Modeling the Post-Peak Behavior for Crashworthiness Prediction of Composite Structures

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Abstract

Composite structures exhibit superior specific energy absorption (SEA) than metallic structures. However, the application of composites in primary energy absorbing (EA) structures is still limited. The lack of reliable predictions for composite EA structures is considered to be one of the key factors. This paper discusses the importance of modeling the post-peak behavior in material models for crashworthiness prediction of composite EA structures and presents a model recently developed and implemented as a material subroutine in LS-DYNA®.

Introduction

Fiber reinforced polymer composites exhibit high Specific Energy Absorption (SEA) values [1]. They have great potentials in reducing the mass of energy absorbing (EA) structures such as front rails in vehicles [2-4], airplane or helicopter subfloors, and landing gears. A major challenge in the design of composite EA structures is crashworthiness predictions. Although such analysis has become routine in the design of metallic EA structures, a reliable prediction for composite EA structures is still lacking.

As shown in Fig.1, the EA capability of a material is commonly evaluated with axial impact experiment of tubular structures. The SEA is calculated as the energy absorbed during the experiment divided by the mass of the crashed tube portion. A material with high EA is expected to maintain a progressive crush mode while sustaining a sufficiently high crush load after the initial impact. This is achieved by large plastic deformation in metallic tubes, and by extensive failure and fracture in composite tubes. Fig.2 compares the typical failure morphologies of steel and composite tubes after axial impact experiments. As shown, the steel tube buckled and folded without fracture. The composite tubes were crushed into debris or split into pieces. To predict the EA performance of composite tubes, the material model must be able to describe the entire damage and fracture process of the material. This requirement sets the material models for crash simulations of composites apart from those for other applications.

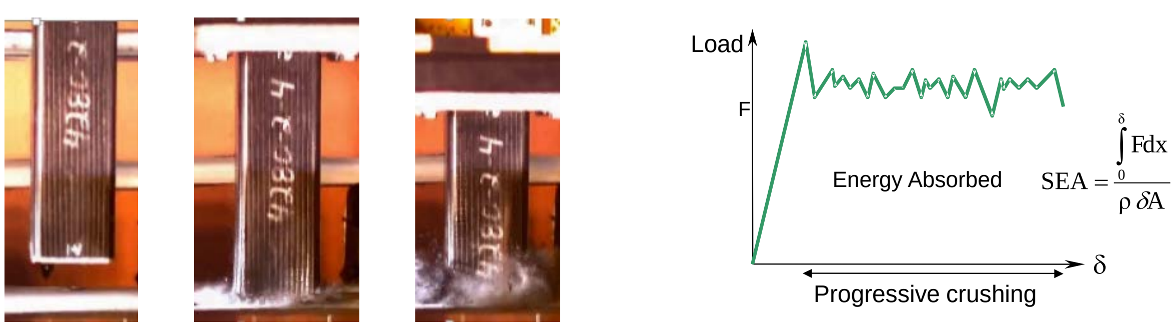
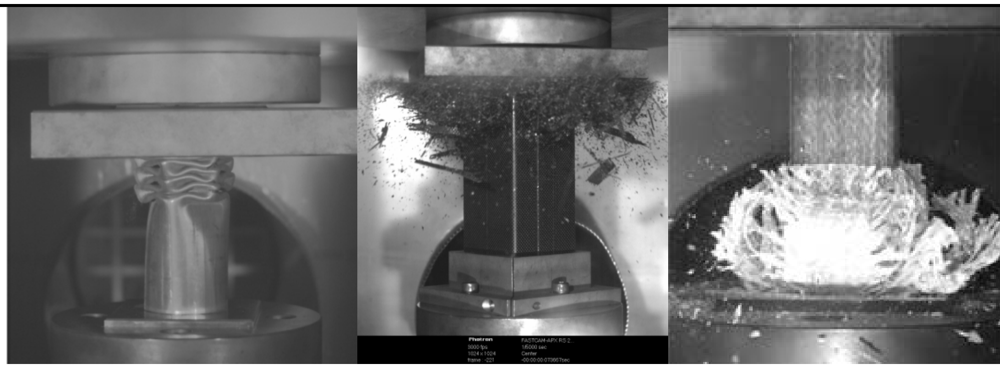


Figure 1. Left: The energy absorbing ability of a material is often evaluated by axial impact experiment of tubular structures. Right: The Specific Energy Absorption (SEA) value is computed by the area under the load- displacement curve divided by the mass of the crashed tube portion.



DP steel tube PW carbon composite Braided carbon composite

Figure 2. Failure morphologies of tubes made of different materials after axial impact experiment. From left: dual phase steel, plain weave carbon/epoxy composite, and triaxial braided carbon/epoxy composite.

The two common types of composite models are the progressive damage (PD) models and continuum damage mechanics (CDM) models. Both types of models have been used in crash simulations of composite EA structures. To model the sustained load carrying capability of composite EA structures, the constitutive model must describe the stress-strain behavior beyond the strength of the composite, i.e. the so-called post-peak behavior. This has been modeled by extending the stress-strain curve as it enters a perfect plasticity state in PD models and by strain softening through damage evolution in CDM models. So far, neither types of models can provide satisfactory predictions.

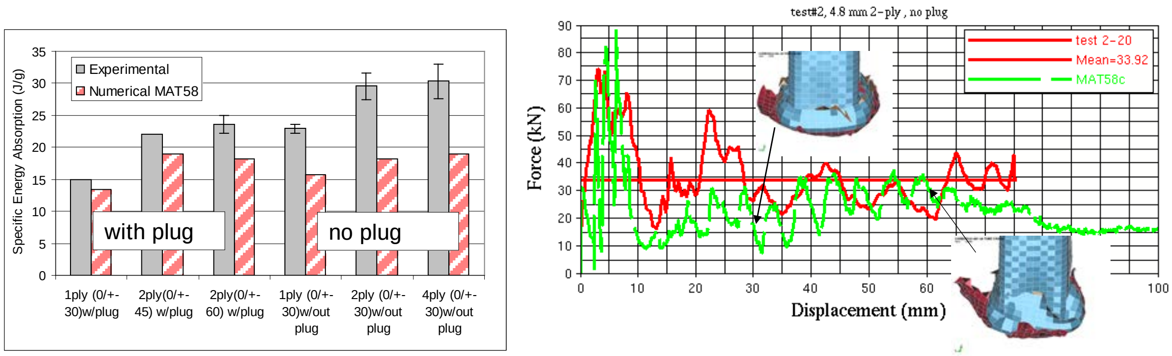
This paper will present the progress in modeling the post-peak behavior with CDM based composite models.

Experience with CDM Model

A common composite material model used in crashworthiness prediction is MAT58 in LS-DYNA, a classic composite CDM model known as the Matzenmiller-Lubliner-Taylor (MLT) [5]. Its implementation in LS-DYNA during 1990s was supported by the Automotive Composite Consortium (ACC) [6,7], a collaborative research organization including Ford, Chrysler and General Motors.

To evaluate the predictive capability of MAT58, Xiao et al [8,9] simulated axial crash of triaxial braided carbon epoxy composite tubes of six different configurations. The tube crash experiments were performed under two test conditions: either with or without a plug initiator attached at the crash end of the tube. It was observed that MAT58 consistently under-predicted the SEA value of these tubes. Furthermore, the under-prediction was about 10-20% for tubes with a plug initiator and 30-40% for tubes without a plug initiator, Fig.3a. In experiments, all tubes displayed a progressive crush mode. In simulations, however, tubes without a plug initiator buckled globally as the crash exceeded certain length. For example, the tube buckled at 60mm in the inserts of Fig.3b.

This phenomenon was not understood until 2003 when an experiment by DeTeresa et al. [10] became available. To support the constitutive model development for composite tube crush applications, DeTeresa et al. measured the so-called ‘‘total stress–strain responses’’ of a braided carbon epoxy composite under tensile and compressive loading. Among them, there was a compression-tension experiment. The straight-sided specimen was clamped by grips at its two ends, as shown in Fig.4a. The unclamped length was short enough to prevent global buckling. The specimen was loaded under displacement controlled mode in compression to a strain level much beyond its compressive strength and then the crosshead direction was reversed to tension. The recorded stress–strain lotus is plotted in Fig. 4b. This experiment was simulated with MAT58. The simulated stress-strain locus is also plotted in Fig.4b.



(a) (b)

Figure 3. Comparison of simulation and experimental results of axial crash of triaxial carbon composite tubes [9]. (a) Predictions for SEA are 10–20% lower for tubes with a plug initiator and 30–40% lower for tubes without a plug initiator. (b) The force and displacement curve of a tube without a plug initiator. The inserts are at 30mm and 60mm displacements. The tube buckled at 60 mm.

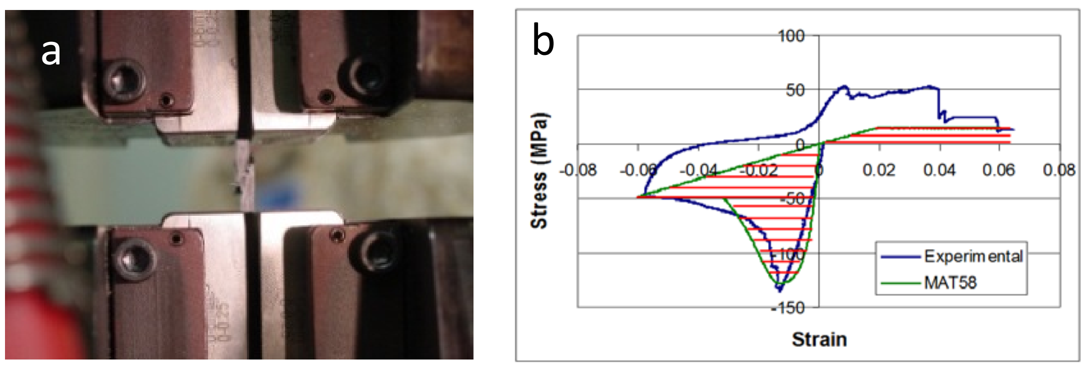


Figure 4. (a) Measuring the total stress–strain responses under compression [10]. (b) Comparison of simulated and experimental stress-strain response of results of a triaxial carbon composite specimen subjected to compression-tension loading [11]. The area enclosed by solid blue line corresponds to the energy absorbed by the material during experiment whereas the shaded area to the predicted energy absorption.

Figure 4b revealed a fundamental deficiency of CDM models in crash simulations [9,11]. The CDM models attribute the nonlinear response of a material to elastic softening induced by damage, even though the damage in the composite may lead to irreversible deformation, as revealed by the unloading segment of the experimental curve. Such models can provide a reasonable stress-strain description for both the pre-peak and post-peak region as far as loading is monotonic. The problem starts when unloading occurs. Modeling the large deformation solely by the means of elastic softening lead to a much lower stiffness in the damaged composite than it is in the experiment. As a result, the area enclosed in the simulated stress-strain locus is much smaller than the experimental value. In other words, it will under-predict the total energy absorption. Excessive softening also increases the tendency of global buckling of the structure and causes numerical difficulties in simulations. As tubes crashed without a plug initiator experiences a much higher peak load than those with a plug initiator, the material at the crash frond would suffered much severe damages and hence a larger error in SEA prediction.

Having recognized the importance of correctly representing the unloading path in crashwothiness prediction of composite structures, McGregor et al. [12] modeled the unloading path of compressively damaged composites in the CODAM model, Xiao developed a heuristic model [13] and a coupled composite damage plasticity model [14]. These works have led to significant improvement in crash simulations. However, the robustness of crash simulation is far from satisfactory. Furthermore, with a single damage evolution law, these models cannot accurately represent the material response in both the pre- and post-peak regions.

Recent Developments

To address these problems, an enhanced continuum damage mechanics (ECDM) model [15] and a shell-beam (SH) method [16] have been developed.

Enhanced Continuum Damage Mechanics (ECDM) Model

Fig. 5 is a schematic of the uniaxial tensile stress-strain response of ECDM in one material direction. ECDM employs two sub-models, i.e. a pre-failure model and a post-failure model, to describe the stress-strain behavior in the pre-peak and post-peak regions. The post-failure model is further divided into two stages: a strain softening and a residual state stage. This setup allows one to consider the growth of damage and irreversible strains in different regions under different evolution laws corresponding to different damage/deformation mechanisms. There are two criteria in the ECDM model: an initial failure criterion and a final failure criterion. The initial failure criterion determines the peak strength, while the final failure criterion determines the element deletion conditions. The details about the ECDM model can be found in [15].

The ECDM model was evaluated in quasi-static and dynamic tube crash simulations of triaxial braided composites. Figure.6 compares the stress-strain responses simulated by using ECDM and MAT58 with the experimental results for a triaxial braided composite under tension at axial, transverse and 45º directions. With two damage evolution laws, ECDM described the stress-strain behavior at both pre- and post-peak regions with good accuracy. MAT58 provided a reasonable description for the pre-peak region. In the post-peak region, it can only describe a graduate softening instead of the sudden stress drop as observed in the experiment.

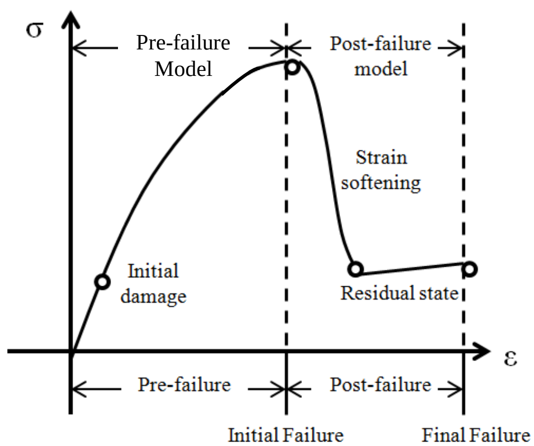


Figure 5. Schematic of the uniaxial stress-strain response of the ECDM model [15]. The model is composed of two sub-models: a pre-failure model and post-failure model. The post-failure model considers two stages: strain softening and residual state with two different property evolution laws.

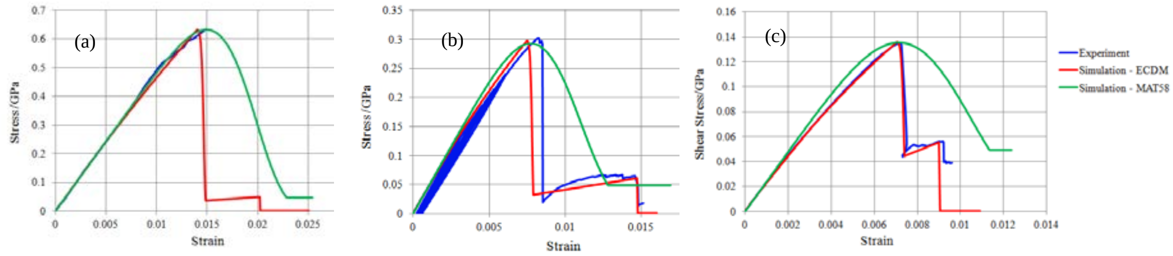


Figure 6. Comparison of experimental results with simulations using the ECDM model and MAT 58 for simple tension tests with (a) 0º, (b) 90º and (c) 45º triaxial braided composite specimens.

Shell-Beam Element

The thickness of automotive components are often relatively thin as compared to its in-plane dimensions. For computational efficiency, the thin-walled structures such as the front rail are usually modeled with shell elements in vehicle crash finite element models. However, axial crash simulations of composite tubes modeled with shell element have the tendency towards instability, particularly for tubes without a plug initiator. To improve the stability, a new type of element, the so-called shell-beam (SB) element, is designed, as shown in Fig. 7. A SB element is composed of 2 shell elements and 4 beam elements, which are connected by sharing the common nodes. In FE models, one layer of SB elements may be used to represent one composite layer, one lay-up block, or an entire laminate. The details about SB method can be found in [16].

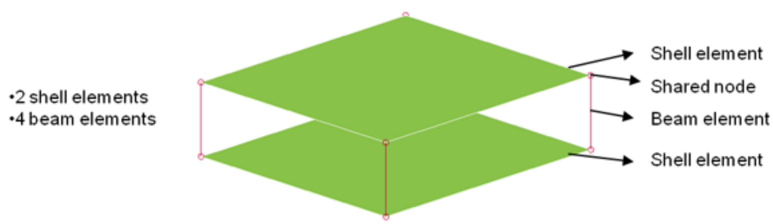


Figure 7. Schematic of the shell-beam element [16].

Tube Crash Simulations

The tube crash simulations of triaxial braided composites were performed by using ECDM and MAT58 with SB element. Figure 8 compares the crash frond morphology predicted by the two models with that obtained by experiment for a 2x2" tube of 2-ply triaxial braided composites with a plug initiator. Figure 9 compares the load-displacement curves. Without the irreversible strain, the crash front predicted by MAT58 was rather flat. With the irreversible strain, the crash frond predicted by ECDM model retained its curled shape which resembles the crash frond observed in experiments. The predicted total displacement also matched the experimental result better than MAT58.

Figure 10 compares the predicted SEA value, peak force, average crash force, and the crush length for two types of tubes with and without a plug initiator. Figure 11 compares the predicted failure morphology at the end of simulations with experimental results. The predictions matched the experimental results much better than those with MAT58 in Fig.3. The predicted failure morphologies of tubes of different configurations also closely resemble the experimental results.

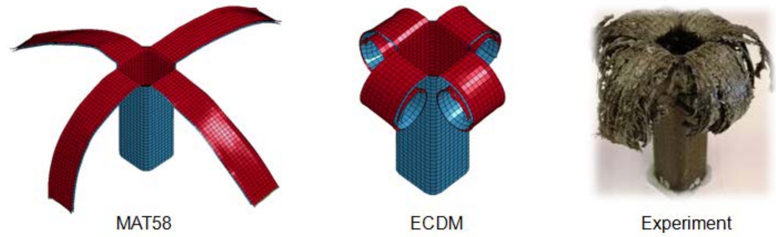


Figure 8. Comparison of the crash front morphologies predicted by MAT 58 and the ECDM model with the one obtained by experiment for a 2x2" tube of 2-ply triaxial braided composites with plug initiator.

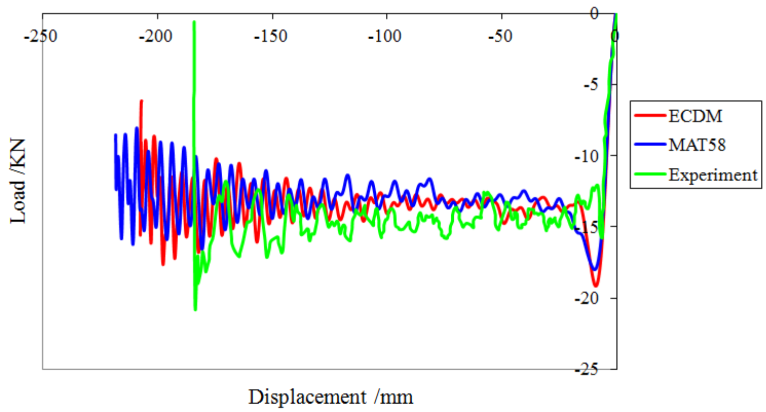


Figure 9. Comparison of experimental results with the predicted force-displacement responses using the ECDM model and MAT58.

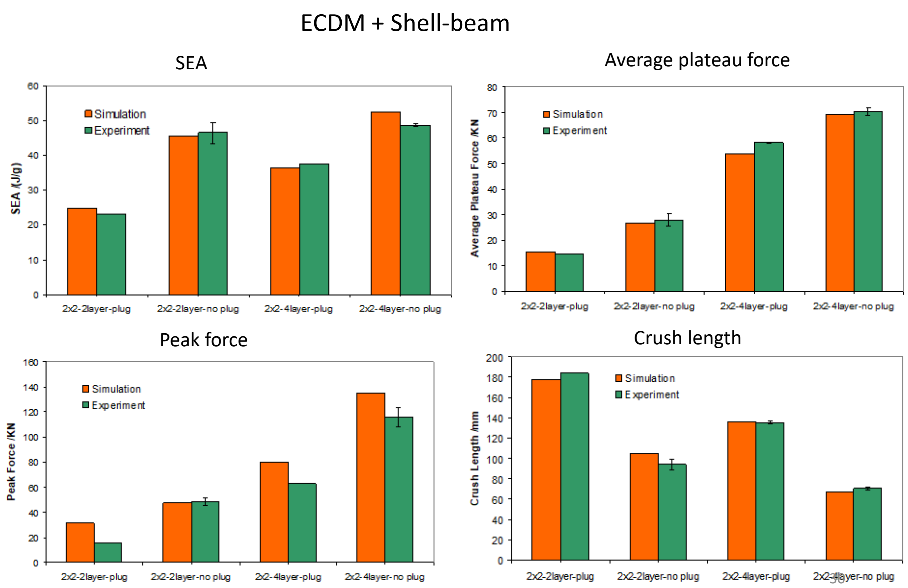


Figure 10. Comparison of predicted SEA, peak force, average crush force, and crush length for 2x2" tubes of 2-ply and 4-ply triaxial braids with and without a plug initiator.

Figure 11. Comparison of predicted failure morphologies with experimental results.

Conclusions

Crashworthiness prediction of composite structures requires material models to address not only the loading but also unloading stress-strain response of damaged materials. The classic continuum damage mechanics (CDM) models do not consider the irreversible strain and hence are deficient in such predictions. It has been shown previously that CDM models with modified unloading path or extended with irreversible strain can improve simulations significantly. Recent developments include an ECDM model and SB method. The ECDM model employs two separated sub-models to represent the pre- and post-peak regions which can accurately model the entire stress-strain curve. The SB method provides an efficient way to solve the instability issue associated with shells under axial impact. These developments significantly improved the robustness and accuracy of the axial crash simulations of composite structures.

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