STUDY OF NOTCH-SENSITIVITY OF CARBON-GLASS INTRAPLY LAMINATES FOR AEROSPACE APPLICATIONS

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Keywords: Intraply hybrid, carbon fiber, glass fiber, center-notch tension, mode mixity, notch sensitivity, digital image correlation

1 Introduction
Hybrid composites consisting of two or more types of fibers reinforced in a common matrix system [1] have gained interest in recent years. Particular interest in aspects of cost-savings and performance enhancement by a combination of a rigid fiber with a compliant fiber has been observed. In their research starting from early 1990’s, Boeing and NASA extensively studied mechanical performance of hybrid composites [2-9].

A number of hybrid composite types have been conceptualized: interply, intraply, interply-intraply, tow-to-tow hybrid among others. Improvement of large-notch tension performance has been identified as one possible application for effective use of a “tow-level” hybrid. Ilcewicz et al. [2] suggested that an intraply laminate of carbon fiber and glass fiber could provide a residual strength similar to its carbon-only counterpart. In their sequential studies [3, 4], Walker et al. carried out a wide range of investigations on hybrid composites. In these studies, the authors witnessed a great deal of improvement in residual strength, fracture strength, and notch sensitivity among other properties. However, it was also observed that hybrid laminates subject to center-notch tension testing tended to yield matrix splitting and delamination over a large area as compared to carbon-only counterpart in which small amounts of crack-tip damage growth was observed.

In unidirectional composite laminates, mixed-mode deformations arise when either (i) fibers are oriented at an angle with respect to the loading axis under configurationally symmetric loading condition, (ii) fibers are aligned parallel to loading direction but subjected to configurationally asymmetric loading, or (iii) both. A number of studies have been reported regarding these loading conditions, focusing on evaluation of the mode-I and mode-II critical stress intensity factors [10-14]. Interestingly, some of those studies found different, even contradictory, trends of the critical stress intensity factors. For instance, Donaldson [10] reported that the mode-I critical stress intensity factor remained nearly constant whereas the mode-II critical stress intensity factor increased exponentially as the angle between the crack and loading axis decreased from 90° to 10°. To the contrary, Seif and Shahjahan [11] concluded that the mode-I critical stress intensity factor increases continuously with increasing crack inclination angle whereas the mode-II critical stress intensity factor increases up to 45° and then decreases. Such a discrepancy could stem from a fact that evaluation of stress intensity factor in an anisotropic body such as composite laminate is not straightforward. And the tendency becomes even stronger in multi-directional composite laminates.

In the current study, in which tendencies of notch sensitivity and fracture mode in multi-directional center-notch tension tests were investigated, direct measure of the stress intensity factors was not attempted but rather their ratio, mode mixity, was computed in order to quantify dominance of a fracture mode.

2 Specimen Preparation
2.1 Material Selection
T800S carbon fiber (Toray Carbon Fibers (America), Inc., AL, USA) impregnated with 3900-2 resin system has been shown suitable for aerospace structures as exemplified in long use for various aerospace structures. Fiber properties and quality ensure a wide range of applicability in primary structures. For this reason, a composite laminate, T800S/3900-2 manufactured by Toray Composites (America), Inc. (TCA hereafter), WA, USA, was chosen as a primary material.

As for secondary material selection, a number of factors were taken into consideration:

a. Cost saving: cost reduction could be achieved by having one-to-one replacement with a low-cost material.

b. Higher strain at failure relative to primary fiber: carbon fiber in general provides a good strength but, due to its high modulus and low ultimate strain, it intrinsically exhibits...
moderate to low failure energy. In order to
compensate such an intrinsic weakness, the
secondary material must have high ultimate
strain and preferably high toughness.
c. Comparable mechanical/thermal properties:
the secondary material must possess
comparable properties, particularly strength,
in order to avoid substantial mismatch in
those. In addition, thermal mismatch would
induce potential residual stress, by which final
product could be ill-shaped. For this reason,
thermally robust material should be chosen.

After careful selection based on the best balance of
these considerations, S2 Glass® fiber (449-AA-750
S2 glass roving, AGY LLC, SC, USA) was selected
for the secondary material.

2.2 Construction of Hybrid Prepreg

Hybridized prepreg was fabricated in-house at the
TCA Composite Materials Research Laboratory
(CMRL) using T800S and S2 Glass® fiber
impregnated with 3900-2 resin, by means of a
prepreg pilot machine. A thin layer of 3900-2 resin
was filmed on a layer of glossy paper and was rolled
up. The paper with filmed resin was applied by heat
and pressure to a repeating array of T800S (24,000
of filament count) carbon as well as S2 Glass®
fibers. The nominal spread width of a single carbon
fiber tow (primary material) is 5.34 mm, in a “band”
of seven tows for a width of 37.38 mm. The width of
a glassfiber tow (secondary material) is 2.52 mm and
a band is comprised of two rovings, for a total width
of 5.04 mm. Thus each repeating unit is 42.42-mm
wide. The estimated volumetric carbon-to-glass fiber
ratio is 7.4:1. Assuming their thicknesses are
identical, the volume fraction of carbon fiber is 88%
of reinforcing fiber. Final product of prepreging is
shown in Fig. 1. A control material was also
fabricated, using T800S carbon fiber only with the
3900-2 resin, which will be referred as “plain
carbon” throughout the context herein.

2.3 Specimen Preparation

Two different stacking sequences were utilized:
unidirectional (UD) layup and hard layup (HARD).
In the UD layup, fibers in every ply are aligned in
one direction; i.e., [0]_. A quasi-isotropic layup is
one in which plies are stacked so that the resulting
laminate is balanced and symmetric and for which
the constitutive properties are nearly isotropic in the
plane. A simple quasi-isotropic layup can be
modified to a “hard” layup by increasing percentage
of 0° plies such as [45/0/,-45/0/45/0/90]_, in which
the ply orientation parallel to the loading direction
(0°) is 60% of the total plies. The word “hard” refers
to a strong emphasis of 0° plies beyond quasi-
isotropic layup. Intuitively, hard layups possess
improved modulus and tensile strength in the
loading direction. In the present study, the hard
layup used is 60/30/10 (Numbers indicate percentage
of ply orientations, 0°, ±45°, and 90°,
respectively). Note that the hybrid specimen was
made of hybridized plies for ±45° and 90° but made
of plain carbon for 0°.

Thermal curing was applied to aforementioned
prepregs under manufacturer’s recommended
processing. After cured and machined, each
specimen was surface-prepared depending on testing
techniques. Testing techniques in the present study
used strain gage method and digital image
correlation (DIC) to observe the strain distribution.
Details on sample preparation for DIC are given in
the ensuing section.

2.4 Surface Patterning for DIC

Machined specimens were patterned with black and
white paints alternatingly to create random speckles.
The resulting speckles were optimally sized on trial-
and-error basis for obtaining the desired resolution.
In this work, the typical speckle size was such that it
covered 8–12 pixels of the imaging array of the
cameras used. The mean value of the recorded
grayscale ranged between 100 and 120 on a 0–255
scale (8-bit depth).

3 Mechanical Testing

3.1 Evaluation of Elastic Properties

Since the materials used in this study were trial lab-
scale products based on commercially available
analogs, it was imperative that their elastic
properties be directly measured. A general-purpose
load frame coupled with strain gage measurement
was used to evaluate elastic constants including
longitudinal and transverse Young’s moduli (E₁ and
E₂, respectively), shear modulus (G₁₂), Poisson’s
ratio (ν₁₂), tensile strength at failure in fiber
direction (σ₁), and cross-fiber direction (σ₂), shear
strength at failure (S₁₂), and tensile strain at failure
fiber direction (ε₁) and cross-fiber direction (ε₂).
In-plane elastic properties for the laboratory-scale
plain carbon (denoted by T800S), plain glass (S2
Glass®), and carbon/glass hybrid (Hybrid) are listed
in Table 1.

From this evaluation one can readily see that some
property losses due to the hybridized fiber are

inevitable. As for the longitudinal modulus, a 9% reduction was witnessed. The loss was more pronounced in tensile strength, by more than 20%. Aside from the fact that fiberglass possesses lower modulus and strength than carbon fiber, a number of factors play a role in reduction of mechanical properties of hybrid, such as sizing-matrix mismatch, thermal/mechanical mismatch between two fiber types, etc.

3.2 Center-Notch Tension Test

In order to comprehend failure mechanisms of hybrid materials, additional notched tension tests were carried out. These tests were also designed to demonstrate effectiveness of hybridization.

3.2.1 Description

Center-notch tension (CNT) was carried out by TCA CMRL for notch-sensitivity assessment. The specimen dimensions were chosen so that single specimen would be sufficiently large to accommodate multiple repeating units across the width. The dimension specification for the center-notched tension panels is described in Fig. 2. Four different pre-notch lengths were machined at the center with a blunt tip. The oblong elliptical pre-notch tip was further sharpened with a razor blade in order to resemble a naturally induced crack. Photomicroscopic study showed that notch-tip radius is less than 1 \( \mu \)m. The four notch-to-width ratios \((a/W)\) selected for study are 0.06, 0.134, 0.2, and 0.4. The specimens were tension-tested until apparent failure took place. The front surface was speckle-patterned in order to facilitate the DIC technique. Five strain gauges were installed near at the notch tips and at far fields on the back surface to monitor strain distribution. Strain gage 1 was installed collinearly with the notch length, near the notch tip so that the strain response in immediate proximity to the strain concentration could be monitored. Gage 2 was installed in the same way as Gage 1 but with a fixed distance from the specimen edge. This gage serves a purpose that strain history would be recorded independently from the pre-notch length. Gage 3 was located at far field along the specimen centerline in order to monitor overall strain response. Gages 4 and 5 are 0-90 stacked rosette gages, installed along the centerline of the uncracked ligament to monitor longitudinal and transverse strains which may not be affected by the presence of the extremities. Details on strain gage installation are also given in Fig. 2.

Tension testing was carried out at a fixed loading rate (0.05 mm/sec). Test specimens were illuminated with high-intensity light-emitting diode (LED) lamps while a camera was photographing (temporal resolution: 1 fps, spatial resolution: 16 mega-pixels). Each specimen was tested until a clear audible sound was detected. The audible event was later confirmed with visual inspection of photographed images, in which crack initiation was visible.

3.2.2 Strain Histories

Notch sensitivity is defined as a change in fracture strength with increasing crack length [3]. Strains developed in the vicinity of the notch tip are a good measure of notch sensitivity. In addition, strain histories measured elsewhere also give insight of how a medium under external displacement reacts. In the present study, five total strain gages were instrumented over the specimen surface and the strain response was recorded until specimen failure unless premature failure of a strain gage took place. A typical plot of five strain responses measured is shown in Fig. 3.

3.2.3 Evaluation of Mode Mixity

Even in a symmetric loading configuration, a composite laminate could experience non-symmetric (“mixed mode”) deformation due to its anisotropy. In the present study where hard panel configurations were investigated, this is certainly the case. However, unlike the case for unidirectionally oriented panels as reported in Refs. [10-14], the laminates used here are multi-directional and thus existing methodologies for solving a mixed-mode UD case either do not apply or have limitations in their application. For this reason, a complex analysis formulism [16] was employed herein.

It was reported that glass-hybridized carbon fiber laminates containing notches tend to fail in a splitting manner parallel to the loading direction [3]. For purposes of damage-tolerant design, such splitting failures are not desirable because they often lead to low stress at failure. Net section failure is further preferred because it is more predictable to design to, and because propagation of splitting failure is capable of causing significant damage to a laminate without substantial visible exterior damage. In the present study, the tendency of failure mode was quantified by the mode mixity \((\psi)\), defined as

\[
\psi = \tan^{-1}\left( \frac{K_I}{K_{II}} \right)
\]  

(1)
in which $K_I$ and $K_{II}$ represent the mode-I and mode-II stress intensity factors, respectively. Displacement fields measured by DIC methodology were utilized for computing $K_I$ and $K_{II}$. The displacement components $u$ (sliding displacement) and $v$ (opening displacement) in the vicinity of a stationary crack tip of an orthotropic body subjected to mixed mode (mode-I and -II) loading are expressed as [17]:

$$
\begin{align*}
    u &= K_I \frac{2r}{\pi} \text{Re} \left[ \frac{1}{\mu_2 - \mu_1} \left( p_{1} \mu_{5} z_1 - p_{2} \mu_{6} z_2 \right) \right] \\
    &+ K_{II} \frac{2r}{\pi} \text{Re} \left[ \frac{1}{\mu_2 - \mu_1} \left( p_{1} z_1 - p_{2} z_2 \right) \right] \\
    v &= K_I \frac{2r}{\pi} \text{Re} \left[ \frac{1}{\mu_2 - \mu_1} \left( q_{1} \mu_{5} z_1 - q_{2} \mu_{6} z_2 \right) \right] \\
    &+ K_{II} \frac{2r}{\pi} \text{Re} \left[ \frac{1}{\mu_2 - \mu_1} \left( q_{1} z_1 - q_{2} z_2 \right) \right]
\end{align*}
$$

(2)

where quantities $p_j$, $q_j$, and $z_j$ are defined as

$$
\begin{align*}
    p_j &= \mu_j^s s_{11} + s_{12} - \mu_j s_{16} \\
    q_j &= \mu_j^s s_{12} + \frac{s_{22}}{\mu_j} - s_{26} \\
    z_j &= \sqrt{\cos \theta + \mu_j \sin \theta}
\end{align*}
$$

(3)

and $\mu_j (j = 1, 2)$ are the two roots with positive imaginary part of the equation,

$$
\begin{align*}
    s_{11} \mu^4 - 2 s_{16} \mu^3 + (2 s_{12} + s_{66}) \mu^2 - 2 s_{26} \mu + s_{22} &= 0
\end{align*}
$$

(4)

where $s_{ij}$ are the elements of the compliance matrix. Two polar coordinates, $r$ and $\theta$, are defined in Fig. 4.

4 Discussion

4.1 Mixed Mode Fracture

In this section, mode mixity of the hybridized CNT laminates will be discussed. DIC post-test analysis produced two displacement fields: namely, sliding displacement and opening displacement. Each displacement field, especially near the notch tip, contains information on the complex fracture behavior of the multi-directional specimen. In order to extract a fracture parameter from the two displacement fields, Eqs. (2)-(4) were applied, coupled with a nonlinear least-squares method [18]. In-plane elastic properties of HARD specimens used in this analysis are listed in Table 2.

Photographed images of the crack-tip vicinity with displacement fields superposed are shown in Fig. 5. The displacement is highest in the red-colored region and it progressively decreases as the color shifts along the arrows. Note that the color codes of the two displacement fields are not equally scaled. In the sliding displacement (Fig. 5(a)), it is evident that the specimen body along the notch length undergoes minimum (or negative) deformation whereas the upper and lower regions with respect to the notch are subjected to maximum (or positive) deformation. In the opening displacement (Fig. 5(b)), on the other hand, the upper and lower halves are subject to nearly equal but opposite-sign deformations. Fig. 5(a) and 5(b) show a typical symmetry and anti-symmetry, respectively. However, with a close visual inspection, one can readily see that contour lines in both plots are skewed toward a certain direction. This indicates that the CNT samples in this study do not experience mode-I loading (i.e., normal extension). Such a mixed-mode loading can be quantified as below.

Once the displacement fields were obtained, data collection was made radially and circumferentially with respect to the notch tip. In the case where the rectangular displacement array does not match such an annular collection, spline interpolation was forced. Data in immediate proximity to the notch tip was not collected due to concerns regarding possible plasticity, triaxiality, and/or spatiality. The typical number of data points ranges from 500 to 600.

For mode-I quantification, opening displacement ($u$) is generally used since it is the dominant displacement. Conversely, sliding displacement ($v$) is more associated with mode-II-dominant deformation. This tendency has been demonstrated in a number of studies [18-20].

Mode-mixity profiles with respect to test time for four different notch-to-width ratios are shown in Fig. 6(a). The test temporal resolution, as mentioned above, was 1 fps. However, for the sake of clarity, data points only once every 5 sec are shown in the plot. Up to approximately 60 seconds after the start of the test, the displacement level is still not sufficiently high relative to the signal noise, resulting in severe fluctuation of history curves. For this reason, some early data were excluded. All specimens failed or gave an indication of notch initiation at the end of the evaluated data except for the case with $a/W = 0.06$. The mode mixity analysis demonstrates that the notch tip of all four specimens prior to crack initiation is subject to the presence of a negative in-plane shear component. In other words,
mode-II shearing, likely induced by 0° fiber orientation, is active to a certain degree. However, as the magnitude of mode mixity indicates (note that -45° of mode mixity indicates mode-I and mode-II deformations are equally dominant), mode-II deformation is not as dominant as mode-I. Since the boundary condition for the test is extension normal to the notch length, there is no doubt that mode-I deformation is prevalent. For reference, mode-mixity histories for the same carbon fiber impregnated with a similar epoxy system are given in Fig. 6(b), in which the histories are reproduced after Ref. [21]. In the pure mode-I case, the initial noise-ridden response eventually becomes steady and approaches zero prior to crack initiation. On the other hand, the same material with fibers oriented 45° with respect to notch length (and loading axis) is equally subjected to mode-I and -II loading, as indicated by mode mixity oscillating between -50° and -40°.

Mode mixity prior to the crack initiation approaches zero for all cases, except for $a/W = 0.4$. Thus it was expected that crack initiation and propagation would occur under dominant mode-I conditions. However, crack initiation and early propagation, as observed in $a/W = 0.134$, 0.2, and 0.4, was found to be splitting failure, that is, a mixed-mode failure dominated by mode-II. One example is shown in Fig. 7 in which two images were photographed at different load levels. In Fig. 7(a), two initial splits parallel to the loading axis, emanating from the pre-notch tips, are clearly seen, although they are not equally long. After 0.8 mm of further deformation, total failure took place as shown in Fig. 7(b), in which ±45° delamination on the top ply is clearly visible.

This observation is contradictory to what was expected from mode mixity studies shown in Fig. 6(a). It is speculated that, just prior to the crack initiation, the notch tip is under mode-I-dominant mixed mode and this could remain true even immediately after the crack initiation. However, once the crack grows, the energy accumulated at the tip channels along the interface between the matrix and 0° fibers, which account for 60% of the laminate. This speculation might be confirmed with a high temporal-resolution camera employed in a DIC setup.

4.2 Notch Sensitivity of Hard Laminates

The notch sensitivity was quantified by means of strain responses using strain gages installed at a number of different locations on the surface of HARD laminates. Strain histories from Gage 1 through 4 are shown in Fig. 8. Stress is normalized with respect to the highest value obtained from the specimen with $a/W = 0.06$.

As anticipated, Gage 1 produced highest strains for all $a/W$ ratios (Fig. 8(a)), whereas gages in the far field produced lower strains (Fig. 8(c) and 8(d)). Interestingly, at Gage 3, the strain level is lowest for $a/W = 0.4$ and appears to progressively increase as $a/W$ decreases. This may be due to a small cross-sectional area of the uncracked ligament for a large notch-length specimen, onto which strain is highly concentrated, as opposed to the relatively less strain-concentrated cracked ligament where Gage 3 is installed.

Considering its proximity to the notch tip and the strain histories which it produced, Gage 1 may be the best suited for representing the effects of the notch presence. This topic will be revisited later in this section.

Gage 2 shows little notch sensitivity (See Fig. 8(b)) until values of $a/W$ become large enough that the notch is located near the strain gage. Except for $a/W = 0.4$, strain responses for all notch-to-width ratios are nearly identical, indicating strains are not affected by the presence of extremities inasmuch as they are distant from the measuring point. This also supports the speculation above regarding strain concentration on uncracked ligament in case of $a/W = 0.4$, which causes lower strain levels on the cracked ligament.

Gages 4 and 5, installed in far field on the uncracked ligament, produced nearly identical strain responses for all cases, implying that the effects of extremities vanishes in the far field of the uncracked ligament. The effective longitudinal modulus and Poisson’s ratio evaluated from the Gages 4 and 5 are 93.31 GPa and 0.341, respectively, and are comparable to experimental values found for un-notched coupons, as shown in Table 2.

The notch sensitivity can be visualized by plotting the stress level at a given strain against the notch-to-width ratio, $a/W$. From the previous strain gage analysis, it was concluded that strain histories at or near the notch tip are a good measure of notch sensitivity. Plots of stresses at a given strain level as a function of $a/W$ are shown in Fig. 9. Load-carrying capacity, indicated by stress, becomes lower for a given strain level as $a/W$ increases. The same tendency was observed in a number of reports [3, 4]. However, unlike those reports, the present material shows a relatively large drop of stress from $a/W = 0.134$ to 0.2. This particular pattern must be further studied with more specimens. However, as reported
in Ref. [3, 4], failure stress (or stress at a given strain level) of the present material is less sensitive to notch size than plain carbon laminates.

5 Summary

Intraply hybridization utilizing stiff carbon fiber hybridized with high-strain glass fiber was investigated. From basic mechanical tests such as tension and shear loading, the hybridized panel exhibited acceptable property retention. However, a reduction in tensile strength was observed. The study was extended to further investigation of mode mixity and notch sensitivity of center-notch tension for hard layup laminates, in which 60% of 0° plies, 30% of ±45° plies, and 10% of 90° plies are stacked. Analysis from digital image correlation technique suggested that, with 60% of 0° plies laminated in hard layup, center-notched hybrid laminates are likely subject to a mixed-mode loading state even if the applied external loading condition is pure mode-I, normal extension. Prior to crack initiation, laminates experience mode-I-dominant mixed-mode deformation whereas they appear to be under mode-II-dominant mixed-mode deformation immediately after crack initiation. Notch sensitivity was investigated with multiple strain gages. The result showed a good agreement with published reports. In addition, the present hybridized material showed less notch sensitivity than the plain carbon control material.

Table 1. Elastic properties of the UD laminates used in the present study

<table>
<thead>
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<th></th>
<th>T800S</th>
<th>S2 Glass*</th>
<th>Hybrid</th>
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<tr>
<td>$E_1$ (GPa)</td>
<td>146.9</td>
<td>49.5</td>
<td>134.2</td>
</tr>
<tr>
<td>$E_2$ (GPa)</td>
<td>7.6</td>
<td>13.6</td>
<td>8.3</td>
</tr>
<tr>
<td>$G_{12}$ (GPa)</td>
<td>4.0</td>
<td>4.7</td>
<td>4.05</td>
</tr>
<tr>
<td>$v_{12}$</td>
<td>0.332</td>
<td>0.281</td>
<td>0.325</td>
</tr>
<tr>
<td>$\sigma^1_1$ (GPa)</td>
<td>2.86</td>
<td>1.78</td>
<td>2.25</td>
</tr>
<tr>
<td>$\sigma^2_2$ (GPa)</td>
<td>0.046</td>
<td>0.051</td>
<td>0.050</td>
</tr>
<tr>
<td>$S_{12}$ (GPa)</td>
<td>0.104</td>
<td>0.090</td>
<td>0.102</td>
</tr>
<tr>
<td>$\varepsilon^1_1$ (%)</td>
<td>1.78</td>
<td>2.67</td>
<td>1.89</td>
</tr>
<tr>
<td>$\varepsilon^2_2$ (%)</td>
<td>0.65</td>
<td>0.38</td>
<td>0.61</td>
</tr>
</tbody>
</table>

*Computed after Ref. [15]

Table 2. In-plane elastic properties of the HARD laminates used in the present study (Subscript 1 and 2 indicate two material orthonormal axes, with 1 being parallel to loading axis)

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<table>
<thead>
<tr>
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<tr>
<td>$E_1$ (GPa)</td>
<td>94.62</td>
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<tr>
<td>$E_2$ (GPa)</td>
<td>32.92</td>
</tr>
<tr>
<td>$G_{12}$ (GPa)</td>
<td>15.71</td>
</tr>
<tr>
<td>$v_{12}$</td>
<td>0.351</td>
</tr>
</tbody>
</table>

§ Computed using micromechanics

Fig. 1. Photographic image of hybridized prepreg with carbon-to-glass spacing shown.

Fig. 2. Dimensions of CNT specimen and strain gage installation (indicated by shaded squares). All gages are aligned in loading direction except for Gage 5 that is normal to the loading axis. $L = 300$, $l = 200$, $W = 100$, $d_1 = 4$, $d_2 = 20$, $d_3 = 90$, and $t = 4$ (All units in mm).

Fig. 3. Stress-strain curves obtained from a CNT specimen ($a/W = 0.4$). Gage 4 strain response was multiplied by -1 for legibility.
Fig. 4. Illustration of crack-tip neighborhood: polar coordinates \( r \) and \( \theta \) represent radial distance of a generic point from the notch tip and angular distance with respect to \( x \)-axis, respectively.

Fig. 5. DIC post-test analysis: (a) sliding displacement, \( u \), and (b) opening displacement, \( v \).

Fig. 6. Mode mixity (\( \psi \)) of (a) tested CNT specimens and (b) T800/3900-2 single-edge notched specimen [22] as a function of testing time.

Fig. 7. Failure modes observed in a CNT specimen: (a) initial splitting failure and (b) \( \pm45^\circ \) delamination followed by total failure. Two images are approximately 16 seconds apart.
Fig. 8. Strain histories measured with attached strain gages: (a) Gage 1, (b) Gage 2, (c) Gage 3, and (d) Gage 4. Note that stress is normalized with a highest stress.

Fig. 9. Stress histories as a function of the notch-to-width ratio at a given strain level. Note that stress is normalized with a highest stress.

References


