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Analytical and numerical analysis of composite impact attenuators

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ABSTRACT

Recently automotive crashworthiness trend is the use of thin-walled composite impact attenuators in specific vehicle zones, ensuring the greater quantity of kinetic energy absorption. The paper aims at developing an analytical procedure in order to capture the energy absorption capability of impact attenuators with a square frusta geometry to adopt in the front of a car. An energetic approach is addressed taking into account the energy contributions responsible for the absorption during crushing. Comparison between analytical and numerical data, using an explicit dynamic code as LS-DYNA, shows the efficiency of the proposed relatively simple model for predicting energy absorption of axially collapsing composite shells.

1. Introduction

Recently many efforts have been done to minimize automobiles energy consumption due to the increasingly stringent limits in terms of environment respect and passive safety. The most efficient solution seems the adoption of innovative light materials which can absorb the energy required to achieve an impact at an acceptable level of deceleration. Tests have shown that composites generally are good at absorbing energy with an almost constant crush load, since several different failure mechanisms (fiber breakage, matrix deformation and cracking, fiber debonding and pull-out, delamination) can occur simultaneously. Therefore composites are good candidates in crashworthy applications for automotive, thanks to their lightweight, high strength, corrosion resistance and easy manufacturing [1]. However it is important for such structures to be designed in such way that they fails in a stable progressive manner, in order to absorb much higher kinetic energy than if it fails in an unstable crushing (such as buckling, interpenetration or barreling) [2].

Composites are materials that combine two or more materials, commonly told matrix and reinforcement, that have quite different properties. When combined, they offer properties which are more desirable than those of the individual materials. Composites can be categorized by filler types. The matrix materials are reinforced by fillers in the form of single-crystal whiskers, platelets, long fibers, short fibers, small particles, precipitates or a combination of any of these. In such analysis the attention will be on the fiber reinforced polymer (FRP) composites. Fibers are the principal load-carrying members in FRP composites. Glass and carbon fibers are the most common mineral reinforcing fiber used today. Recently many efforts have been done in order to reduce vehicle weight, substituting structural parts made of conventional material with composite one. In [3–7], the roof, the floor segments, the body panels, the frame parts, the battery access door and the seating systems have been made of glass fiber reinforced plastic (GFRP) composites so that the weight has been reduced from 40% to 60% and the performances has been improved compared to conventional solutions. Lately, in [8–12], metallic components for crashworthiness applications have been made of carbon fiber reinforced plastic (CFRP) composites. Differently from GFRP, due to the low density, high specific strength, impact resistance and high cost, CFRP are more commonly used in high performance automobiles.

Most members of the vehicle body-in-white structure are thin-walled steel columns. Many experimental studies attest that thin-walled tubes of square and circular section are the most weight efficient solution for crashworthy aspects, having high-energy absorption capability in compression and impact loading conditions. Composites are known as high specific energy absorption (SEA) materials. CFRP composites have, in fact, 3–10 times higher SEA than steel materials [13]. Thornton et al. in [14] studied the behavior of various composite tubes, considering different fiber types, lay-ups and thickness to diameter ratio. Their experimental results illustrate that rectangular and square sections are less effective in energy absorption than circular ones. Hull et al. [15] extensively addressed failure mechanisms for composite tubes, commenting upon the influence of geometry and material composition on structural performance. Farley and Jones [16] discussed the effect of crushing velocity on the energy absorbing characteristic of composite tubes with different lay-ups. In the Mamalis et al.

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book [17] many results done on composite tubes with different sections under various loading conditions are summarized. According to the experimental observations discussed in [17], thin-walled structures under axial loading can deform in four different modes: deformation confined at impact wall (Mode I), longitudinal crack progression (Mode II), centrally confined circumference crack (Mode III), large hinge progressive folding (Mode IV). It is challenging to arrange the column of material such that the destructive zone can progress in a stable manner (Mode I) due to the large amount of crush energy absorption. It is fundamental to estimate the mean load of crushing while choosing a material and geometry for an impact energy absorbing application.

As far as the crashworthiness design, information about the crushing force and the final deformation of such structures subjected to axial loading are necessary to pass specific homologation tests. Lately many experimental studies have been combined with numerical analysis to predict the final deformation of such composite structure for various applications: progressive damage in braided composite tubes [18], structural components of a Formula 1 racing car [19], crash-boxes for automotive application based on advanced thermoplastic composite [20], BAR Honda rear impact structure [21], certification of the composite rimp energy absorber for a star Mazda series [22], composite helicopter cruciform elements [23], composite frontal crash-box for a Formula SAE car [24]. But, as far as the author are aware, very few authors analyzed the collapse mechanism of composite shells from the theoretical point of view [17,25–28], due to the difficulty to analytically model the brittle behavior and heterogeneity of these composite structures. In particular, Mamalis et al. model the crumpling and bending process of thin-walled components of fiberglass materials with different shapes, taking into account the energies involved in total axial crushing. Velmurugan et al. instead adopt a simpler analytical approach considering only the first load cycle. Each analysis simplifies the energy formulation using some experimental evidences.

The present study addresses an analytical and numerical investigation on the progressive crushing of thin-walled composite square frusta under axial loading with the attempt to predict, with a good level of accuracy, the mean loads and the total displacements during collapse. The analysis is based on previous research [17,25–29] on similar structures in order to improve the mathematical modeling reducing some simplifications dictated by experimental evidence. The theoretical modeling is based on an energetic approach, identifying the main energy contributions responsible for internal absorbing and balancing them to the work done by the external load. During the crushing, after the initial peak, the load oscillates around a mean load. This is due to the arise of a main circumferential intrawall crack, the splaying of the material strips, the formation of two lamina bundles bending inwards and outwards and the generation of a triangular debris wedge of pulverized material. Comparison between analytical and numerical data, obtained using a non-linear dynamic code as LS-DYNA, in terms of mean loads and total crushing is satisfactory; despite the complexity of the phenomenon and the simplifications adopted, the analytical model is able to reproduce with a level of accuracy greater than 90% the energy absorbing capability of such composite structures under axial loading.

2. Crashworthiness aspects in the front module of a vehicle

A vehicle deceleration history with a desired characteristic of progression is the main goal of the vehicle body structure crashworthiness design [31]. Differently from a passenger vehicle, a formula racing car engine is located in the rear part of the vehicle so the impact velocity is high. The design of an impact attenuator of a formula racing car, whose energy absorption is made by a sacrificial front structure, can be very similar to an electric vehicle one since the electric devices are located in the rear part of the vehicle. Figs. 1 and 2 show the front structure of a nowadays car and an innovative electric vehicle, respectively. In particular in Fig. 1 a conventional impact module is placed between the front bumper and the passenger compartment, while in Fig. 2 an innovative square frusta structure is located in the front module of an electric car.

As it is obvious, the passenger compartment should remain undeformed and not intruded into as possible, therefore the behind structure does not provide any absorbed energy contribution. The classic front module of a car generally is composed of four longitudinal thin-walled beams, two for each side of the vehicle; two are placed in the upper part of the engine compartment, just below the hood, and two of bigger dimensions at an intermediate height behind the bumper. Recently, a crash-box, responsible of absorbing energy in case of impact at low velocity thus avoiding large structural damage to the other parts of the front structure, is located at each side of the front extremity of the two main beams. Just behind the front bumper there is a transverse front beam which locates and supports bumper and it is connected at its extremities to the longitudinal main beams.

A crucial consideration to take in mind dealing with a front impact module as the one in Fig. 2 is that under axial loading the process of crushing heavily depends on the structure material, and in particular in composites it is brittle and complex associated with their heterogeneity. As examined in literature, square frusta modules fail in four major modes, depending on structural dimensions, material properties and testing conditions. A composite impact attenuator is designed to produce a Mode-1 crushing mechanism, thanks to its advantage to guarantee the highest energy absorption which may be described as a ''mushrooming'' or fountain failure (Fig. 3a). A typical force–displacement curve of axial crushing can be seen in Fig. 3b. Usually there is an initial force peak, followed by stable crushing where the force are kept at an almost constant level. The initial peak is higher since no failure modes have yet been triggered. The zone between the force peak and the stable crush zone is called the transition zone. The transition zone is highly dependent on how the crushing is triggered. The constant force in the stable crush zone makes the deceleration of an impacting object constant. This, together with the high stiffness-to-weight ratio, is what make composites good in applications where a crashworthy structure is important.

3. Composite square frustum: analytical model

In this section a progressive collapse of a square frustum maintaining a constant crushing strength throughout the crushing process and ensuring the highest energy absorption is analyzed.

As in [29], the total crush procedure can be obtained repeating the first single crush cycle choosing suitable frustum side width at

Fig. 1. Classic front module.

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