The Role of Individual Failure Mechanisms on Crush Energy Absorption in a Composite Tube

This application brief summarizes work done at Michigan State University and reported in [1]

Introduction

A Design of Experiments (DOE) study was performed to estimate the contribution of various energy absorbing mechanisms to the total energy absorbed during quasi-static crush of circular composite tubes (see Figures 1 and 2). Failure mechanisms such as material failure, delamination, friction between plies and friction between a metallic initiator and the tube were explicitly represented in an axisymmetric finite element model. The DOE study was controlled with HEEDS Professional design exploration software [2], and Abaqus [3] was used to perform the finite element analysis. The results of this study not only provide a better understanding of tube crush behavior, but also guide the development of better models for design of composite crush tubes. A brief description of this study and its results is presented herein. For more complete details, please see [1].

Tube Crush Model

The use of inexact models to perform studies that will guide the way toward better models may at first appear to be inconsistent, but the potential benefits of this circular reasoning are substantial. These benefits include the ability to estimate directly and separately the effects of various failure mechanisms – a result that cannot be achieved experimentally – by explicitly representing each mechanism using detailed and validated models. Provided the results of such a study are consistent with observed experimental evidence and are further interpreted appropriately, the conclusions should be valid and valuable qualitatively if not quantitatively.

Since shape was not a variable of interest in the current parametric study, only circular tubes were considered. Circular tubes can be modeled easily and accurately using an axisymmetric model. The circular tube modeled had a length of 4 inches, an outer diameter of 2.5 inches and a thickness of 0.075 inches. An axisymmetric finite element model of the tube was created, and the initiator was modeled as an analytical rigid surface with a radius of 5/16 inches (see Figure 3). All the nodes in the upper edge of the tube were clamped and the initiator was given a displacement in the upward direction of 0.69375 inches; this value was selected because it was the highest value of displacement for which all DOE design simulations converged.

Figure 1. Typical metallic crush initiator and beveled composite tube. Specimens and photographs are courtesy of the Automotive Composites Consortium.

Figure 2. Sample failure mechanisms in a cross-ply stitch mat composite tube. Specimens and photographs are courtesy of the Automotive Composites Consortium.

Variations in material behavior associated with different constituent materials or fiber reinforcement microstructures were beyond the scope of the current study. Of greater interest here was the overall contribution (or ranking) of ply material damage to the total energy absorption. For this reason, an attempt was made to model a typical composite material response using as simple a model as possible. After investigating several progressively fracturing material models, the isotropic concrete damaged plasticity model in Abaqus [3] was selected for use in the current study to simulate energy dissipated due to material failure.

An interface element technology [4] was used for connecting and simulating crack growth between two independently modeled finite element subdomains representing the composite plies (see Figure 4). Because the plies are modeled separately, they can experience friction along their common interface after complete delamination. The interface element was implemented in the finite element code Abaqus as a User Element Subroutine (UEL). The interface element technology was specially formulated to simulate delamination growth in composite laminates. Thanks to its special features, the interface element approach makes it possible to release portions of the interface surface whose length is smaller than that of the finite elements, thus it can accurately track the delamination crack front. In addition, the penalty parameter can vary within the interface element, allowing the damage model to be applied to a desired fraction of the interface between the two meshes.

DOE Study

In the current study, five DOE factors were selected associated with the following primary failure mechanisms:

- A: Friction between the tube and the initiator
- B: Ply material damage energy absorption
- C: Presence of delamination
- D: Delamination damage energy absorption
- E: Friction between delaminated plies

The last three factors are all associated with delamination, since one of the main goals of this study was to better understand the need for explicit modeling of delamination during progressive tube crush analyses.

A two-level full factorial DOE study was performed. Hence two values or levels (low and high) were assigned to each variable (or factor), and all possible

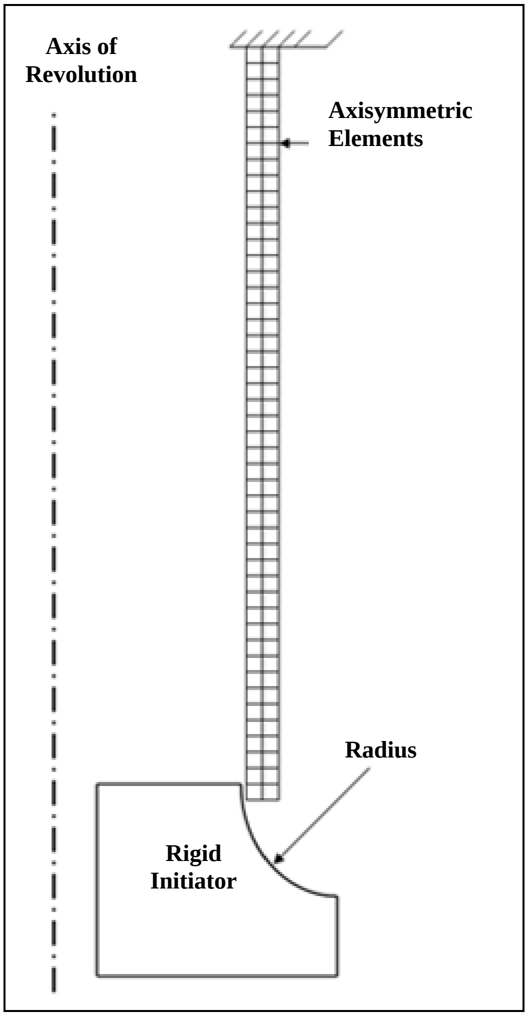

Figure 3. Axisymmetric model and rigid initiator.

Table 1. Summary of DOE factors in the study.

Label	Mechanism	Factors	Low Value	High Value
A	Friction between tube and initiator	Tube / initiator friction coefficient	0.0	0.3
B	Ply material damage	Strain ratio	1.2	2.4
C	Presence of delamination	Interface element	Present	Not Present
D	Delamination damage	Relative displacement ratio	5	10
E	Friction between delaminated plies	Ply / ply friction coefficient	0.0	0.2

combinations of tube crush behavior were analyzed. In total there were $2^5 = 32$ possible combinations. The values of the factors are summarized in Table 1.

Note that factors D (relative displacement ratio) and E (friction between the plies) are relevant only when delamination takes place. Hence only 20 of the 32 numerical experiments were required for a complete DOE study. The DOE sampling and ANOVA post-processing were performed using the commercial design exploration and optimization software, HEEDS Professional [2].

Each experiment was performed by changing the appropriate values in the Abaqus input file and executing the finite element analysis to obtain the force-deflection curve. A typical force-deflection curve is shown in Figure 5. The total energy absorbed for each experiment was obtained by integrating the force-deflection curve using a simple trapezoidal rule. Once the energy absorption was obtained for each tube experiment, the sensitivity of the response to each factor was calculated.

Results and Discussion

The contribution of each factor is shown in Table 2. Factors that had the greatest contributions were A, B, and C. The contribution of all interactions was negligible except for AC, which was also low. Approximately 61.97% of the variability in the response can be explained by factor A, 10.39% by factor B, 25.55% by factor C and 1.73% by interaction of factors A and C.

It was well known that external friction (A) and material failure (B) contribute substantially to the energy absorption during tube crush. The role of delamination was not understood as clearly. The results of the current study indicate that delamination plays an important role in determining how much energy is absorbed, but delamination itself does not absorb very much energy in a relative sense. Rather, the presence of delamination tends to reduce the bending stiffness of the tube rather substantially, which in turn reduces the radial (normal) forces between the initiator and the tube. Hence, the friction between the initiator and the tube, being proportional to the normal reaction force, is reduced when delamination is present so that less energy is absorbed by the external friction mechanism.

Even though there is a strong relationship between the presence of delamination (C) and the energy absorbed due to external friction (A), the interaction AC is still relatively small. This is because even when external friction is reduced by the presence of delamination, the contribution of external friction is still about the same, on the order of 50%.

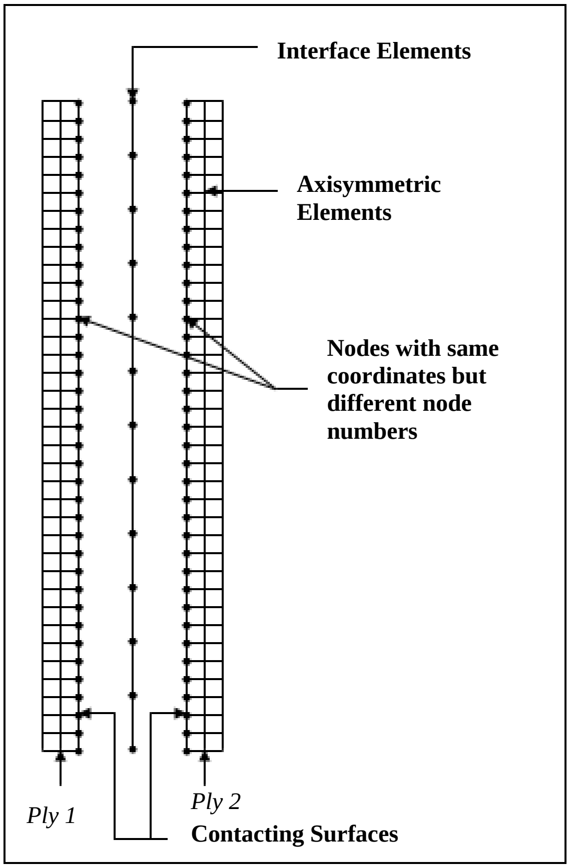

Figure 4. Modeling of adjacent plies using an interface element.

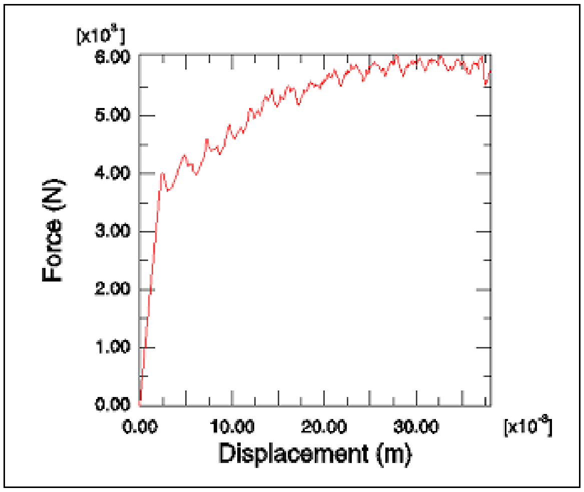

Figure 5. A typical force-deflection curve during tube crush

While external friction is obviously very important, the results indicate that the total energy absorbed is not sensitive to the friction between the plies (E) or to the strain energy released during delamination (D), both of which were negligibly low.

Conclusions

A DOE study was performed to investigate the main energy absorbing mechanisms during quasi-static crush of a circular composite tube. Failure mechanisms such as material failure, delamination, friction between plies and friction between a metallic initiator and the tube are explicitly studied.

The results confirmed that friction between the tube and the initiator was the dominant mechanism, representing approximately 50% of the total energy absorption.

Neither the delamination mechanism nor friction between the delaminated plies absorbed a significant amount of energy. However, the total amount of energy absorbed was decreased substantially when delamination occurred due to a reduction in the tube wall bending stiffness and an associated reduction in the normal forces between the tube wall and the initiator, which affects the friction forces. So even though the delamination mechanism does not contribute significantly to the energy absorption in composite tubes, the presence of delamination must be explicitly accounted for in models of tube crush in order to accurately capture the other contributing factors such as external friction and material failure.

REFERENCES

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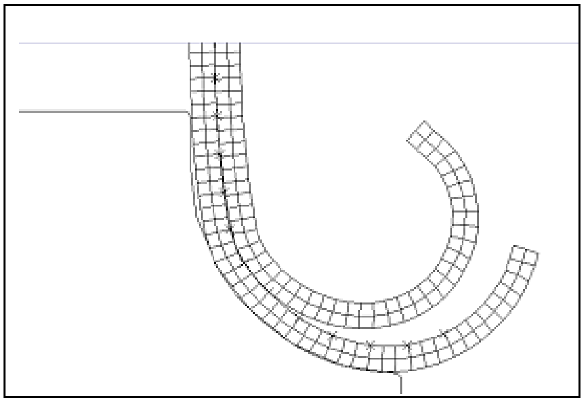

Figure 6. Crushed tube illustrating delamination.

Table 2. ANOVA calculations.

Factor	Contribution %
A	61.97
B	10.39
C	25.55
D	0
E	0.06
AB	0.18
AC	1.73
AD	0.01
AE	0
BC	0
BD	0
BE	0.01
CD	0
CE	0.06
DE	0
ABC	0
ACD	0.01
ADE	0.01
AEB	0
AEC	0
BCD	0
BDE	0
BEC	0.01
CDE	0
BDA	0
ABCD	0
ACDE	0.01
BCDE	0
CABE	0
DBAE	0
ABCDE	0