.7)</td>
</tr>
<tr>
<td>Hot rolled 4140 Steel (HR4140)</td>
<td>1.02 (148)</td>
<td>205 (29.7)</td>
</tr>
</tbody>
</table>

Table 2. Mechanical Properties of Resin Systems

<table>
<thead>
<tr>
<th>Resin Type</th>
<th>Hardness</th>
<th>Modulus of Elasticity, GPa (ksi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vantico RP6442 Polyurethane (42)</td>
<td>Shore A 85 ±5</td>
<td>0.007 (1.025)#</td>
</tr>
<tr>
<td>Vantico RP6444 Polyurethane (44)</td>
<td>Shore D 60±5 *</td>
<td>1.38 (200)#</td>
</tr>
<tr>
<td>RSI Version G polyurethane (Vr. G)</td>
<td>90D</td>
<td>20 (2,900)#</td>
</tr>
<tr>
<td>Fiberglast System 2000/2060 Epoxy (Epx)</td>
<td>86-88 D</td>
<td>18 (2,620)</td>
</tr>
</tbody>
</table>

*approximate values, *Shore D hardness of 60 is roughly comparable to Shore A 110 hardness, and a polyester resin hardness.

Table 3. Average Charpy Impact Energy of Specimens

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Charpy Impact Energy , J (lbf)</th>
<th>Density, g/cc (lb/in³)</th>
<th>Thickness, mm (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al 6061</td>
<td>21.02 (15.50)</td>
<td>2.651 (0.0958)</td>
<td>9.78 (0.385)</td>
</tr>
<tr>
<td>CR 1018</td>
<td>28.07 (20.70)</td>
<td>7.695 (0.2780)</td>
<td>10.00 (0.394)</td>
</tr>
<tr>
<td>HR 4140</td>
<td>134.5 (99.19)</td>
<td>7.817 (0.2824)</td>
<td>10.04 (0.395)</td>
</tr>
<tr>
<td>FG/Epx</td>
<td>12.48 (9.200)</td>
<td>1.699 (0.0614)</td>
<td>8.42 (0.331)</td>
</tr>
<tr>
<td>FG/44</td>
<td>28.07 (20.70)</td>
<td>1.505 (0.0549)</td>
<td>10.86 (0.428)</td>
</tr>
<tr>
<td>FG/42</td>
<td>20.20 (14.90)</td>
<td>1.657 (0.0599)</td>
<td>9.88 (0.389)</td>
</tr>
<tr>
<td>FG/Vr. G</td>
<td>12.20 (9.000)</td>
<td>0.893* (0.0323)</td>
<td>10.16 (0.400)</td>
</tr>
<tr>
<td>Gr/Epx</td>
<td>13.22 (9.750)</td>
<td>1.235 (0.0446)</td>
<td>9.91 (0.390)</td>
</tr>
<tr>
<td>Gr/42</td>
<td>22.20 (16.37)</td>
<td>1.154 (0.0417)</td>
<td>12.70 (0.500)</td>
</tr>
<tr>
<td>Gr/44</td>
<td>17.74 (13.08)</td>
<td>1.243 (0.0449)</td>
<td>11.81 (0.465)</td>
</tr>
</tbody>
</table>

* Version G was very porous due to the high humidity, results may be suspect. Specimens were machined to listed thickness.

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Figure 1. Normalized Charpy Impact energy for all composites and baseline metals.

Figure 2. Charpy Impact strength for all composites and baseline metals.
Figure 3. Comparison of flexible composite specific impact strengths with baseline metals.

Figure 4. Comparison of composite specific impact strengths with baseline and high impact strength Hot Rolled 4140 Steel.

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Figure 5. Aluminum, RP 6442 (green), RP6444 (red), and Version G Charpy impact specimens after testing.

Figure 6. Average Charpy impact energy for the repeated impacts of E-glass/RP 6442.
Figure 7. The fracture toughness of the baseline metals and the E-glass reinforced elastomer composites. Al 6061 fracture toughness values were taken from [9] and HR 4140 fracture toughness values were obtained from [10].