ANALYSIS OF CARBON NANOTUBE INTEGRATED COMPOSITE STRUCTURES USING MULTISCALE APPROACH

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1. Abstract

This paper focuses on the benefits of using nanocomposites in structural level components that are typically used in aerospace applications. Initially a multiscale approach is used to determine the mechanical properties of such nanocomposites. A three-stage approach is considered. First, effective carbon nanotube (CNT) properties are obtained based on the composite cylinder method. Second, the effective properties of the effective CNT embedded in an epoxy matrix forming a nanocomposite are obtained using the Mori-Tanaka method. Finally, the effective properties of a composite lamina are obtained assuming that the matrix material properties of the lamina are those calculated for the nanocomposite in Step 2. Then these effective properties are used to analyze the structural response of a T and hat stringer using detailed finite element models. The stringer is analyzed under pull-off loading. Initial damage is detected via the virtual crack closure technique implemented in the finite element analysis. It is shown that the use of nanocomposites in the manufacturing process of such composite stringers will improve the overall performance against unique composite failure modes. Different configurations are analyzed to provide insight on their structural performance.

2. Introduction

In recent years, modeling of composites containing CNTs has received wide attention [1-4]. In the analysis of nanocomposite integrated structures it is important to bridge the various length scales ranging from the continuum scale down to the nanometer scale, and therefore approach discrete limits. This is a challenging task and needs to be addressed in order to understand the impact of the nano material at the structural level. Throughout the literature there are models which address material behavior at the various length scales. Several review articles on the analysis and use of nanocomposites are available [5-7].

There appears to be sufficient evidence indicating that CNTs should be a very promising candidate as the ideal reinforcing material for advanced composites with high strength and low density; which are of interest to aerospace, automobile, and many other applications. It is also well known that composite structures in the form of laminates are extremely susceptible to crack initiation and propagation along the laminar interfaces in various failure modes. Delamination is considered to be 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 [8]. Delaminations may be introduced during manufacturing or in service. Many useful techniques have been successfully employed to improve the delamination resistance in composite structures such as three-dimensional (3D)-weaving [9], stitching [10], braiding [11], Z-pin anchoring [12], and the use of short fibers or microscale particles in the polymer matrix [13]. These methods enhanced the interlaminar properties, but at the cost of in-plane mechanical properties [14].

In this study the authors focus on improving the delamination capability of composite stringers that are widely used as stiffeners in composite panels for aerospace applications by incorporating the use of carbon nanotubes in local hot spots in the structure. Due to their widespread applications a significant amount of research has been reported, both modeling and experimental, in the analysis of composite stiffeners [15-20]. This research shows that delamination propagation initiates from the tow filler-ends of composite stringers and can cause complete failure of the joint [21 - 22]. The existence of such tows will reduce the structural integrity of the stringers and may cause delamination of the upper web from the flange, which may lead to failure of the joint [23]. In order to prevent such failure from occurring structural metallic reinforcement 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 [24]. Therefore, in this study, the authors focus on delamination that occurs around the tow filler and along the skin-stringer interface for both a T and hat stringer.

3. Multiscale Analysis

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 material is the Mori-Tanaka method, which was originally developed in 1973 by Mori and Tanaka [25]. The composite cylinder method is another method attempted to determine the bounds and expressions for the effective elastic moduli of materials reinforced by parallel hollow circular fibers [26]. The model utilizes 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.

The objective of the current study is to analyze the effect of the CNTs, embedded in polymer matrix, at the structural level. Therefore, it is important to use a multiscale modeling approach, capable of bridging the various length scales. The micromechanical approaches relying on volume averaging are used to determine the effective properties; the composite cylinder method is used in conjunction with the Mori-Tanaka approach. The effective mechanical properties are ultimately used in the finite element modeling. Figure 1 shows a general outline of the approach presented in this paper. The reader is referred to the following references [25-28] for more detail information on acquiring the properties of a nanocomposite at different length scales using micromechanics.

4. Modeling

In order to validate both the modeling techniques and the method of analysis, the results were first compared with available experimental data [29]. The computer software CATIA was used to create the CAD geometry, and the commercial software Abaqus was used for the analysis. Particular attention is paid to issues such as boundary conditions, model size, mesh refinement, contact behavior, etc. 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 2 shows the 3D finite element models developed, as well as the actual specimen that was tested.
The modeling techniques that are considered in the analysis utilize solid continuum elements (C3D8I) for the composite parts as well as the metallic fixtures and fasteners. An Abaqus connector modeling routine (star-fastener) is used to represent fasteners in the model. These connectors use multi-point constraints (MPCs) 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 thru-thickness constraints to the surfaces in the fastener stackup.

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 in Abaqus that is given as a power law as shown in Eq. (1)

\[
\frac{G_{eqin}}{G_{eqinC}} = \left( \frac{G_I}{G_{IC}} \right)^m + \left( \frac{G_{II}}{G_{IIIC}} \right)^n + \left( \frac{G_{III}}{G_{IIIIC}} \right)^o
\]

where \(G_I, G_{II}, G_{III}\) are the strain energy release rates for mode I, II, III fracture respectively, and \(G_{IC}, G_{IIIC}, G_{IIIIC}\) are the toughness allowable for mode I, II, III fracture respectively. When this damage index reaches 1 it implies that a node has been released and damage has initiated. In order to use the virtual crack closure technique in Abaqus an initial flaw must be embedded in the model. Usually the flaw is inserted in locations where delamination is most likely to occur. Since different flaws behave differently, three dissimilar flaw types are considered and studied in this paper. In order to correlate to the available experimental data, a 0.5 inch x 0.5 inch flaw is used and inserted between the tow filler and the web midway along the stringer span, since delamination was observed to initiate from that location [29]. It is noteworthy to mention that preload is applied to all the fasteners common to the skin and stringer in the models. It should also be noted that resin toughness values were used in the analysis to predict the initial damage (onset of damage) [30].

Figure 3 shows the correlation between the FEM and the experimental data for the simply supported model. It should be noted that two specimens were tested for the simply supported case as shown in the figure. Ten percent error bars are depicted on that chart, and it can be observed that the results from the FE models fall within those tolerances. This correlation is considered to be excellent; therefore, confidence is gained with both the analysis method and modeling techniques, and will be used for the remaining analysis.

5. Composite Stringer 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 fine grid mesh (especially in the area of interest) to be able to accurately capture the joint behavior under the critical loading conditions. In order to better understand the structural performance several different damage scenarios are considered. Table 1 summarizes the different flaws considered in this study. A schematic diagram of the different flaw types is shown in Figures 4 and 5 for the T and hat stringers, respectively. A comparison between using pure adhesive and adhesive with 1, 3, and 5 weight percent CNT is considered. Mode I, II, and III fracture toughness for adhesive is used in the analysis. It was found that the fracture toughness values increase significantly for adhesive that incorporates CNTs in their mixture [31], which motivated the authors to consider that as an alternative to overcome some of the structural weaknesses in composite joints.

<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>Flaw 2</td>
<td>Pulloff</td>
<td>Adhesive</td>
<td>2</td>
</tr>
<tr>
<td>Flaw 3</td>
<td>Pulloff</td>
<td>Fabric</td>
<td>3</td>
</tr>
<tr>
<td>Flaw 4</td>
<td>Pulloff</td>
<td>Adhesive</td>
<td>4</td>
</tr>
<tr>
<td>Flaw 5</td>
<td>Pulloff</td>
<td>Fabric</td>
<td>5</td>
</tr>
<tr>
<td>Flaw 6</td>
<td>Pulloff</td>
<td>Adhesive</td>
<td>6</td>
</tr>
</tbody>
</table>
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 that lies behind the use of both materials as fillers in the manufacturing of such stringers in the industry [32]. Moreover, the effect of using matrices that include CNTs in 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 analysis mentioned in section 3. The 3D finite element mesh of the T and hat stringer models is shown in Figures 6 and 7, respectively.

It is important to note that the value of the failure load depends on the location where the flaw is embedded in the structure. Both flaw types 1 and 2 are embedded in the stringer midway along the stringer span-wise direction where the peak pull-off loading will occur; whereas flaw 3 is inserted at the stringer termination between the stringer base and skin interface where the abrupt change is geometry occurs and delamination is most likely to take place.

6. Numerical Results

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 Nanocomposite Lamina

The literature is rich with research on predicting the properties of nanocomposites that include CNTs embedded in polymer matrix [33-35]. 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, specifically the longitudinal and transverse modulus for the third length scale in our study, which represents the nano-unidirectional composite lamina.

The effect of varying the CNT volume fraction and CNT aspect ratio on the mechanical properties are presented. Figures 8-11 show the results for a nanocomposite unidirectional lamina that have multiwall CNTs (3 walls) embedded in the matrix. The fiber is made of AS4 carbon. The mechanical properties are inspected as the CNT volume fraction is changed. From Figures 8 and 9, it can be observed that as the CNT volume fraction increases the axial Young’s modulus increases, while the lateral one is reduced slightly. In Figures 10 and 11 the variation of the nanocomposite mechanical properties as a function of CNT aspect ratio are shown. The results show that the mechanical properties were affected by the change in aspect ratio. The axial elastic modulus increases substantially as the aspect ratio increases up until 100. The lateral modulus, however, exhibits a smaller increase with aspect ratio.
b. Failure Analysis of Composite Stringers Incorporating Carbon Nanotubes

The results from the analysis of the T stringer are presented next. Figures 12-14 show the initial failure load by applying a pure pull-off load for the three different flaw types. Note that four different configurations regarding the use of CNT in the structure are considered and summarized in Table 2. Figure 12 represents the pull-off failure load of the structure that incorporates a flaw of type 1. The general trend that is observed for both types of tow materials (fabric and adhesive) is the increase in failure load with increase 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.

Table 2. Different configurations considered in the analysis

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Use of CNT</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>Adhesive Tow (CNT was used in the adhesive layer surrounding the tow filler and the tow filler itself as well as the interface between the skin and stringer)</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 as well as the interface between the skin and stringer in addition to the composite laminates used to construct the stringer)</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 as well as the interface between the skin and stringer)</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 as well as the interface between the skin and stringer in addition to the composite laminates used to construct the stringer)</td>
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</table>

Type 1 flaw is noted to be mode I dominant; this relies on the angle opening around the tow filler where the pull-off load tends to open that radius, creating high energy release rates. Therefore the use of CNT is shown to give additional through thickness capability preventing or delaying such event from occurring.

Figure 13 represents the pull-off failure load of the structure that incorporates a type 2 flaw. In this case the failure load increased with increase in CNT weight percentage for both types of tow materials. It can also be observed that the failure load for the adhesive tow is larger than that for the fabric tow. By considering only the adhesive tow results the failure load is higher for the case when both the adhesive and composite contain CNTs. A similar observation can be made in the case of the fabric tow. Type 2 flaw is also found to be mode I dominant under pull-off loading, and the use of CNT is shown to provide additional through thickness capability. Note that the failure load is much higher than that reported for type 1 flaw which indicates that the risk of failure is larger if the structure experiences pull-off loading with type 1 flaw damage included.

Figure 14 represents the pull-off failure load of the structure that incorporates a type 3 flaw. As in the previous two cases the failure load increases with increase in CNT weight percentage; however, for the fabric tow the failure load increases up until 5% CNT by weight, where it then 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 for the fabric tow. Type 3 flaw is found to have a mode mix of both I and II under pull-off loading, and the use of CNT is shown to give additional through thickness capability in this case as well.
Analysis of carbon nanotube integrated composite structures using multiscale approach

Results are now presented for hat stringers subject to the same loading condition. Figure 15 represents the pull-off failure load of the structure that incorporates a type 1 flaw. It can be observed that the failure load increase with 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. For type 1 flaw, mode I fracture is usually dominant. The opening of the radius surrounding the tow filler due to pull-off creates high energy release rates. Therefore, the use of CNT is shown to give additional through thickness capability, preventing or delaying such event from occurring. By comparing back to the T stringer results, it is noticeable that the failure load is higher for the hat stringer for this type of damage; therefore, it can be said that hat stringers are more resistant to this type of damage compared to T stringers.

Figure 16 represents the pull-off failure load of the structure that incorporates a type 2 flaw. In this case the failure load increased with increase in CNT weight percentage for both types of tow materials. It can also be observed that the failure load for the adhesive tow is significantly larger than that for the fabric tow. By considering only the adhesive tow results, the failure load is higher for the case when only the adhesive tow contains CNTs; therefore, there is no additional gain from using CNTs in the composite. On the other hand, when considering the fabric tow configuration the failure load is higher for the case when both the tow material and composite contain CNTs. Type 2 flaw is also found to be mode I dominant under pull-off loading, and the use of CNT is shown to give additional through thickness capability. The variation in failure load compared to T stringers, for this type of damage, is not as significant as observed previously, thus either stringer type can have comparable performance under pull-off loading.

Figure 17 represents the pull-off failure load of the structure that incorporates a type 3 flaw. As in the previous two cases, the failure load increases with increase in CNT weight percentage; however, for the fabric tow the failure load increases up until 5% CNT by weight, followed by a slight drop. When examining the adhesive tow results, the failure load is higher for the case when both the adhesive and composite contain CNTs and the same statement holds for the fabric tow. Type 3 flaw is found to have a mode mix of both I and II under pull-off loading, and the use of CNT is shown to give additional through thickness capability in this case as well.
From the previous results it can be concluded that when considering a structure that is subjected to pull-off loading (all aircraft structures fall under this category) the use of CNTs in the manufacturing process of such stringers in specific hot spot locations, such as the tow-stringer web interface or the bondline location between the skin and stringer, offers definite advantage. The delamination that occurs in those locations can be prevented or delayed and a higher structural performance can be obtained.

Fig. 15. Pull-off failure load for flaw 1 considering different configurations (hat stringer)

Fig. 16. Pull-off failure load for flaw 2 considering different configurations (hat stringer)

Fig. 17. Pull-off failure load for flaw 3 considering different configurations (hat stringer)

7. Conclusion

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 considered was a typical T and hat 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.

Detailed finite element models of the stringers were constructed in order to assess the use of nanocomposites in structural level components to overcome composite failure modes such as delamination. 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 configurations and flaw types were considered in this study. It was shown that using CNT in the manufacturing process of such stringers may improve the overall performance up to 50% by comparing the initial failure loads. It was also concluded that when considering a structure such as the stringers presented in this study that usually experience high pull-off loading, the use of CNTs in local hot spot locations such as the tow-stringer web interface or the skin-stringer bondline, the delamination that occurs in those locations can be prevented or delayed; hence, providing a more robust structural design. Such a solution would help in eliminating the need for typical preventive measures used in industry; such as adding local metallic fittings, which are not desirable due to the added weight and complexity in the manufacturing and assembly process.
8. Acknowledgements

The authors are grateful for the support of NAVAIR grant sponsored by Integrated Systems Solutions, Grant number: W911NF-12-1-0353. Dr. Nam Phan is the program manager.

9. References


