ADVANCEMENTS IN FAIL SAFE RESPONSE WITH BISTABLE COMPOSITE STRUCTURES

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ABSTRACT

Cars have dent resistant side panels, crumple zones and composite bumpers to absorb and disperse impact energy protecting occupants. Each of these improvements share a common feature: once activated or deformed, their load carrying capacity is diminished. A bistable structure is such that, once activated, it has a second stronger phase which has the ability to sustain higher loads. This allows for a better distribution of damage, and in addition the structure keeps its integrity for a longer time. Initial tests have verified this concept proving that a bistable structure under tensile loading has the capacity of absorbing more energy than a similar monolithic structure under the same load conditions. Bistable structure behavior has also been shown for a system composed of advanced fiber reinforced composites, which has the potential of being a break-through for applications where energy absorption is sought.

KEYWORDS

Composites, Fail Safe, Energy Absorption

1.0 INTRODUCTION

The concept of a bistable structure is attributed to Cherkaev and Slepyan [1-3] in 1995. Their work showed that a considerable increase in energy could be absorbed for the same volume of material while remaining cohesive after impact due to the waiting links. A similar concept using high deformation visco-elastic solids was identified by Dancila [4] in 1998. This paper will present the application of this concept of bistable structures to stitched sandwich composite materials. Stitching has been shown to improve interlaminar strength as well as increase absorption of energy by sandwich structures [6-17].

Recent work by the authors, [18], focused on metallic structures. A bistable structure is composed by two parts, called ‘main link’ and ‘waiting element’. The main link is typically straight and designed to break first. As this happens, the waiting link, typically curved and attached to the broken main link, is able to carry additional load, with the structure behaving as a material-driven mechanism. The authors showed in [18] that the concept could be broken into three major components. The first two utilize multiple singularities (necking) which occur at the onset of fracture in ductile materials. The third, expanded in later sections of this paper, uses the fracture of each main link and extra length in the associated waiting link to ‘recharge’ the structure releasing the built up strain energy allowing the entire structure to be loaded again. The concept was proven to absorb more energy per unit volume of metallic material(s) than a standard structure. It also showed that the gain is proportional to the number of bistable linkages in series in the chain.

As previously mentioned, the focus of this paper is the third type of element, referred to as Tensile Element 3 (TE3) [18]. These types of bistable elements employ a main link material which exhibits a relatively brittle response with little or no plastic deformation before fracture. This allows a situation where any slack in the waiting link translates into the elastic reduction in strain of other unbroken links. The benefit with this linkage is that they do not experience any plastic deformation, and consequently much of the strain can be recovered by varying the length of the waiting element with respect to the main link and overall chain. Once main link breaks, a brittle response waiting link can perform the same function as the main link, by absorbing energy and then relaxing after the next fracture, essentially “recharging” the element. Early work utilized fiber reinforced composites due to their relative ease of manufacture when compared with other elastic response materials.
2. COMPOSITE BISTABLE LINKAGES

2.1 BISTABLE CONCEPTS

The response of these elements is highly dependent on the length of the curve and length of the waiting link compared with the main link. It is therefore easier to describe the element as a ‘percent wait’, i.e. in terms of the difference between the main and waiting link divided by the length of the main link and multiplied by 100%. The effect of the percent wait is further affected by the number of links in the chain, the elasticity of the chain (elements in series) and the strain at failure of the main link.

The optimal arrangement of these links is in a chain, but there can be many benefits of combining elements in both parallel and series. A representation of this concept is shown in Figure 1. Typically, a panel exhibits significant constraint causing mostly local damage to occur. By using this open net arrangement, as the nodes (connection areas) local to the point of load move, adjacent nodes are displaced. As these latter nodes move, interaction of parallel chains further distributes the damage across a greater amount of the net material.

The idea that these structures can absorb more energy than a typical one is easily understood with the following thought process. Consider a bistable structure where the main link is formed by one single ply and the waiting link by two plies. The baseline specimen, to be used for comparison, would have three. The energy absorbed is the area under the force/displacement curve. Composites have nearly a pure elasticity of the chain (elements in series) and the strain at failure of the main link is considered to be equal to zero. In that case, it can be assumed that the energy absorbed by the base line is \( \frac{1}{2} \times (\text{max load of one ply} \times 3) \times (\text{max strain of the ply} \times \text{its length}) \). Assuming that the waiting links carry no load until after the main link breaks, the energy absorbed when the first link breaks is \( \frac{1}{2} \times (\text{max load of one ply}) \times (\text{max strain of the ply} \times \text{its length}) \). The length of a node can be considered to be equal to zero. In that case, it can be seen that a series of only three of these linkages will absorb the same amount of energy as a baseline specimen, while still having the unbroken waiting links carrying the load. By fitting six bistable links within the same length will allow to absorb twice as much energy as the base line. It is this basic idea which makes these structures such a powerful design tool.

Figure 1 - Net of bistable elements

2.2 CONSTRUCTION OF BISTABLE COMPOSITE SPECIMENS

One failure mode that composite bistable specimens exhibit is the tendency to delaminate between the main link and waiting link plies. This destroys the node, thus creating one link out of two. Through-the-thickness stitching is a practical solution but prepregs are not easily stitched because of the need to stitch the material before cure and the need to wet out the stitching fibers. The stitching for this study was done on a Consew industrial sewing machine, which was manually operated using its drive wheel. Kevlar 29 4×400 yarn was used for its resilience through the tortuous thread path from skein to completed stitch. Paper on both the top and bottom of the assembled layers protects the weave from the fabric feed on the bottom, and provides also a grid pattern for stitching on the top. The paper is removed before infiltration. The grid used provided spacing between the rows and individual stitches of 5mm.

To give the waiting links their needed curve shape, Last-a-Foam with a density of 64.1 kg/m³ (4 lbs/ft³) was utilized as a core material. The foam was hand shaped to create the waiting link’s shape and thus its overall length relative to the main link. Earlier work demonstrated the effectiveness of three particular shapes of foam: the large circular segment, the medium circular segment, the small circular segment (Figure 2).

![Figure 2 - Side View of the Three Foam Shapes Used](image)

As can be seen in Figure 2, the shapes are similar to each other, but each provides a greater percent wait to the structure as the transition is made from smallest to biggest.

Preliminary work showed that keeping the plies of the main link taut and flat greatly reduced variation in the final product. To achieve this requirement, a quilting hoop was bent out of round to provide the necessary tension for the fabric inserted in it.

The specimens for this work were produced using the Vacuum Assisted Resin Transfer Molding (VARTM) process. This is similar in concept to conventional RTM, however the sole motor force for the resin is the applied vacuum, and not the pressurization of the resin. The specimens used for this study were infiltrated with Epon 862 with EpiKure 9553 as the hardener and cured at 37°C for 120 minutes.

The final step involved in the manufacture is to apply tabs for testing. G-10 was the tabbing material used with Hysol 809 as the adhesive. 25mm-wide strips were cut.

2.3 FAILURE MODES

There are three predominant failure modes displayed in early experimentation. The first is failure from a small radius. Since the waiting link must straighten, the inside portion of the shape must be sufficiently large to survive the necessary rotation. Once straight, the plies will start to carry...
equal strain. Thus the inside of the curve is most critical and may cause failure.
The second common mode of failure is the debond of large portions of excess matrix, which formed in the pockets and shape transitions during infiltration as shown in Figure 3.

Figure 3 – Specimen with Excess Matrix

The effect of these inclusions and outer surface imperfections is likely to be reduced by more exact forms and a shaped upper plate.

Figure 4 shows the force/displacement plot from the test data of the specimen shown in Figure 3 (which formed the eight iteration of this project). Both specimens (the one with core and the one which had it removed) experienced a drop in load as the matrix debonded. Since the matrix prior to the ‘pop’ allowed for the waiting link to stay curved, an associated drop in load can be noticed. When the matrix breaks free, failure quickly follows due to fiber damage.

The third cause of failure is the aforementioned debonding between the layers which make up the waiting and main links. The large shock caused by the sudden release of load from the structure is enough to break the layers free. This type of element is necessarily more sensitive, especially for elements will percent wait less than maximum strain. These types will not only experience the sharp load drop, but will not fall to zero and ‘catch’ the load (up to 1500 N for some combinations of material and shape). This is where the benefit of through-the-thickness stitching comes into play. There is an ideal amount of stitching where the overall node length is minimized but, for the time being, optimization will be ignored and the configuration with overly safe four rows of stitches will be assumed. Figure 5 shows the load/displacement curve for a stitched node containing only one stitch row. Due to localized damage from stitching, the main links will break along one of the stitch rows. With the fibers loose on the other side of the stitch, the initial disbond corresponds to the load drop at 1500 N. The initial debond did not completely free the end of the second main link, and therefore the latter can still carry some load. Highlighted is a region of the curve which shows through response the fibers pulling through the stitches. Once free, the two attached waiting links straightened and broke at a lower load than it is typical across the stitch row, due to damage from the pullout.

Node Containing Single Stitch Row

3. TESTING

3.1 TEST SETUP

Three types of fibers were compared, in addition to three different groups of specimens. Their waiting links were made with three core shapes in the form of small, medium and large circular segments as seen in Figure 6.
Waiting link. The role of the core in deflecting the main links out of plane was also identified.

The tests were performed in an MTS load frame at a constant displacement of 0.508 mm/min (.02 in/min). Note that the nodes are excessively large for this basic evaluation, thus they will be not conclusive for the concept to verify. Therefore, without node optimization, the material between the nodes will not be considered in the representative baseline. Using the previously mentioned sizes, the baselines consisted of three plies, 25 mm wide with a total equivalent length of 3 × 50 mm or 150 mm overall. These baseline specimens were also monotonically loaded at the same rate as the bistable specimen.

3.2 TEST RESULTS

The results of the tests showed a number of interesting phenomena. First, due to the strain required for straightening, only the fiberglass specimens successfully went bistable. Their combination of survivability at high strain, combined with decent load carrying capacity, accounts for the high level of energy needed to produce fracture. Kevlar iterations without core were not tested since the previous tests on E-Glass and T-300 specimens showed that removal of the core caused excessive damage, thus preventing proper response. No benefits were observed from the core removal.

Table 1- Test Results. Bistable Behavior Is Shown in Green.

<table>
<thead>
<tr>
<th>Fiber</th>
<th>Core</th>
<th>Small Circular Segment</th>
<th>Medium Circular Segment</th>
<th>Large Circular Segment</th>
<th>Baseline</th>
</tr>
</thead>
<tbody>
<tr>
<td>E-Glass</td>
<td>Yes</td>
<td>16.1</td>
<td>18.5</td>
<td>20.7</td>
<td>27.9</td>
</tr>
<tr>
<td></td>
<td>No</td>
<td>14.9</td>
<td>19.8</td>
<td>7.4</td>
<td>27.9</td>
</tr>
<tr>
<td>Kevlar</td>
<td>Yes</td>
<td>7.5</td>
<td>7.8</td>
<td>8.1</td>
<td>20.2</td>
</tr>
<tr>
<td></td>
<td>No</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>20.2</td>
</tr>
<tr>
<td>T-300</td>
<td>Yes</td>
<td>5.0</td>
<td>5.7</td>
<td>4.6</td>
<td>14.9</td>
</tr>
<tr>
<td>Woven</td>
<td>No</td>
<td>5.6</td>
<td>5.5</td>
<td>6.5</td>
<td>14.9</td>
</tr>
</tbody>
</table>

Bistable behavior is highlighted in green. The results of Table 1 show that even though T-300 has the highest load carrying capacity, its small strain at failure prevents it from absorbing the most energy. The Kevlar specimens allowed more straightening than the T-300, but still proved insufficient for this geometric arrangement to survive. Figure 8 below shows the response of the Kevlar specimens. One point to notice here is that, with less wait, the specimen will ‘catch’ the load at a higher point. Also, in the case of the large circular segments, the waiting link is not fully straightened at fracture, or even after the rest of the chain elastically relaxes. Another point to be made with this graph is that, even though the Kevlar specimen with the small wait had to catch the load at the highest level, fatal damage was not created. Instead, it was the level of rotation needed to straighten that proved to be the limiting factor. This can be seen by the decreasing load at failure for the waiting links as the core size increases.
The E-Glass was the only fiber type to survive the straightening and has the desired bistable behavior (Figures 9-11). Note that each peak is successively higher than the previous one, since the weakest will typically fail first. Additionally, the fiberglass specimen in Figure 9 has a higher strain at failure than the Kevlar specimen in Figure 8. The waiting link will catch the load at a higher level.

The medium circular core specimens showed promise since catching the load means that the specimen did not entirely discharge its elastic energy. Therefore, it cannot absorb its potentially maximum level.

The large circular core absorbed the most energy when the core was not removed. This did prove somewhat sensitive to damage caused by the poor response of the specimens with the core removed. It should be observed that none of the bistable specimens absorbed more energy than their baselines. This disproves the simple assumption that three elements in series would be sufficient to improve the structure.

4.0 SUMMARY AND CONCLUSIONS

Bistable structures were introduced, and results on composite designs were presented and discussed. The original idea of the efficiency of a series of three elements was proven incorrect because bending, core failure, manufacturing shortcomings occurred. This work, however, does prove that concept is possible with composites, and highlights the performance of fiberglass structures.

This paper also identified candidate materials, ruling out Kevlar and carbon fiber due to their low strain survivability. While it might be possible to obtain a successful design based on these fibers, the combination of exceedingly thin sections with long slow curves would nullify any benefit which might be realized. Future work will expand on the concepts discussed in this paper.

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