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A new shell-beam element modeling method and its use in crash simulation of triaxial braided composites

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ABSTRACT

To overcome the instability encountered in axial crash simulations of composite tubes with shell elements, a new modeling technique: the shell-beam (SB) element method, has been developed. This method creates an element which is capable of deforming in the through thickness direction while retaining the efficiency of the shell elements. The SB element was evaluated with virtual one-element, cantilever beam and in-plane compression tests. The results showed that the SB element is effective in terms of overcoming the instability and convergence issues of traditional 2D and 3D discretized elements under in-plane compression. The SB element was further evaluated together with an in-house material model, called the enhanced continuum damage mechanics (ECDM) model, in crash simulations of triaxial braided composite tubes with five configurations and seven test conditions. The simulations captured both the failure morphologies and force-displacement responses obtained in experiments.

1. Introduction

Fiber-reinforced composites exhibit a higher specific energy absorption (SEA) than metals under axial crash loadings [1,2]. This makes composites an ideal candidate for lightweighting of crash energy absorbing structures, such as the front rail in vehicles. Although the automotive industry has been investigating the use of composites in vehicle crash energy management since late 80s [1,2], composites have not been widely used in primary vehicle structural components. Besides cost, a major obstacle is the lack of a robust and accurate composite crash simulation model.

During frontal crash, the front rail is subjected to axial crush loading. Since the rail usually has a tubular form, the axial crush simulation of composite tubes has become a benchmark to evaluate the predictive capability of composite crash simulation models [3–6].

A tube structure under axial crushing force may fail catastrophically or progressively, as depicted in Fig. 1 [7]. The progressive failure is preferred since it results in more stable crash and higher SEA. The SEA value is calculated by the area under the load-displacement curve divided by the mass of the crushed portion of the structure. A catastrophic failure may be caused by global buckling or rupture of the tube away from the crush front. To avoid these failure modes, the front end of the tube is usually chamfered to reduce the initial crush load and trigger progressive failure. To further improve the stability, a plug-type initiator may be used, such as the one shown in Fig. 2. The plug initiator provides a stable and highly controllable crash performance but results in a lower crush force and hence a lower SEA.

Fig. 2 illustrates the damage/failure processes of triaxial braided square composite tubes with and without a plug initiator under axial crush. In general, the failure started by damage and breakage at the chamfered edge, followed by tear/tensile rupture at the four corners, delamination, separation, and bending and splaying of the layers in composite tube walls. For tubes with a plug initiator, the layers were forced to bend outwards. Without a plug initiator, the layers bent both inwards and outwards and a debris wedge was formed at the crush front.

A number of studies have attempted to model composite tubes under axial impact [5–15]. These works reveal two major shortcomings in the current models: (1) the models rarely capture both the failure morphologies and force-displacement responses; and (2) the simulations have the tendency of instability, particularly when it comes to axial crash of composite tubes without plug initiators.

In reported works, few works were able to capture both the failure morphologies and force-displacement responses. For example, the simulations of McGregor et al. [10] and Xiao et al. [6] showed good correlations with the experiment in terms of the force-displacement responses but were unable to simulate the unique frond-like failure morphology in the crash front. On the other

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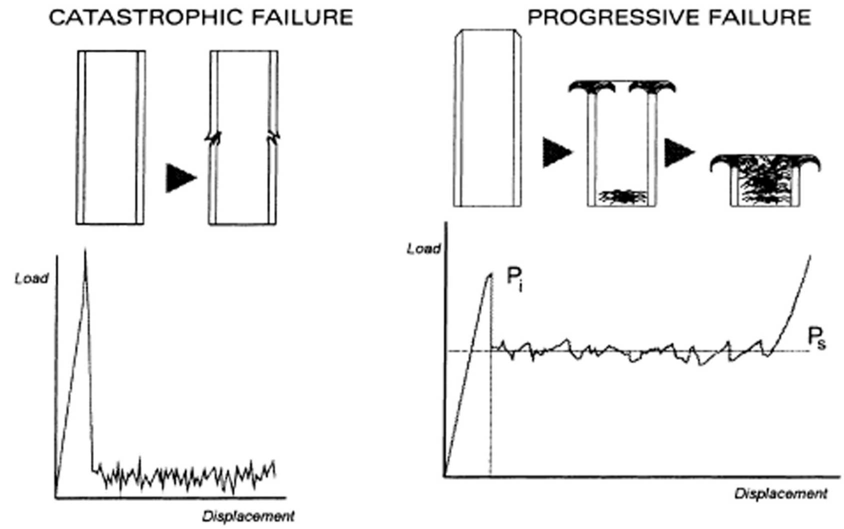

Fig. 1. Schematic of axial crushing with and without a trigger mechanism [7].

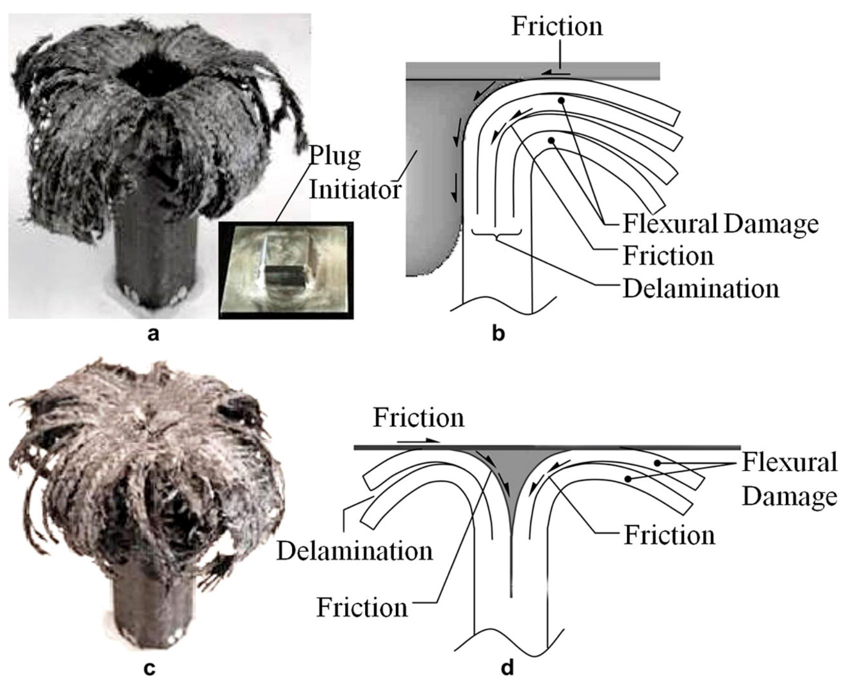

Fig. 2. Schematic of damage/failure mechanisms of braided composite tubes in the crash front with and without plug initiator [8].

hands, Mamalis et al. [13] were able to produce a stable, progressive splaying of the tube walls under static crushing but the predicted force-displacement response did not match the experimental results.

For computational efficiency, the thin-walled structures such as the front rail are modeled with shell elements in vehicle crash simulation models. To be compatible with vehicle simulations, the composite tubes are often modeled with a single layer or multiple layers of shells. 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, various fixes have been attempted, such as introducing an artificial debris wedge [8] to mimic the support as seen in Fig. 2; moving the nodes at the tube tip inwards or outwards to create an initial separation of the layers [16]; and etc. However, the simulated failure morphologies were still not satisfactory.

This work is aimed at developing a robust, accurate, and computationally efficient composite crash model. Towards this goal, improvements have been made in two aspects. To accurately describe the stress-strain behavior of composites under crash loading, an enhanced continuum damage mechanics (ECDM) model has been developed [17] and implemented in a commercial explicit finite element (FE) code LS-DYNA as a user material model. To improve the stability of models with shells, a new modeling technique, the shell-beam (SB) element has been proposed.

This paper presents the SB element and its evaluation through one-element, cantilever beam and plate crash tests, and tube crash simulations. The simulations were performed using LS-DYNA with ECDM for a triaxial braided composite. The selection of this particular composite is due to the availability of data. Braiding is one of the manufacturing techniques with the potential for high speed and high volume production. Thus, braided composite tubes have the potential to meet the low cost and high volume requirements