Multiscale Approach to Analysis of Composite Joints Incorporating Nanocomposites

Zeaid Hasan,‡ Aditi Chattopadhyay,¶ and Yingtao Liu†
Arizona State University, Tempe, Arizona 85004

DOI: 10.2514/1.C032652

This study focuses on the benefits of using nanocomposites in aerospace structural components to prevent or delay the occurrence of unique composite failure modes, such as delamination. A three-scale approach was considered to determine the mechanical properties of the nanocomposites. First, the effective carbon nanotube properties were calculated based on the composite cylinder assemblage method. Second, the effective properties of the carbon nanotube embedded in an epoxy matrix were obtained using the Mori–Tanaka method. Finally, the effective properties of the composite lamina were also acquired using the Mori–Tanaka method assuming that the nanocomposite obtained in stage two was the matrix of that lamina surrounding the fibers. These properties were then used to analyze the structural response of a T-section stringer using detailed finite element models. The stringer was analyzed under different loading conditions and assuming different flaw types in the structure. Initial damage was detected via the virtual crack closure technique implemented in the finite element analysis, and it was assumed to be the characteristic variable to compare the different behaviors. It was found that the use of nanocomposites in the manufacturing process of composite stringers would improve the overall performance against unique composite failure modes.

Nomenclature

\[ \begin{align*}
C & = \text{effective stiffness tensor} \\
E & = \text{Young's modulus} \\
G & = \text{shear modulus} \\
G_{11} & = \text{mode 1 strain energy release rate} \\
G_{22} & = \text{mode 2 strain energy release rate} \\
G_{12} & = \text{mode 3 toughness allowable} \\
\nu & = \text{failure index} \\
W & = \text{volume-averaged strain energies} \\
\kappa & = \text{bulk modulus} \\
\lambda & = \text{mode 1 toughness allowable} \\
\nu & = \text{Poisson's ratio} \\
\end{align*} \]

I. Introduction

Composite materials such as graphite epoxy are ideal candidates for many applications, including aerospace and automotive, due to their high strength-to-weight ratios [1]. However, composite laminates are extremely susceptible to crack initiation and propagation along the laminar interfaces. In fact, delamination is one of the most common life-limiting crack growth modes in laminated composites, as their presence may cause severe reductions in the in-plane strength and stiffness, leading to catastrophic structural failure [2]. Delaminations may be introduced during the manufacturing process or in service. Many useful techniques have been successfully employed to improve the delamination resistance in composite structures such as three-dimensional (3-D) weaving [3], stitching [4], braiding [5], Z-pin anchoring [6], and the use of short fibers or microscale particles in the polymer matrix [2]. These methods enhanced the interlaminar properties, but at the cost of in-plane mechanical properties [8].

Extensive research has been performed on the use of carbon nanotubes (CNTs) in various applications due to their unique and superior physical and mechanical properties. In particular, the superior Young’s modulus of CNTs combined with their flexibility and lightness makes them ideal fillers for high-performance nanocomposites. Thus, single-walled carbon nanotubes (SWCNTs) or multiwalled CNTs (MWCNTs) incorporated inside a polymer matrix could significantly improve the properties of polymeric materials. Since the nanocomposite is a macrocontinuum scale, whereas the individual phases can range from the continuum down to the nanometer scale, this creates challenges while attempting to model them analytically or numerically. Therefore, multiscale analysis is the tool necessary to analyze such nanocomposites. Several research articles and book chapters can be found in the literature that discusses multiscale analysis in the context of nanomaterials [9–20].

A significant amount of research has been conducted to predict the properties of nanocomposites that include CNTs embedded in polymer matrix [21–23]. Mechanical properties of nanostructured materials can be determined by a select set of computational methods. One of the most widely used approaches for determining the stress or strain concentration tensors, for use in determining the effective properties of composite materials, is the Mori–Tanaka method [24]. This method was originally developed for calculating the average internal stress in matrix materials with inclusions. This generated a significant amount of work in the analysis of composite materials based on the idea of equivalent inclusions [25]. This method was used to compute the effective properties of the constituents in micromechanics. Other applications, such as crack effects and void growth in viscous metals, were also investigated [26]. The application of the Mori–Tanaka method in micromechanics modeling of nanocomposites has also been reported [27,28]. The composite cylinder assemblage (CCA) method is also a well-known approach that is used to determine the bounds and expressions for the effective elastic moduli of materials reinforced by parallel hollow circular fibers [29,30]. The CCA method uses the direct strain energy equivalency between the response of concentric circular fiber
cylinders embedded in a matrix, representing aligned fibers randomly dispersed in the matrix, and effective material response. In this study, both the composite cylinder assemblage and the Mori–Tanaka methods are used in conjunction to determine the effective elastic properties.

In this study, we focus on improving the delamination capability of composite stringers that are widely used as stiffeners in composite panels for aerospace applications by incorporating CNTs in local hot spots in the structure. Due to their wide applications, a significant amount of research has been reported, both modeling and experimental, in the analysis of composite stiffeners [31–36]. These researchers showed that delamination propagation initiates from the tow filler ends of composite stringers and can lead to complete failure of the joint [37,38]. The existence of such tows reduces the structural integrity of the stringers and may cause delamination of the upper web from the flange, which will lead to failure of the joint [39]. To prevent such failure from occurring, structural metallic reinforcements must be added to prevent delamination, thereby adding weight and complexity to the manufacturing and assembly process, which is usually not a desired solution. In addition, skin-stringer debonding is another failure mode that could lead to catastrophic failure of the structure [40]. Therefore, in this study, we focus on delamination that occurs around the tow filler of T-section stringers and the interface between the stringer and skin, as shown in Fig. 1 [28,41].

To the best of our knowledge, there is a lack of reported research investigating the effect of using nanocomposites at the structural level; particularly their applications to prevent or delay the onset of failure in structural components. This paper quantifies the effect of CNTs on the performance of nanocomposites at the structural level, specifically composite joints, and investigates the ability to improve the associated failure modes. Two loading conditions are taken into account; these are pulloff and combined axial/pulloff loading. The virtual crack closure technique is used to determine the initial damage, which will be considered as the dependent variable in this study to compare the results and determine the percent improvement from using nanocomposites.

The paper is organized as follows. First, a description of the multiscale analysis is presented that provides the effective mechanical properties of the nanocomposites at the different length scales. Second, validation of the numerical analysis that is based on finite element modeling is presented, where results are compared with available experimental data in the literature. Third, the analysis of the T stringer is discussed and the structural responses are evaluated and compared for different CNT weight percentages and different loading conditions. Finally, some concluding remarks are presented based on the research results.

II. Multiscale Modeling of Nanocomposites

Modeling of nanomaterials involves a systematic procedure that aids in transitioning from one scale to another; the work presented here is based on a multiscale approach that allows for the transition from a SWCNT or MWCNT to a composite lamina. The CCA method is used to determine the effective properties of the CNT. Multilayered composite cylinder assemblage could be taken into account in this method to simulate MWCNTs with interfacial layers, as shown in Fig. 2. To acquire the effective elastic properties of aligned fiber composites using this method, the volume-averaged strain energies of both the composite cylinder assemblage \( W \) and the effective homogeneous cylinder \( W_{\text{eff}} \) are obtained from the volume average of the strain energy, which are set as equal, providing a set of boundary value problems to be solved. The solution to these boundary value problems enables the calculation of the effective in-plane bulk modulus, axial Young’s modulus, axial stiffness component, axial shear modulus, and the in-plane shear modulus.

The effective CNT properties are used as inputs into the Mori–Tanaka method. The effective stiffness tensor is obtained by embedding a solid cylinder having the effective CNT properties in the unknown effective composite and obtained as follows [42]:

\[
C = \left( \frac{\nu_m C_m L_m}{\nu_m} + \sum_{l=1}^{p} \nu_l \frac{C_l L_l}{\nu_l} \right) \left( \nu_m I + \sum_{l=1}^{p} \nu_l \frac{L_l}{\nu_l} \right)^{-1}
\]

(1)

\[
\tilde{L}_l = \left[ I + S \frac{L_m}{I} \left( L_m - L_m \right) \right]^{-1}
\]

(2)

where \( C \) represents the effective stiffness tensor, \( L \) is the concentration tensor, \( \nu \) is the volume fraction, \( S \) is the Eshelby tensor, and \( I \) is the identity tensor. The concentration tensor \( L \) relates the average strain in the effective cylinder to the average strain of the matrix and is perturbed by some amount to account for interactions between inclusions. \( S \) is obtained for cylindrical inclusions embedded in the matrix. Once the effective properties of the nanocomposite are obtained, they are used as the new matrix material.
to formulate the nanocomposite lamina. Both unidirectional and woven composites can be considered using this approach. To analytically model such a composite, the stiffness matrix for an infinitesimal slice must be obtained. This is done by summing the stiffness matrices of the constituents as follows [43]:

\[
K_{ij} = \sum_{I} v_I(x, y) \tilde{Q}_{ij}^{I}(x, y), \quad i, j = 1-6 \tag{3}
\]

where \(\tilde{Q}_{ij}^{I}\) is the transformed stiffness matrix (to the global frame) of the \(I^{th}\) element. Superscript \(I\) refers to either fill strand \(F\), warp strand \(W\) (when considering woven composites), or matrix \(M\). To calculate the global stiffness matrix \(K_{global}(x, y)\), the local matrix \(K_{ij}(x, y)\) is evaluated for a small slice over the longitudinal or lateral directions of the infinitesimal splice in an averaged manner as follows:

\[
K(y) = \frac{1}{a} \int_{0}^{a} K(x) \, dx \tag{4}
\]

\[
K_{global} = \frac{1}{a} \int_{0}^{a} K(y) \, dy \tag{5}
\]

where \(a\) represents the fiber width. Equations (4) and (5) are then used to back out the effective properties of the nanocomposite lamina. A flowchart of the multiscale methodology used in this study to obtain the effective properties at different length scales is shown in Fig. 3.

### III. Stringer Analysis with Embedded Carbon Nanotubes

Delamination is considered to be one of the main forms of failure in laminated composite structures, especially when there is no reinforcement in the thickness direction. Residual thermal stresses, matrix-curing shrinkage, and manufacturing defects are all factors that determine how damage will initiate and grow in a composite structure. The high stress gradients that occur in specific hot spots in the structure, such as tow fillers and skin/stringer bondlines, promote damage initiation and may cause a significant loss of structural integrity. The use of nanocomposites in such critical locations may alleviate these problems and help improve the overall structural performance.

In this section, the finite element models and the method used to analyze the structure are discussed. To validate both the modeling techniques and the method of analysis, the results are first compared with available experimental data [44]. The computer software CATIA is used to create the CAD geometry, and the commercial software Abaqus is used for the finite element analysis. Particular attention is paid to issues such as boundary conditions (BCs), mesh refinement, and contact behaviors. Selecting the proper fastener modeling technique is also a key issue. Two models are constructed: one with simply supported boundary conditions and another clamped at the ends with fasteners. Figure 4 shows the 3-D finite element models developed, as well as the actual specimen that was tested. The modeling techniques that are considered in the analysis use solid continuum elements (C3-D8I) for the composite parts as well as the
metallic fixtures and fasteners. An Abaqus connector modeling routine (star fastener) is used to represent the fasteners in the model. These connectors use multipoint constraints to constrain nodes on each surface in a fastener stackup with respect to a central reference point that lies on the fastener axis centerline. Separate “axial” and “shear” connector definitions are used at each fastener location to provide both in-plane and through-thickness constraints to the surfaces in the fastener stackup. The connectors are shown in Fig. 5, where $K$ represents the fastener stiffness in the given direction.

The virtual crack closure technique is used in this analysis to detect initial damage. When the stress intensity reaches the critical strain energy release rate, the central pair of nodes is released. A damage index is defined as shown in Eq. (6):

$$\lambda = \frac{G_{equiv}}{G_{equiv_c}} = \left( \frac{G_I}{G_{IC}} \right)^m + \left( \frac{G_{II}}{G_{IC}} \right)^n + \left( \frac{G_{III}}{G_{IC}} \right)^o$$

where $G_I, G_{II},$ and $G_{III}$ are the strain energy release rates for modes I, II, and III’s fractures, respectively; $G_{IC}, G_{IIc},$ and $G_{IIIc}$ are the toughness allowables for modes I, II, and III’s fractures, respectively, and superscripts $m, n,$ and $o$ are equal to 1 in this study. When this damage index reaches a unit value, it implies that a node has been released and initial damage has been detected. To use the virtual crack closure technique, an initial flaw must be embedded in the model. Usually, the flaw is inserted in locations where delamination is most likely to occur. To correlate to the available experimental data, a $0.5 \times 0.5$ in. flaw is used and inserted between the tow filler and the web midway along the stringer span, as shown in Fig. 6, since delamination was observed to initiate from that location [44]. It is noteworthy to mention that preload is applied to all the fasteners in the model. It should also be noted that resin toughness values are used in the analysis to predict the initial damage [45]. Figure 7 shows the value for mode I energy release rate around the embedded flaw. It is

Fig. 5 Axial and shear fastener representations used in the models.

Fig. 6 Embedded flaw used in the model.

Fig. 7 Mode I energy release rate around the embedded flaw used in the model.
noted that the failure is usually dominated by this failure mode, and the contributions of modes II and III are not significant. Figures 8 and 9 show the correlation between the finite element models (FEMs) and the experimental data for both the simply supported and clamped models, respectively. Note that the correlation was done to the initial damage load and not the final failure load. A total of 20 specimens were tested (8 for the simply supported boundary condition case and 12 for the clamped boundary condition case) with dimensions 2 in. wide and 14 in. long [44]. It can be observed that the predicted initial damage from the FEMs is within 10% from the results obtained from the test. Note that the initial damage predicted by the models is lower, indicating that the models provide a more conservative estimate. This correlation provided us confidence in both the analysis method and modeling techniques, and therefore is used for the remaining analysis.

After having correlated to available experimental data, the next step is to create a comparatively larger detailed model with the same modeling methods that incorporate the use of a fine grid mesh (especially in the area of interest) to be able to accurately capture the joint behavior under the critical loading conditions. To better understand the structural performance, several different damage scenarios and loading conditions are considered. Table 1 summarizes the different flaws and loading condition combinations used in this study. A schematic diagram of the different flaw types is shown in Fig. 10. Comparison between using pure adhesive and adhesive with 1, 3, and 5 wt % CNT is studied. It was found that the fracture toughness values increase for adhesives that incorporate CNTs in their mixture [46–48], which provides confidence in considering the incorporation of CNTs as an alternative to overcome some of the structural weaknesses in composite joints. The fracture toughness values used in the analysis for the nanocomposite are obtained from [46–48].

IV. Results and Discussions

This section presents the results of the analysis. Initially, the effective mechanical properties are shown, followed by the results obtained from the failure analysis.

A. Mechanical Properties of Nanocomposites

The literature is rich with research on predicting the properties of nanocomposites that include CNTs embedded in polymer matrix [42]. However, the study of composites consisting of CNTs, fibers, and a matrix material has not been given the same effort. The goal of the results presented here is to provide insight on the effect of adding CNTs on the mechanical properties at the structural level. The fibers are assumed to be made of AS4 carbon. Table 2 shows the elastic and geometric properties of the CNT used in the analysis. Figure 11 presents the variation of the nanocomposite unidirectional lamina mechanical properties as a function of CNT volume fraction. The results show an increase in the axial and lateral elastic modules as the CNT volume fraction increases. The same behavior can be seen in the shear modules. Poisson’s ratio on the other hand decreases as the volume fraction increases.

In Fig. 12, the variation of the nanocomposite mechanical properties as a function of the CNT aspect ratio are shown. The results show that all the mechanical properties are affected by the change in aspect ratio. The axial elastic modulus increases substantially as the aspect ratio increases.

<table>
<thead>
<tr>
<th>Flaw type</th>
<th>Loading condition</th>
<th>Tow material</th>
<th>Case</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flaw 1</td>
<td>Pulloff</td>
<td>Fabric</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Adhesive</td>
<td>2</td>
</tr>
<tr>
<td>Flaw 2</td>
<td>Pulloff</td>
<td>Fabric</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Adhesive</td>
<td>4</td>
</tr>
<tr>
<td>Flaw 3</td>
<td>Pulloff</td>
<td>Fabric</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Adhesive</td>
<td>6</td>
</tr>
<tr>
<td>Flaw 1</td>
<td>Pulloff + axial</td>
<td>Fabric</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Adhesive</td>
<td>8</td>
</tr>
<tr>
<td>Flaw 2</td>
<td>Pulloff</td>
<td>Fabric</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Adhesive</td>
<td>10</td>
</tr>
<tr>
<td>Flaw 3</td>
<td>Pulloff + axial</td>
<td>Fabric</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Adhesive</td>
<td>12</td>
</tr>
</tbody>
</table>
aspect ratio increases up to 100. The lateral modulus, however, exhibits a smaller increase with aspect ratio. The effect of aspect ratio is not large on the shear modules, where it decreases up to an aspect ratio of 50 and then remains constant. The Poisson’s ratio $\nu_{12}$ decreases slightly as the aspect ratio increases.

### Table 2 Mechanical and geometrical properties of CNTs

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young’s modulus</td>
<td>159.5 Msi</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.14</td>
</tr>
<tr>
<td>Wall thickness</td>
<td>$13.26 \times 10^{-9}$ in.</td>
</tr>
</tbody>
</table>

B. Failure Analysis of Composite Stringers Incorporating Carbon Nanotubes

A schematic diagram of the model is shown in Fig. 13. Initially, a baseline model is constructed that uses typical adhesive properties without the use of any CNTs. In addition to the different flaw types, two designs are considered: one that uses adhesive to fill the tow region and another that uses fabric. The reason for investigating both designs lies in the use of both materials as fillers in the manufacturing of T stringers in industry [49]. Moreover, the effect of using CNTs embedded in the matrix of the composite laminates of the skin and stringer is also studied. Note that all the effective properties for the different nanocomposites are obtained from the multiscale analysis mentioned earlier in this paper. The loading conditions considered are pulloff and combined axial/pulloff.

It is important to note that the value of the failure load depends on the location where the flaw is embedded in the structure. Figure 14
shows the running load of the stringer along its spanwise direction due to applied pulloff load. As observed, the peak running load exists midway along the stringer; hence, both flaw types 1 and 2 are embedded in the T stringer in that location, whereas flaw 3 is inserted at the stringer termination between the stringer base and skin interface, where the abrupt change in geometry occurs and delamination is most likely to manifest.

Figures 15–17 show the initial failure load by applying a pure pulloff load for the three different flaw types. A total of four different configurations depicting the use of CNT in the structure are considered and summarized in Table 3. Figure 15 represents the pulloff failure load of the structure that incorporates a type 1 flaw. The general trend that is observed for both types of tow materials (fabric and adhesive) is the increase in failure load with increased CNT weight fraction due to the added through-thickness capability. It is also noticeable from the figure that, for all values of CNT weight fractions, the failure load for the adhesive tow is considerably larger.
than that for the fabric tow. When examining the adhesive tow results only, the failure load is higher for the case when both the adhesive and composite contain CNTs, unlike the fabric tow design.

The type 1 flaw is noted to be mode I dominant, which relies on the angle opening of the radius where the pulloff load tends to open that radius, creating high-energy release rates. Therefore, the use of CNTs is shown to provide additional through-thickness capability, preventing or delaying such an event from occurring. Figure 16 represents the pulloff failure load of the structure that incorporates a type 2 flaw. In this case, the failure load increases with CNT weight percentage for both types of tow materials. It can be noted that the failure load is much higher for this flaw type compared to the previous case, which means that the structure under pulloff loading has more capability of sustaining additional load with the inclusion of this flaw type, which is an important observation when designing the structure from the damage tolerance perspective. The type 2 flaw is also found to be mode I dominant under pulloff loading, and the use of CNTs is shown to give additional through thickness capability.

Figure 17 represents the pulloff failure load of the structure that incorporates a type 3 flaw. As in the previous two cases, the failure load increases with an increase in CNT weight percentage; however, for the fabric tow, the failure load increases up to 5% CNT by weight, where it drops slightly. When examining the adhesive tow results, the failure load is higher for the case when both the adhesive and composite contain CNTs, but this statement does not hold regarding

### Table 3  Different configurations considered in the analysis

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Use of CNT</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Adhesive tow (CNT was used in the adhesive layer surrounding the tow filler and the tow filler itself. CNT was also used in the adhesive layer that exists between the skin and stringer interface.)</td>
</tr>
<tr>
<td>2</td>
<td>Adhesive tow (CNT was used in the adhesive layer surrounding the tow filler and the tow filler itself. CNT was also used in the adhesive layer that exists between the skin and stringer interface. In addition, CNT was used in the composite laminates of the stringer and skin.)</td>
</tr>
<tr>
<td>3</td>
<td>Fabric tow (CNT was used in the adhesive layer surrounding the tow filler and the tow filler itself. CNT was also used in the adhesive layer that exists between the skin and stringer interface.)</td>
</tr>
<tr>
<td>4</td>
<td>Fabric tow (CNT was used in the adhesive layer surrounding the tow filler and the tow filler itself. CNT was also used in the adhesive layer that exists between the skin and stringer interface. In addition, CNT was used in the composite laminates of the stringer and skin.)</td>
</tr>
</tbody>
</table>
the fabric tow. The type 3 flaw is found to have a mode mix of both I and II under pulloff loading, and the use of CNTs is shown to give additional through-thickness capability in this case as well.

From the results presented, it can be concluded that, for an aerospace structure (such as stringers) subjected to pulloff loading, the use of CNTs in specific hot spot locations, such as the tow-stringer web interface or the bondline location between the skin and stringer, can prevent or delay the onset of delamination. The results for the combined loading are shown in the Appendix.

V. Conclusions

The present study focused on the benefits of using nanocomposites in structural level components that are typically used in aerospace applications. An example of such a structure was a typical T-stringer. A multiscale approach was used based on micromechanics to determine the effective properties of the nanocomposite at different length scales. These effective properties were used in the finite element modeling. A detailed model of the T-stringer bonded to a skin was constructed in order to assess the use of nanocomposites in structural-level components and to improve some of the weak spots in such structures. The virtual crack closure technique was adopted in order to determine the initial damage of the structure, defined as the initial load drop in the load displacement curve. Different configuration, flaw types, and loading conditions were considered in this study. It was shown that using CNTs in the manufacturing process of such stringers may improve the overall performance up to 35% by comparing the initial failure loads. It was also concluded that, when considering a structure that undergoes pulloff or combined axial/pulloff loading, the delamination that typically occurs around the tow filler and skin-stringer bondlines can be delayed by incorporating CNTs in those hot spot locations, thus providing a much more robust structural design.

Appendix: Combined Loading Results

The combined loading effect is addressed next. Both the axial and pulloff loads are applied simultaneously; hence, the cause of initial damage is not distinguishable. Figure A1 shows a schematic diagram of the loading condition. Figures A2–A4 show results for the same weight fractions, flaw types, and tow materials shown previously for the pure pulloff case. In these figures, only the axial load at which initial failure occurred is reported. Figure A2 represents results from considering a type 1 flaw. It can be observed that the axial failure load increases with an increase in the CNT weight fraction. Also, the axial failure load for the adhesive tow is always larger than that of the fabric tow for all cases. There is, however, no substantial gain in failure load if the CNTs are used in the adhesive only or in both the adhesive and composite; therefore, incorporating the CNTs in the adhesive only would reduce costs and manufacturing complexity. Figure A3 represents the axial failure load of the structure that incorporates a type 2 flaw under a combined axial/pulloff load. The general trend to be observed for both types of tow material is that, as the CNT weight fraction increases, the failure load increases. It is also clear from the figure that, for all values of CNT weight fractions, the failure load for the adhesive tow is larger than that for the fabric tow. The failure load for both cases with CNT is larger for the adhesive and composite configuration, except when the CNT weight fraction is 5%. Figure A4 represents the axial failure load of the structure that incorporates a type 3 flaw under axial/pulloff loading. For both types of tow materials, it can be observed that the failure load increases with CNT weight fraction. It is also obvious from the figure that, for all values of CNT weight fractions, the axial failure load for the fabric tow is larger.
than that for the adhesive tow. In addition, the failure load for cases of CNT being present in adhesive only is larger than that when CNT is used in both adhesive and composite.

Figures A5–A7 show results for the same weight fractions, flaw types, and tow design, as well as the loading condition (combined axial/pulloff); however, the pulloff load at which initial damage occurred is reported this time. Figure A5 shows the initial pulloff failure load from a combined axial/pulloff type loading and considering a type 1 flaw. The dominating trend is that the failure load increases as the CNT weight fraction increases, and the failure load is higher for the adhesive tow for all weight fractions less than 5% where the loads are higher for the fabric tow. In addition, there is no substantial gain in pulloff failure load if the CNTs are in the adhesive only or both the adhesive and composite. Therefore, having them in the adhesive only would reduce costs and manufacturing complexity while maintaining an almost similar failure load. Figure A6 shows the initial pulloff failure loads for the same specimens; however, the flaws are of type 2. It can be seen from the figure that the failure load is always higher for the adhesive tow, for all cases. A dominant trend of failure load increase as CNT weight fraction increases can be observed as well, whereas the gap between the failure load for both the availability of CNT in the adhesive only and in both the adhesive and composite is reduced while the CNT volume fraction increases. Figure A7, on the other hand, shows the results for the type 3 flaw. The fabric tow is capable of rendering a higher initial pulloff failure load than the adhesive one for all CNT weight fractions. It should be noted from the previous results that the axial failure load is much higher than the failure that occurs due to pulloff; hence, it can be concluded that such stringer designs are more tolerable to axial loading than pulloff. Moreover, combined loading consideration is an important part in the analysis and design process of such structures, since as observed from the results, the failure loads could be under- or overestimated, providing a structure that might be less conservative or overly designed, respectively.

Acknowledgments

The authors are grateful for the support of the Naval Air Systems Command grant sponsored by Integrated Systems Solutions; grant number W911NF-12-1-0353. Nam Phan was the program manager.

References


[40] Sai Prasanna Kumar, J., Raghava, G., and Joseph Stanley, A., “Fracture Toughness of Multi Walled Carbon Nano Tubes Modified Polymer

