DAMAGE TOLERANCE AND NDE OF POLYMERIC COMPOSITES

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INTRODUCTION

As composites are being used as primary load bearing members, the increased understanding of damage tolerance of the material is becoming important. When load is applied to a structure containing a crack or damage, a small area ahead of the crack undergoes very high stress. These stresses cause further damage in this small zone. Initially this damage is at the microlevel: in isotropic materials the microdamage is in the form of slippage and microcracks at grain boundary; in composites the microdamage constitutes of matrix microcracks, matrix-fiber interface cracks and fiber pull out. The size of this damage zone varies depending on the material type and the damage tolerance i.e. energy absorbed by the damage zone is directly proportional to the damage zone.

The damage zone can be mapped by various destructive and nondestructive methods. A destructive method is cutting the specimen and observation by SEM. Nondestructive methods are optical shadowgraph and photoelasticity\(^1\) for transparent and translucent materials and Holographic interferometry for opaque materials.\(^2\) Poe et. al. (3) have measured the attenuation of ultrasound to detect impact damage in thick composites. Also, we have measured changes in the damage zone. This method provides us with the damaged area and also the changes in stiffness in the damage zone. This method provides us with the damaged area and also the changes in stiffness in the damage zone. Since the damage zone is small (\(\sim 4 \text{ mm}\)) we have used focussed ultrasonic transducer. We present here the results of our ultrasonic investigation of short glass-fiber reinforced PVC composites.

SPECIMEN DETAILS

The specimens are short glass fibers in polyvinyl chloride (PVC) epoxy. The fibers are randomly distributed in the composite. Fine rubber particles are also mixed in the epoxy and act as impact modifiers. The details of the specimen size and the constituents are shown in Fig. 1. An equilateral triangle-shaped notch is cut into the specimen by diamond saw. These specimens were loaded in an Instron machine at a cross-head speed of 0.5 mm/min. The specimen is loaded up to the failure, the failure here means the propagation of the crack from the corner of the notch. On subsequent specimens, loading is stopped when a large damage zone has formed ahead of the notch but the crack has not propagated.
1.6 mm 0.8 mm

<table>
<thead>
<tr>
<th>Sample</th>
<th>PVC (phr)</th>
<th>Impact Modifier (phr)</th>
<th>Glass (phr)</th>
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</thead>
<tbody>
<tr>
<td>3</td>
<td>90</td>
<td>Nil</td>
<td>1</td>
</tr>
<tr>
<td>8</td>
<td>80</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>13</td>
<td>74</td>
<td>16</td>
<td>10</td>
</tr>
<tr>
<td>4</td>
<td>80</td>
<td>Nil</td>
<td>20</td>
</tr>
<tr>
<td>14</td>
<td>74</td>
<td>16</td>
<td>20</td>
</tr>
</tbody>
</table>

(phr: parts per hundred)

Fig. 1. Details of the test Specimen.

THEORY

The wavespeed in the samples has been measured by a fully automated technique. If the pulses from a specimen can be separated in time domain, then for a signal given by $f(t)$ the fast Fourier transform of the signal is defined by

$$ F(\omega) = \int_{-\infty}^{\infty} f(t) e^{i\omega t} \, dt $$  \hspace{1cm} (1)

Now if the FFT of the front surface reflection from the specimen is $F(\omega)$ and the FFT of the back surface reflection is given by $S(\omega)$, then it is straightforward to show that

$$ \frac{S(\omega)}{F(\omega)} = \frac{T_{12} T_{21} R_{21}}{R_{12}} \exp(i2kh) $$ \hspace{1cm} (2)

where $T_{ij}$ is the transmission and $R_{ij}$ the reflection coeff. from medium $i$ to medium $j$

$\omega$ = sample thickness

$k = k_1 + ik_2$ is the complex wavenumber

$k_1 = \omega / c$ wavenumber

$k_2$ = attenuation

$\omega$ = signal frequency

$c$ = wave velocity in the plate

It can be observed from Eq. 2 that the wave velocity can be obtained from the slope of the phase vs frequency curve of $S(\omega)/F(\omega)$ from

$$ c = 4\pi h / \text{slope} $$ \hspace{1cm} (3)

and the attenuation coefficient is obtained from $k_2(\omega) = (\ln M) / 2h$ where

$M = |S(\omega)/F(\omega)| R_{12}/(T_{12} T_{21} R_{21})$. The advantages of this measurement are high precision, repeatability, and automation. Interested reader is referred to (4) for further details.
Table 1. Wavespeed in undamaged Glass/PVC Composites

<table>
<thead>
<tr>
<th>Fiber %</th>
<th>Modifier</th>
<th>Wavespeed (mm/µsec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0</td>
<td>2.37</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
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<td>0</td>
<td>2.43</td>
</tr>
<tr>
<td>20</td>
<td>16</td>
<td>2.21</td>
</tr>
</tbody>
</table>

Fig. 2. Effect of impact modifiers on wavespeed in Glass/PVC composites.
RESULTS AND DISCUSSION

We have first tested the undamaged specimen for the effect of impact modifiers and glass fiber content on the wavespeed in the samples. The summary of results obtained is presented in Table I and plotted in Fig. 2. It is observed that the wavespeed is reduced by 7% when the sample has 16% impact modifier and 10% glass content and reduced by 9% when 16% impact modifier and 20% glass. The impact modifiers tend to soften the composite and at higher impact modifier content the two values come close. This phenomenon is also observed in the tensile tests of the samples. The stress-displacement curves for three samples with 10% glass fiber show the decrease in stiffness of the material.

The effect of the impact modifiers and glass fibers on the frequency response of the samples is next studied. It was observed that the amplitude of the received signal is reduced due to an increase in attenuation of the three samples but the frequency response remains essentially the same. The effect of fiber content on two samples with no impact modifiers is studied next. It was observed that the difference in glass content did not change the frequency response as well as the amplitude of the signal for samples with 10% and 20% glass content.

The study of the damage zone ahead of the notch is now performed. First, it may be noted that with low fiber content the samples were translucent and the shadowgraph of the samples could be performed. A light is passed through the sample and the photograph made from the other side of the sample. Due to intense damage, the light is scattered and the image is shown as a shadow on the specimen. A typical shadowgraph is shown in Fig. 3. Next, we have subjected the samples to c-scan. The scan was performed by focused transducers with a focal spot of 250 \( \mu \)m. The

Fig. 3. Shadow-graph of damage ahead of a notch in sample #3 (10% glass no impact modifier).
reflected signal was recorded for the scan. The step size was 250μm and thus we have covered the entire damage zone comprehensively. All the scans were of 0.25 mm x 0.25 mm square area containing the damage zone. A c-scan for sample #3 is shown in Fig. 4. The shadowgraph of the same damage zone was shown earlier in Fig. 3. It is seen that a very detailed picture of the damage zone is obtained. The relative reduction in signal amplitude is substantial and hence the relative damage density can be easily and precisely estimated. Damage zones in the other 4 samples were also obtained but not reported here due to paucity of space.

We have next performed the wavespeed and attenuation measurements in the damage zone. The automated technique requires the frequency range over which the slope calculations are performed. To obtain this range a series of records are obtained of the frequency response of the damage zone as shown in Fig. 5. The locations of measurements are shown in the insert. It is observed that the range of frequency response remains essentially constant even in the highly damaged zone. Now we perform the attenuation measurements over the same locations and the attenuation as a function of frequency are shown in Fig. 6. It is observed that over the test frequency range the attenuation remained constant for lower damage, but as the damages increased the attenuation varied with frequency. The phases as a function of frequency for the locations mentioned early are shown in Fig. 7 and show that the curves remain straight lines. The wavespeed scan (v-scan) of the damage zone is presented in Fig. 8. The scan shows an increase in wavespeed which is erroneous. The reason for this error is that in the c-scan measurement, the thickness of the sample was kept constant. The change in the thickness (necking) was measured and the v-scan data was corrected and the resulting 1-D scan is shown in Fig. 9. Also shown in the figure is the uncorrected scan result. It is observed that the wavespeed is reduced by about 9% in the damage zone which translates to about 19% reduction in stiffness in the highest damage zone.

We have tested the damage zone ahead of an inter laminar crack in a graphite/epoxy laminate. The crack was created by a double cantilever type of loading of the laminate. The c-scan of the area ahead of the crack is presented in Fig. 10. We observe that a very definitive damage zone can be mapped. At this stage it is not clear if this damage zone is the micro damage zone only or if it contains the areas of other damage such as fiber bridging.

Fig. 4. C-Scan of damage ahead of notch in sample #3.
Fig. 5. Frequency response of waves passing through the damage zone.

Fig. 6. Attenuation as a function of frequency of waves passing through the damage zone.
Fig. 7. Phase as a function of frequency of waves passing through the damage zone.

Fig. 8. Velocity scan of a notch in Glass/PVC specimen.

Fig. 9. Velocity scan across the damage zone, corrected for change in thickness.
CONCLUSIONS

The impact modifiers have a profound effect on the stiffness of the composites and also on the size of the damage zone ahead of the notch. Focused transducers have been used to map damage zones ahead of cracks. Velocity scans (v-scan) can be produced as easily as c-scans and can be used to study the stiffness variations in materials.

ACKNOWLEDGMENT

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REFERENCES


Fig. 10. C-Scan of damage ahead of a notch in DCB, Graphite/Epoxy specimen.