Characterization of Adhesive Failure and Modeling for Dynamic Analysis

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ABSTRACT

One of the ways of increasing fuel efficiency of a typical automobile is to reduce its overall weight. To this extent, plastics, especially fiber reinforced plastics are finding an increasing role as automotive structural components. The automotive structural systems made up of these structural fiber reinforced plastic components, should satisfy the needs in terms of safety, strength, NVH and durability, in addition to being affordable, manufacturable with desired fit and finish and recyclable.

In general, structural components made up of fiber reinforced plastics are adhesively bonded together to form structural systems, capable of carrying automotive structural loads under static and dynamic conditions. Fiber reinforced plastics and the adhesive used to bond them to form a structure are inherently viscoelastic in behavior. It is imperative therefore, to understand the behavior of these adhesively bonded fiber reinforced plastic components, in terms of their load carrying capacity at different temperatures and different load or strain rates. One of the key factors in this understanding is to characterize the adhesive failure itself at different temperatures and different strain rates of loading.

The present paper is an attempt to present some results from an ongoing research work on fiber reinforced adhesively bonded large injection molded thermoplastic automotive structural systems. In particular the paper presents the results from the test methodology and the mathematical models used to characterize the failure mechanics of adhesively bonded automotive body sections, at different temperatures and different load or strain rates.

INTRODUCTION

Bonded joints tend to be damage tolerant due to high damping behavior of adhesive layer and less expensive due to lower fabrication cost. The use of adhesives can increase the joint strength, distributes the load more evenly, and enables alternating joining methods to be reduced or eliminated. Dissimilar materials (e.g. steel, aluminum, plastics, glass, etc.) can be joined together by bonding even where it is impossible to gain access to either side of the joint, thereby increasing design flexibility as indicated by Reddy [1].

The failure load and pattern depend on different sets of variables such as adhesive type, adhered type, surface preparation, chemistry between adhesive and adherend, testing speed, geometry, temperature, magnitude and direction of loading. Effects of most of these variables have been discussed by Wilson and Sheasby [2], Kimura and Fujii [3], Doyle [4], Schoreder [5] and Ward and Westerbeek [6].

Although experiments have been conducted to evaluate bond strength, little effort has been put to model the failure of bond. Nardini [7], Tahmasebi [8] and Wagner [9] describe a finite element approach to represent adhesive by spring type elements. Kathawate [10] and Nardini [7] also discuss the modeling of adhesive with 2D elements. Sheasby [2] and Nardini [7] discuss how the bondline thickness, forming radius and fillet size influence the stress developed in the adhesive and adherend and also to overall strength of the bonded system.

Dynamic behaviors of bonded joints are not well understood. Dynamic testing of adhesively bonded joints poses a significant challenge itself. The complexity in failure mode and deformation response of joints under dynamic loading requires careful and thorough analysis to develop reliable predictive models. For crash analysis, dynamic modeling of adhesively bonded joints is a major need and a focused effort is undertaken in this investigation to develop implementable dynamic modeling approach. In addition temperature is also a variable for fiber reinforced plastic materials. Failure mechanisms at elevated temperature tend to be more ductile compared to the brittle nature of failure at low temperature. Therefore special attention is paid to ensure that the actual failure mechanisms be captured in the model predictions.

In all the present paper attempts to present results from an ongoing research program aimed at developing a mechanism-based modeling approach for dynamic analysis of adhesively bonded fiber reinforced plastic hat sections. In particular experimental and analytical methodology and results depicting the effect of temperature and loading rate on the failure modes is presented as a part of this paper.
EXPERIMENTAL MODEL

Figure 1 shows the geometry of the model used in the experiments to characterize the mechanical behavior of the bonded joint under different load rate and temperature conditions. Essentially this consists of an adhesively bonded fiber reinforced plastic hat section cut out of a valve cover bonded assembly.

Two different tests, a quasi-static test and a dynamic (impact) test on the bonded joints are performed at three different temperature conditions (-40°F, 73°F and 210°F). The quasi-static tests are conducted using a servo-hydraulic MTS machine. The computer controlled MTS machine is equipped with a hydraulic pump, a load unit, a load control panel, a digital controller and a data acquisition unit. A specially designed heat chamber around the test specimen is used for quasi-static testing at elevated temperature. For the low temperature case a specially designed cold chamber is used to maintain the required temperature levels of the sample being tested. In both low and elevated temperature cases, thermocouples are used to monitor and maintain the desired temperature. The load rate for all quasi-static tests is 1 mm/min. The test set up for the quasi-static test is shown in figure 2.

The test setup developed for the analysis of the dynamic response of the adhesively bonded hat section is shown in figure 3. The test machine consists of a movable part that is used to impact the samples, a fixed structure that acts like a bracket for the samples and a guide for the movable part. The total height of the machine is about 3.5 m. Two steel cables of 4-millimeter diameter are used like guides for the movable part. In order to reduce the friction between the cables and the movable part, two nylon ear-rings have been used. The actual height of fall is approximately 2.2 m. The movable part has a mass of 10.5 kg. This simulates kinetic energy equivalent to a 3000 pound mass moving at a speed of …miles per hour for the impact problem. During the test, two arms impact the steel plates and the impactors are also modeled. Each element model used for this purpose. As seen from Figure 5, the steel plate attached to composite sample as shown in the figure. This in turn transfers the impact energy to the adhesive joint. For the dynamic test involving low temperature the samples are pre-conditioned to a few degrees below the desired low temperature (to take care of any instantaneous heat transfer seconds before impact) and then impacted. For the elevated temperature a heat chamber is designed around the test sample and necessary high temperature is maintained and monitored using thermocouples.

MATHEMATICAL MODEL

QUASI-STATIC MODELING

Four different modeling techniques [11,12] are used to mathematically model the adhesively bonded system. The first approach is to model the adhesive material by springs as described in [11]. The second is based on the 2 dimensional approach similar to the one described in [12]. The third approach also described in [12] uses solid elements to model the adhesive material. The first three approaches depict the load displacement response up to failure quiet well and are in good agreement with experimental result [12]. However they provide little or no information beyond the initial failure as no fracture criteria is associated with the models suggested in [11,12]. The first three analyses are done using the finite element software ABAQUS [14]. A fourth method based on the nodal failure model is then used to accurately predict the initiation and propagation of failure along the interface. Figure 4 shows the finite element model based on this approach. Crack tip nodes are used to initiate a crack. The crack propagation is based on the following failure criteria. When the function ‘f’ reaches a value equal to 1, the crack starts propagating, where f is defined as

\[ f = \sqrt{\frac{\sigma_n}{\sigma_n^f}} + \left(\frac{\tau}{\tau^f}\right)^2 \]  

(10)

\( \sigma_n \) is the normal stress component at the interface, \( \tau \) is the shear stress component at the interface, and \( \sigma_n^f, \tau^f \) are the normal and shear failure stress components. Actually failure propagates when the local stress across the interface at a specified distance ahead of the crack tip reaches a critical value. So an initial distance has to be specified ahead of the crack tip. After debonding, the delaminated surface behaves as a frictional contact surface and prohibits any penetration between the two layers. This criterion is described in detail by Haq [13]. For analysis using the nodal failure model the software LS-DYNA3D[15] is used. The finite element model used for the quasi-static analysis is shown in figure 4.

The same four approaches are used to model the system at different temperatures using the corresponding true stress true strain data at these different temperatures.

DYNAMIC MODELING

As far as the dynamic modeling is concerned all analysis is done using LS-DYNA3D[15], with the substrate modeled by shell elements and the adhesive being represented by solid elements. Figure 5 shows the finite element model used for this purpose. As seen from Figure 5, the steel plates and the impactors are also modeled. Each node of the impactor is then assigned an initial velocity of 4m/s to model the 4 feet drop in the experiment. The total mass of the impactor is 10.5 Kg.

The interface failure is modeled using the following failure criteria. Contact_tiebreak_nodes to surface is specified between the composite and the adhesive. Interface gets separated when the failure load is reached at the interface. The following failure criteria is used
\[
\left( \frac{F_n}{NFLF} \right)^2 + \left( \frac{F_s}{SFLF} \right)^2 \geq 1
\]

Where NFLF is the normal failure force and SFLF is the shear failure force. \( F_n \) is the normal force and \( F_s \) is the shear force at the interface. Failure occurs when the left hand side of the above equation becomes greater than or equal to 1.

For modeling the composite failure the substrate itself is modeled using the piecewise linearly plastic material model with failure available in LS-DYNA3D [15]. The finite element model corresponding to the dynamic case is shown in figure 4.

**ANALYSIS AND RESULTS**

Figure 6 shows the comparison between the analysis and the experiment for the room temperature quasi-static tests. It is clear that the use of springs or the use of 2-D models to represent the adhesive provide good results up to failure and the nodal failure model is able to capture the displacement response all the way up to the final failure of the system. The nodal failure model seems to better approximate the experimental behavior. Table 1 summarizes the peak load and the corresponding computed stiffness from experiments and the analysis. Some discrepancy in the analytical data is due to the fact that the as molded material properties for the substrate were not available at the time of analysis.

Figure 7 shows the force displacement curve from the quasi-static experiment and analysis at elevated temperature (210°F). Again in this case the nodal failure model seems to correlate with the experimental data better. In the case of negative temperature, due to the increasing brittle nature of the substrate, the primary mode of failure was the brittle failure of the substrate. It is known that in brittle type failure the load displacement relationship is fairly linear. The fact that all the different analytical procedures described predict experimental results well up to failure, results from all the different approaches of analysis compared well with the experimental data.

The quasi-static experiments at negative temperature (-40°F) tests indicated the composite or the substrate failure. The tests at elevated temperature (210°F) indicated cohesive failure of the adhesive as the primary mode of failure. In all 30 samples is used for each test at different temperature.

Figure 8 shows the force displacement response from the dynamic test and the corresponding finite element analysis using the nodal failure criteria described above at room temperature (73°F). The tests indicated adhesive failure as the primary mode of failure although some samples indicated failure of the composite itself. Again the nodal failure model seems to correlate with the experimental data well.

As far as the low temperature (-40°F) dynamic (impact) tests, the main mode of failure is one of adhesive type, although in some cases composite failure is observed. In the high temperature (210°F) case the primary mode of failure observed under dynamic loading is one of composite failure. The analytical data in Figure is obtained using the nodal failure model. Even in the dynamic case 30 samples for each test at different temperatures is used. All experimental results are an average of all the test data for each temperature and loading condition.

**CONCLUSIONS**

Depending on the strain rate of loading (quasi-static or low strain rate on one end and dynamic or high strain rate loading on the other) and different temperature conditions (-40°F on one end and 210°F on the other), variety of different failure modes are observed.

It is interesting to note that although the primary mode of failure at high temperature under quasi-static loading is one of cohesive type. At the same temperature under dynamic loading the primary mode of failure is one of the adhesive failure and in some cases involve adhesive/composite failure. Therefore the loading rate even at the same temperature seems to significantly alter the failure behavior especially at high temperature due to the viscoelastic nature of the substrate material (fiber reinforced plastic) and also the adhesive material.

As a part of continuing research, effort is being focussed on statistical analysis of failure from the test results at different temperature conditions and different strain rate conditions. The idea is to develop a three dimensional failure envelope that could provide a value of the maximum load carrying capacity of the bonded system or the maximum energy absorbed by such sections. The strength or the load carrying parameter can then be plotted against temperature and a geometric parameter such as the ratio of the thickness of the substrate to the bond thickness for different combination of materials, temperature and loading conditions. Failure mode corresponding to each specific case can also be noted. This database of failure envelopes then can be used to guide engineering design of adhesively bonded fiber reinforced plastic sections.

Now with the knowledge of a specific failure mode for a specific combination of material, geometry, temperature and loading, a specific failure criterion can be developed. This then with the nodal failure model can be used to qualitatively predict the failure behavior of adhesively bonded fiber reinforced plastic sections made up of different substrate and adhesive combinations.

In all the present paper is an attempt to present some results from an ongoing research work aimed at characterizing the adhesive failure and modeling for dynamic analysis of bonded fiber reinforced plastic sections.
REFERENCES

15. LS-DYNA3D,v950,LSTC Inc., California.

<table>
<thead>
<tr>
<th>Results From</th>
<th>Ultimate Load (Newton)</th>
<th>Stiffness (N/mm)</th>
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<td>Experiment</td>
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</tr>
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</table>

TABLE 1