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A progressive intraply material deterioration and delamination based failure model for the crashworthiness of fabric composite corrugated beam: Parameter sensitivity analysis

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CDM
Continuum damage mechanics
SEA
Specific energy absorption
FEA
Finite element analysis
RVE
Representative volume element
FEM
Finite element model
CODAM
Composite damage

ABSTRACT

A high-accuracy progressive failure model based on continuum damage mechanics (CDM) is proposed to simulate the quasi-static axial crushing of composite corrugated beam. To predict various physical phenomena, both of the intra-ply damage and inter-ply interface damage are considered. The damages of intra-ply fiber and matrix are initiated with stress failure criteria and progressive damage propagation is modeled with a stiffness discount method and energy criteria. The deformation gradient algorithm is effectively used for the erosion of failure elements. Further, the delamination damage is predicted by a triangle traction-separation model with a mix-mode fracture energy criterion. To obtain insights into complicated failure mechanisms, a parameter sensitivity study is carried out to study effects of numerical parameters on failure responses, including element erosions, failure strengths, elasticity modulus, friction properties, etc. Results show that the established model correlates well with experiment on failure modes, impact loads and energy-absorbing characteristics. It is found that element erosion parameters are the most influential parameters for impact loads. The fiber compression strength and friction coefficients exhibit dramatic effect on energy-absorbing capability and failure modes of specimen.

1. Introduction

Advanced composite energy-absorbing structures offer many advantages over conventional metal materials due to higher strength and stiffness to weight ratio and specific energy absorption (SEA) [1–11]. As well as, they can dissipate massive amounts of impact energy through a combination of fracture mechanisms such as fiber fracture, matrix cracking, fiber-matrix debonding and delamination [12–20]. For this reason, various composite energy-absorbing structures have been more and more widely applied to aircraft, automotive, high-speed rail, marine, etc. [21–35]. Among them, composite corrugated beams with higher energy-absorption efficiency are gaining increasing attention in the applications of helicopter sub-floor and aircraft fuselage structures [27,33]. Considerable experimental works have been recently carried out to study the crashworthiness characteristics of composite corrugated beam under axial impact load [36,37]. However, there still exist some limitations to understand failure behaviors of composite

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corrugated beam through experimental study.

The finite element techniques as an effective method offer the opportunity to develop a numerical failure model, which can accurately simulate progressive failure process of composite. The complex composite behaviors can be effectively modeled with the constitutive failure models provided by several numerical studies [38–49]. It is also indicated that a constitutive failure model consists in different modeling strategies including failure initiation criteria, degradation scheme, material properties, etc. [41]. In the recent years, some numerical failure models have been established and used to analyze the failure behaviors of composite corrugated beam in order to understand the mechanisms. Feraboli et al. [50] utilized available material model (MAT54) to simulate damage progression of composite tape sinusoidal specimens and also discussed the sensitivity of various input parameters. The adopted failure model was based on degradation of strength property and 2D Chang-Chang failure initiation criterion [51], which was able to capture the load-displacement curve. Similarly, it was found that the same model (MAT54) was also adopted by Duan et al. [52] to investigate the structure optimization of composite sinusoidal specimens. However, the inter-ply failure behavior could be not predicted by the single shell model in Refs. [50] and [52], and thus failure modes failed to be captured.

To predict failures of fiber, matrix and particularly delamination failure, several studies on failure models of corrugated beam considering intra-ply and inter-ply failure have been recently conducted. A 3D damage model [53] for predicting the axial impact response of composite structure was validated by Chiu et al. [49], where the Puck failure initiation criterion and bilinear traction-separation considered in the model. Results showed that the simulated failure modes of frond, petal and delamination correlated well with experimental observations, but the peak and average loads were inaccurate. This discrepancy is mainly due to complicated failure mechanisms simulated by stacked shell model. Jiang et al. [54] used the exponential degradation model to investigate the trigger geometry of composite waved beam subjected to quasi-static axial crushing. In their works, the onsets of intra-ply and inter-ply failure were initiated with the maximum stress criterion and quadratic nominal stress criterion respectively. Results indicated that matrix debris and two types of inter-ply failure including middle delamination cracking and splaying were in agreement with experimental specimen. However, a higher initial peak load obtained from simulation was observed with an error of about 26.4%. Based on above studies, both of failure modes and load responses were not always predicted accurately. This is mainly attributed to that the impact response is highly sensitive to change in various input parameters and modeling strategies.

Due to the complexity of failure mechanisms, the prediction of failure behaviors of composite corrugated beam under the impact event is still a greatly challenging task. Thus, to obtain deep insights into complex failure mechanisms, there is an urgent demand for developing a high-fidelity failure model and further conducting a parameter sensitivity study to predict failure behaviors of fabric corrugated beam.

In the present work, a progressive failure model is proposed to analyze the failure behaviors of composite corrugated beam under axial quasi-static load. Based on CDM, failures of inter-ply delamination interface and intra-ply fiber and matrix are modeled by stress-based criteria, stiffness discount method and fracture energy criteria. To gain extensive insights into various mechanisms, a parameter sensitivity study is conducted to study effects of various parameters, including non-physical element erosion parameters, material properties and friction properties, etc., on impact responses. Through the sensitivity analysis, it is demonstrated that how the susceptive parameters influence simulation accuracy and impact responses of corrugated specimens.

2. Crashworthiness characteristics metrics

The performance of crashworthy composite structures can be mainly evaluated by several parameters including peak force (F_P), average crush force (F_{avg}), crush load efficiency (CLE), total energy absorption (EA) and specific energy absorption (SEA) [55]. Typical representation of a relative load-displacement plot is shown in Fig. 1.

- F_P is the highest force experienced during the crush event and has a direct correlation with the extent of potential injury to passengers.
- F_{avg}, or sustained load, is the mean force during steady-state crushing of the specimen and is a good indicator of the energy absorption capability of crashworthy structures.

$$F_{avg} = \frac{\int Fdl}{l} \tag{1}$$

where F is the crush force and l is the stroke.

- CLE is the ratio between F_{avg} and F_P, and is an important characteristic to evaluate the stability of crushing load. A high-energy absorbing crashworthy structure undergoes progressive failure where the peak force is not obviously higher than the average crush force.

$$CLE = \frac{F_{avg}}{F_P} \tag{2}$$

- EA is the total area under the load-displacement diagram.

$$EA = \int Fdl \tag{3}$$

- SEA, a critical assessment index of performance for energy-absorbing structures, is the energy absorbed per unit mass of crushed structure expressed in J/g.

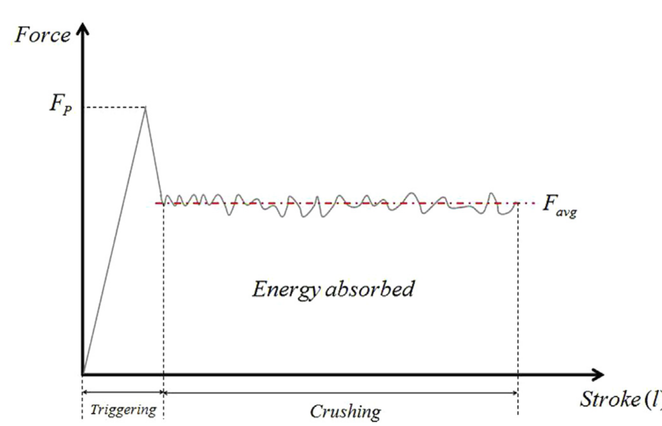

Fig. 1. Typical representation of a relative load-displacement plot.