Thin-Walled Structures 119 (2017) 531–543

Contents lists available at ScienceDirect

Thin-Walled Structures

journal homepage: www.elsevier.com/locate/tws

Full length article

# Research on the progressive damage model and trigger geometry of composite waved beam to improve crashworthiness

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## ARTICLE INFO

*Keywords:*
Damage model
Composite
Waved beam
Crashworthiness
Trigger geometry

## ABSTRACT

A nonlinear progressive damage model is proposed to predict the failure response of composite waved beam subjected to quasi-static axial crushing. To predict the failure model, both of the intra-laminar failure and delamination are considered. Based on continuum damage mechanics(CDM), the in-plane damage initiation is modeled with the maximum-stress failure criterion. To simulate the failed material, a stiffness degradation method combined with exponential damage evolution laws is adopted. A fracture-energy approach in conjunction with the characteristic element length is chosen to predict the damage evolution. The delamination initiation is given by a quadratic nominal-stress criterion. Considering the progressive delamination failure process, a cohesive stiffness degradation method and an exponential softening law based on a mix-mode fracture criterion are presented to predict the delamination propagation. To achieve better crashworthiness of composite waved beam, the wedge-trigger, two types of W-triggers and bevel-triggers with hybrid angles are proposed. Additionally, effect of the angle of chamfer-trigger on crashworthiness is investigated. Numerical results show that predictions correlate well with experimental results. Moreover, the present damage model can accurately capture intra-laminar and inter-laminar failure mechanisms. The proposed bevel-triggers perform significant effect in decreasing the peak load, and angles of chamfer-trigger make little difference in the crashworthiness.

## 1. Introduction

Crashworthiness can be defined as the ability of an aircraft to guarantee the safety of occupants in the case of potentially survivable accidents [1]. To improve the crashworthiness, composite materials, offering superior potential as absorbers, have been widely applied to crashworthy design of key aerospace structures due to their higher specific strength, specific stiffness and specific energy absorption (SEA) capability over conventional engineering materials [2–7]. A multitude of numerical researches have been already devoted to the crashworthiness of various composite structures, such as thin-walled conical frusta, fuselage frame, T-stiffened structure and tubular structures with square, circular and channel sections [8–18].

Composite waved beam structures, with high energy absorption efficiency, are considered as one of the most primary energy-absorbing components for application to aerospace. Failure mechanisms to dissipate energy and various failure modes of composite waved beam structures subjected to impact loading, including matrix cracking, fiber rupture, fiber/matrix interface debonding and interlaminar delamination, are very complex. In recent years, failure mechanisms and influencing parameters of the composite waved beam have been extensively investigated to improve the crashworthiness. Feraboli et al. [19] conducted a numerical investigation into a 2D progressive failure material model of composite tape sinusoidal specimens utilizing an approach developed by Chang and Chang [20]. Additionally, parametric studies were also carried out to analyze the sensitivity of input parameters in the model. Analogously, Duan et al. [21] utilized the material model [19] as well and investigated the optimization of composite corrugated beams in terms of thickness and radius to improve crashworthiness. Although the results of above numerical models correlated well with experimental results in terms of the average crush load and SEA, inter-laminar failure behavior was not considered in abovementioned modeling of impact on the composite waved beam. To simulate the delamination failure, Sokolinsky et al. briefly introduced a new finite element analysis (FEA) technology and a damage model related to the corrugated composite plate crush analysis in Ref. [22]. Then, they detailed the 2D nonlinear failure model of the corrugated composite plate subjected to quasi-static crushing in Ref. [23]. This stress criteria-based model comprehensively accounted for both intra- and inter-laminar failure mechanisms, and the stable progressive failure

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*Abbreviations:* CDM, continuum damage mechanics; SEA, specific energy absorption; CODAM, composite damage

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http://dx.doi.org/10.1016/j.tws.2017.07.004
Received 18 January 2017; Received in revised form 4 June 2017; Accepted 6 July 2017

process was given. Both the peak and average loads can be also predicted accurately, but the initial impact load was under-predicted. According to CDM [24], Chiu et al. [17] presented a combined failure criterion to simulate the material failure of composites. In the model, fiber- and matrix-dominated damages were predicted by Maximum Strain criteria and Puck criteria [25] respectively. Whereafter, Chiu et al. [26] utilized a 3D progressive failure model based on the combined failure criterion to analyze the failure behavior of composite corrugated beams subjected to crushing loads. Here, various failure modes were fully taken into consideration. The predicted damage morphologies, including large sections of petalling plies, small matrix debris and the splaying of the composite laminate, matched the experimental phenomena. However, there was still a difference between the simulated and experimental results in aspect of the peak and average crush loads. In general, the popular phenomenology-based damage models can not accurately predict the energy absorption characteristics and complex failure mechanisms of composite waved beams simultaneously. Therefore, it is essential to conduct extensive investigations into damage models for predicting the energy absorption characteristics and failure mechanisms of composite waved beams.

It has been well established that a triggering mechanism causes a progressive and stable failure in composite structures, which is crucial for enhancing the crashworthiness of structures [27]. Without an effective failure trigger mechanism, composite structures fail catastrophically while maintaining a high initial peak load and a low energy absorption capacity. As a result, the trigger geometry has been extensively studied for the purpose of reducing the initial peak load and maximizing the energy absorption capacity. Amongst recent published works in the area of the triggering mechanism, various kinds of trigger forms included tulip trigger, chamfer trigger, double-chamfer trigger, plug (crush-cap) trigger and, differently, combined trigger [28–31]. In particular, the chamfer failure trigger has been proved to be very effective at reducing the initial peak load, leading to a high average crush load followed by a high SEA [28,32]. Besides, Jiménez et al. [33] investigated the effect of trigger angle and type on the level of energy absorption of tubes with a box section. Above numerical studies on the triggering mechanism have been mainly focused on circular and square tubes, while there are much less data on composite waved beam structures [19]. In order to make further efforts for the improvement of the crashworthiness of composite waved beams, it is also necessary for extensive researches on the triggering mechanism.

The objective of the article is to present a nonlinear progressive damage model to predict the response and failure of triggered composite waved beam subjected to quasi-static axial crushing. The intra- and inter-laminar damages are considered to give better failure model. For intra-laminar damage, maximum stress based failure criteria are presented to predict the onset of various damage modes. Considering the progressive failure process, the softening behavior of material is controlled by a stiffness degradation method and an exponential damage evolution law. A fracture energy approach combined with the characteristic element length is chosen to predict the damage evolution. Additionally, the inter-laminar damage initiation is modeled with a quadratic nominal stress failure criterion. A cohesive stiffness degradation method and an exponential damage evolution law on the basis of a mixed-mode fracture criterion are adopted to predict the damage propagation. To achieve better crashworthiness of the composite waved beam, the wedge-trigger, two types of W-triggers and bevel triggers with hybrid angles are proposed. Afterwards, effect of the angle of chamfer-trigger on crashworthiness is investigated. Finally, some conclusions are drawn based on the results in detail.

## 2. Nonlinear progressive damage model

### 2.1. Intra-laminar damage model

Generally speaking, carbon fiber composites exhibit a brittle fracture behavior. Thus, the damage model does not take into account the plastic deformation. In the numerical modeling, this fabric-reinforced composite can be modeled as a type of homogeneous orthotropic material on account of its different fiber directions. A schematic representation of woven fabric is shown in Fig. 1. Additionally, the proposed progressive damage characterized by the degradation of material stiffness plays an effective role in the analytical prediction of fabric-composite material failure. By utilizing progressive damage theory, a constitutive damage model can predict damage initiation, damage growth and final failure of composite waved beams.

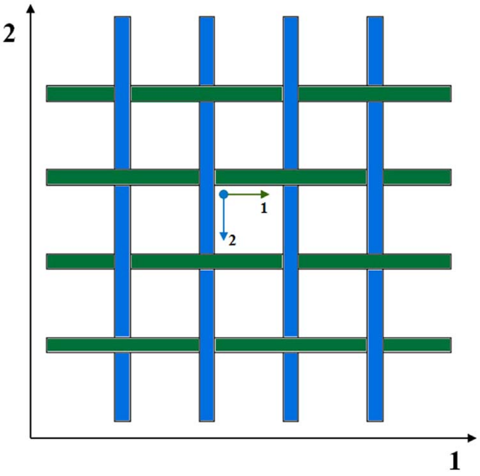

**Fig. 1.** A schematic representation of woven fabric.

#### 2.1.1. Constitutive law

Based on the continuum damage mechanics, a two-dimensional (2D) constitutive model [34] for fiber-reinforced composite exhibits an elastic-brittle behavior. The constitutive stress-strain relation with respect to three different damage variables are given by

$$\begin{bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{12} \end{bmatrix} = C(d_i)\cdot \begin{bmatrix} \varepsilon_{11} \\ \varepsilon_{22} \\ \varepsilon_{12} \end{bmatrix} \tag{1}$$

where $\sigma = \{\sigma_{11}, \sigma_{22}, \sigma_{12}\}^T$ and $\varepsilon = \{\varepsilon_{11}, \varepsilon_{22}, \varepsilon_{12}\}^T$ are the stress vector and the elastic strain vector respectively, while $C(d_i)$ is the stiffness matrix, varying with the damage variables ($d_i$) based on different damage modes.

$$C(d_i) = \frac{1}{D}\begin{bmatrix} (1-d_1)E_{11} & (1-d_1)(1-d_2)\nu_{21}E_{22} & 0 \\ (1-d_1)(1-d_2)\nu_{12}E_{11} & (1-d_2)E_{22} & 0 \\ 0 & 0 & D(1-d_{12})G \end{bmatrix} \tag{2}$$

where $D = 1-(1-d_1)(1-d_2)\nu_{12}\nu_{21} > 0$, $E_{11}$ and $E_{22}$ are the Young's moduli in the principal orthotropic directions, respectively. $G$ is the in-plane shear moduli. $\nu_{12}$ and $\nu_{21}$ are the principal Poisson's ratios. $d_1$, $d_2$ and $d_{12}$ are the damage variables associated with fiber failure, matrix failure and in-plane shear deformation, respectively.

#### 2.1.2. Damage initiation

It is well known that the damage initiation criterion for intra-laminar damage is used to predict the onset of material degradation. The anisotropic damage material model considers the following five damage initiation mechanisms including fiber tension and compression failures, matrix tension and compression failures as well as in-plane shear failure. The well-known maximum stress failure criteria are adopted to predict the point of five damage initiations by comparing the effective stress to the damage initiation stress. These damage initiation criteria have the following general forms.