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Design of novel plug-type triggers for composite square tubes: enhancement of energy-absorption capacity and inducing failure mechanisms

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ABSTRACT

To improve their energy-absorption capacity and induce failure mechanisms, the plug-type triggers of composite square tubes are designed and compared. A progressive failure model verified by the axial quasi-static loading test is proposed. Six different plug initiators including circle convex plug initiator, two types of square convex plug initiators, two types of groove-like plug initiators, and ditch-like plug initiator are given. To understand the triggering mechanism, the crashworthiness of chamfered square tubes is compared. Further, the influence of width of ditch plug-initiator towards energy-absorption characteristics and failure modes is investigated. Results show that well agreements in the failure and energy-absorption mechanisms between the simulation and experiment are identified. Three types of convex plug initiators can reduce the initial peak load and induce the out-ward petaling and splaying mode. The progressive inward-folding mode is similarly triggered by both two groove plug initiators. The ditch plug initiators are recommended as the best plug design with reasonably induced failure modes and an increase of 31.9% in total energy absorption. Comparing with non-plug initiator, square tubes crushed by narrower ditch plug initiator possess higher energy-absorption capacity, with an increase of 51.9% in SEA.

1. Introduction

Due to the high strength and high specific energy absorption (SEA), crushable composite structures (e.g., corrugated plate, square tube, conical frusta, etc.) are considered as exceptionally efficient energy-absorbing components for application to aerospace and automotive engineering [1–10]. Under the collision event, these structures can dissipate a large amount of impact kinetic energy by multitudes of coupled failure modes of matrix cracking, fiber failure and delamination so as to guarantee the safety of occupants [11–14]. Hence, the higher total energy absorption coupled with lower initial peak load should be obtained as much as possible to prevent the catastrophic collapse and maintain the interior of the structure under a survivable crash or impact. Recently, a large number of relevant studies on the energy-absorbing mechanism of composite structures have been performed to improve the energy absorption capacity and reduce the initial peak load [15–21]. All of investigation results demonstrate that the energy-absorbing mechanism of composites mainly depends on the reasonable stacking sequence and structure configuration, material properties, loading condition and triggering mechanism, etc. Among these influential design variables, the triggering mechanism is generally perceived as one of the most critical influence factors for crashworthy performance [22].

By employing an appropriate trigger directed against different structures, it is capable of effectively avoiding the loads transfer to the whole structure due to localized failure caused by the stress concentration. It is further in favor of preventing structures from crushing catastrophically and inducing a progressive failure mode post-crushing to maximize the energy absorption. Accordingly, extensive researches on different trigger configurations, such as bevel trigger, tulip trigger and other weak geometries, have been recently carried out [23–25]. Typically, Jimenez et al. presented an experimental study on the energy absorption capability of two different triggered composites profiles, including bevel and tulip of box-section and I and H of I-section [21]. Comparing with the

Abbreviations: SEA, Specific energy absorption; FEM, Finite element model; EA, Energy absorption; CCP, Circle convex plug initiator with concave surface; SCP-C, Square convex plug initiator with concave surface; SCP-B, Square convex plug initiator with bevel surface; SGP-C, Square groove plug initiator with concave surface; SGP-B, Square groove plug initiator with bevel surface; SDP, Square ditch plug initiator; SCP, Square convex plug initiator; SGP, Square groove plug initiator.

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box section, results showed that I profile decreased energy absorption capability by 15% and peak crush load by 60%, which was regarded as the best candidate for absorbers. Results also indicated that slight modifications as the bevel angle of a bevel trigger could lead to significant variations of the results. Similarly, two types of trigger profiles were also incorporated to experimentally investigate the influence of trigger on the energy absorption of circle and square tubes by Palanivelu et al [26]. It was concluded that the type of 45° chamfer around the edge of the tube could absorb more energy than the type of tulip trigger. An increase of 7%-9% in SEA for chamfered circle tube, compared to tulip type, was recorded. However, in case of square tube, the tulip trigger yielded 16.5% higher SEA than chamfer trigger. In addition to the self-contained trigger, another triggering mechanism that is an external component is also compatible to energy absorbers. Eshkoor et al. examined the crashworthiness characteristics of woven natural silk/epoxy composite tubes with an interesting metallic pieces trigger in Refs. [27–29]. Failures induced by the plug-type trigger, on the other hand, might be more effective on crushable components. Eshkoor et al. [27–29], Xiao et al. [30] and Mcgregor et al. [31] studied the axial crushing behavior of composite rectangular tube with the outward plug initiators. Experimental results showed that plug initiators that caused an outward splaying of tube reduced an amount of peak load value. Additionally, an extra inward-folding crush-cap was further considered in the crushing of composite square tube and reported in Siromani's study [22]. Different from aforementioned plug initiators, Rezaei et al. experimentally studied the axial splitting process of foam-filled circular composite tubes relatively crushed by an external and an internal conical die [32]. Based on discoveries of plug initiator study, it was clearly demonstrated that different geometrical plug-type triggers could effectively induce various failure modes of composite absorbers and further improve the crashworthiness.

In the applications of engineering structure, the type of chamfering was usually put as the preferred trigger thanks to the simple machining procedure. Consequently, numerous experimental and numerical studies on the failure behavior of plate-type and tubular composite energy-absorbing structures with the chamfer trigger and even double-chamfer have been reported [33–35]. For example, Sokolinsky et al. presented a physics-based finite element model (FEM) of a corrugated carbon-epoxy fabric composite plate chamfered by 45° bevel under quasi-static loading condition [36]. Results showed that the numerical prediction followed with experiment, confirming the validity of FEM. The failure of the carbon/epoxy fabric composite square tube with 45° chamfer trigger was studied in Ref. [38], indicating that fiber fracture and tearing at each corner are responsible for the vast percentage of energy absorption. It was additionally found that the material properties used in this square tube specimen were almost consistent with materials of corrugated plate specimen in Ref. [36], merely with slightly differences. However, comparing their energy-absorption capacity, it could be surprisely found that the average SEA corresponding to square tube was only about 36.9 J/g, which was much less than that of corrugated plate (approximatively 87.7 J/g). It is highly unacceptable that the square tube providing a remarkably lower energy absorption capability relative to the corrugated plate. Therefore, there is an urgent demand for enhancing the energy absorption capability of the composite square tube as great as possible through deeper researches on the trigger design to understand the triggering mechanism.

In present work, six different plug-type triggers are designed in detail and numerically analyzed to identify the energy-absorption capacity and induced failure modes of composite square tube. Here, circle convex plug initiator with concave surface, square convex plug initiators with bevel and concave surface, square groove plug initiators with bevel and concave surface, and square ditch plug initiator are mainly considered. The axial quasi-static loading test of composite square tube is firstly used to validate the crushing failure model. Using the verified model, the energy-absorption capacity and failure modes of composite square tube with six plug initiators are numerically evaluated. Furthermore, the effect of width of ditch plug-initiator on energy-absorption characteristics and failure modes is detailedly discussed. The pivotal findings obtained from this study can aid in forming a valuable guide for designing trigger of crushable composite energy absorbers.

Table 1
Material properties of the TORAYCA T700/2510 fabric for square tube.

Description/Property	Square tube [38]
Modulus in 1-direction/E_{11}	55.8 GPa
Modulus in 2-direction/E_{22}	54.9 GPa
Shear modulus/G_{12}	4.2 GPa
Poisson's/ν_{12}	0.043
Tensile strength in 1-direction/X_T	910.1 MPa
Compressive strength in 1-direction/X_C	710.2 MPa
Tensile strength in 2-direction/Y_T	772.2 MPa
Compressive strength in 2-direction/Y_C	703.3 MPa
In-plane shear strength/S	131 MPa

2. Crashworthiness criteria

The typical load-displacement curve and optimized load-displacement curve of structure impact are shown in Fig. 1. Composite tubular energy-absorbing structures are able to absorb large amounts of impact kinetic energy to protect the safety of passengers under the impact event. The energy-absorption capability and impact performance of crushable structures can be evaluated by several typical crashworthiness parameters, such as initial peak load ($P_{\max}$), average load (F_{avg}), total energy absorption (*EA*) and specific energy absorption (*SEA*).

$P_{\max}$ is the maximum crushing load during the impact process but a harmful parameter, which is related directly to the safety of structure and passenger. Thus, reducing $P_{\max}$ as much as possible must be taken into account. From Fig. 1, it shows that the purpose of decreasing $P^1_{\max}$ to $P^2_{\max}$ is deemed as an important design requirement of crushable structure. In order to reduce $P_{\max}$, it is an effective method to introduce the triggering mechanism.

F_{avg} is the average sustained load, mainly determining the total energy absorption which is the area under the load-displacement curve. Thus, F^1_{avg} is usually expected to be increased to F^2_{avg} so as to further increase *EA*, as shown in Fig. 1. For increasing F_{avg}, the triggering mechanism also allows for the induction of progressive failure modes and improvement of impact load.

SEA is the absorbed energy per unit of the crushed structure mass, regarded as the most critical crashworthiness parameter to assess the energy-absorption capability of structure.

$$SEA = \frac{EA}{m} \tag{1}$$

where m is the total mass of crushed materials.

3. Experiment and specimen

The present work primarily investigates the energy-absorption capability and failure mechanisms of composite square tube structure with the triggering mechanism under the axial quasi-static loading condition. The crush experiment of square tube structure is provided by Ref. [37] and the material properties of specimens fabricated by the T700/2510 carbon fiber/epoxy fabric are directly obtained from Ref. [38], which is tabulated in Table 1.

The dimension of square tube specimen is given in Fig. 2. From Fig. 2, the length H of each square tube specimen is 88.9 mm and the inner radius r of tube is 4.45 mm. The cross-section has outer dimensions is $L1 \times L1 = 63.5$ mm. It consists of 16 plies with a stacking sequence of $[0/90]_{4S}$, and is 1.65 mm thick. At the bottom end of each square tube specimen, it was machined with a single-sided 45°-chamfer to facilitate stable crushing. The crush test was performed at an axial quasi-static