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Review

On the crashworthiness performance of thin-walled energy absorbers: Recent advances and future developments

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A R T I C L E I N F O

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A B S T R A C T

Over the past several decades, a noticeable amount of research efforts has been directed to minimising injuries and death to people inside a structure that is subjected to an impact loading.

Thin-walled (TW) tubular components have been widely employed in energy absorbing structures to alleviate the detrimental effects of an impact loading during a collision event and thus enhance the crashworthiness performance of a structure.

Comprehensive knowledge of the material properties and the structural behaviour of various TW components under various loading conditions is essential for designing an effective energy absorbing system.

In this paper, based on a broad survey of the literature, a comprehensive overview of the recent developments in the area of crashworthiness performance of TW tubes is given with a special focus on the topics that emerged in the last ten years such as crashworthiness optimisation design and energy absorbing responses of unconventional TW components including multi-cells tubes, functionally graded thickness tubes and functionally graded foam filled tubes.

Due to the huge number of studies that analysed and assessed the energy absorption behaviour of various TW components, this paper presents only a review of the crashworthiness behaviour of the components that can be used in vehicles structures including hollow and foam-filled TW tubes under lateral, axial, oblique and bending loading.

1. Introduction

The demand for advanced transportation in modern society is increasing on a daily basis. This has led to continuously increasing numbers of vehicles on the roads. Inevitably, vehicular crash accidents have also increased and have become a major worldwide health problem. For better safety circumstances, vehicles' structures should be able to protect occupants through converting most of the kinetic energy during a crash situation into other forms of energy in a predictable and controllable fashion. The capability of a structure to manage and absorb the force of a serious crash and to reduce death and injury risk of the occupants is known as crashworthiness [1,2]. Thus, a crashworthy design has become the main safety criteria of the occupants-carrying vehicles such as aircraft and vehicles. The most popular form of collapsible energy absorbers, that are widely used to absorb the kinetic energy and to improve the crashworthiness behaviour of a structure, is TW components. The common use of TW components as energy absorbing devices is due to many important aspects including superior performance under dynamic loading, cost-effective, high efficiency, ease of manufacturing and installation. Thin-walled energy absorbers were employed in many applications including aircraft subfloor structures [3], front structures of cars and trains [4], Rollover Protective Structures (ROPS) of heavy equipment used in agriculture and construction, such as earthmoving machinery and tractors [5].

The principal factors that affect the energy absorption capability of such TW components are material, structural geometry and loading mode. The most used materials for manufacturing the thin-walled energy absorber are metallic, such as aluminium alloy and mild steel, and Fibre Reinforced Composites (FRCs). The energy dissipating mechanisms of metallic and composite structures are considerably different. The structures made from composite materials are normally brittle and dissipate energy through different combined fracture mechanisms such as delamination, fibre breakage, and matrix cracking, [6], whereas the ductility nature of metallic structures allows them to dissipate energy through progressive plastic deformation.

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Composite materials have gained increasing popularity in crashworthiness applications due to their high specific strength, high specific stiffness and excellent energy absorption performance.

The composite structures absorb greater energy per unit mass (SEA) than the metallic structures such as mild steel and aluminium [7]. However, the design and analysis of composite energy absorbers are difficult due to anisotropic properties of composite material [8]. Also, the composite structures have an environmental effect as it is very challenging to recycle the used composite materials [8]. Additionally, the manufacturing cost of the composite materials is relatively higher than the metallic structures and this has limited their application to specific fields such as aerospace structures and race cars. Many researchers have also used hybrid structures that include both types of material, i.e. metallic and composites, to absorb a greater amount of energy such as composite wrapped thin-walled metal tubes or tubes reinforced with externally bonded fibres [8–13,14]. The hybrid structures combine the desirable properties of each material, the high ratio of strength to weight of the composites and ductility and stable plastic deformation mode of the metals [11]. This paper focuses mainly on the energy absorption behaviour of metallic structures due to their common use as energy absorption devices in the vehicle body and their favourable stable plastic deformation. Expanded and detailed information on the energy absorbing behaviour of composite structures can be found in [1,6,15,16].

The energy absorbing behaviour of metallic TW tubes has received a significant amount of research in the last four decades. The main findings were reported in many review articles and books including those authored by Olabi et al. [17], Alghamdi [18], Abramowicz [19], Qiu and Yu [20], Lu and Yu [1] and Jones [2]. Generally, there are various crushing or loading situations through which metallic thin-walled tubes can be deformed plastically and absorb kinetic energy; the most common situations include axial crushing [21], lateral indentation [22–24], lateral compression [25], tube inversion [26–30], and tube splitting [31–36]. Each one of these crushing situations is associated with one or more deformation modes that play a main role in the energy dissipation process and lead to various energy absorption responses. Energy absorbing performance of thin-walled metallic components can be highly enhanced by using a filler material. The most common filler materials proposed in the literature include polymeric foams such as polystyrene; and metallic foams such as aluminium foam. Recently, glass fibre reinforced polyamide has been also reported in many studies as a filler material [37–39,40].

The design and analysis of an energy absorber are normally performed using experimental and computational techniques, such as finite element method. The computational technique is very effective and efficient tool particularly for conducting the parametric analysis. Models that can describe the energy absorption responses of structures are of great importance for analysing the performance of energy absorbing structures and they can be developed using different methods such as theoretical, empirical, and statistical methods. The theoretical models are established by observing the experimental collapse mode, simplifying the deformation mechanism, adopting some limited assumptions, and employing structural plastic analysis technique [41,42]. On the other side, the empirical modelling is based on observations and experimentations rather than theory where the empirical expressions are derived by employing linear or nonlinear multivariable regression analysis on experimental or FE results [43,44]. Finally, the statistical method employs the design of experiment approach for constructing an approximate model, such as response surface model (RSM), of energy absorption responses using the values of these responses at predefined sampling points [45–47].

In the last few years, the vehicle crashworthiness design has witnessed dramatic progress represented by using TW tubes with unconventional shape and materials as well as utilising new techniques for analysis and optimisation of such components. The aim of the present paper is to review the energy absorbing and crush responses of the most common thin-walled components used as energy absorbers in the automobile industry. The main focus of this review is on the axial, lateral and bending deformation of hollow and foam-filled energy absorbers that made from a metallic material such as mild steel and/or aluminium. Those energy absorbers made from composite materials or crushed through inversion or splitting deformation modes are considered to be beyond the scope of this paper due to the fact that they are not commonly used for a vehicle body. This paper is structured as follows, in the first section; a complete review of the metallic energy absorbing components under axial, lateral and bending loading is given. The second section presents the foam-filled components along with the effect of filler material on the energy absorbing performance of structures. The crashworthiness optimisation methodology and various optimal configurations of thin walled structures are introduced and summarised in the third section. Finally, the opportunities for future developments in the area of structural crashworthiness are reported.

2. Hollow thin-walled energy absorber (HTWEA)

2.1. Dynamic behaviour of metallic materials

The crash components of a road vehicle are mostly manufactured using a metallic material such as aluminium alloy and mild steel. Aluminium structures are considered very effective for developing the lightweight vehicle.

The mechanical properties of the absorber's material, such as yield stress and strain hardening behaviour, play an important role in the crashworthiness behaviour. Metallic materials are normally sensitive to loading rate where their mechanical properties under dynamic loading are different from those observed under quasi-static loading. It should be noted that the material's strain rate sensitivity is a material property and is independent of the geometrical factors of the TW tube [2]. The dynamic behaviour of metallic materials has been substantially investigated and almost a complete understanding has been established. A summary of the studies and findings on the dynamic response of materials that are most relevant to the crashworthiness topic is presented in Table 1. It is evident from this table that the plastic behaviour of the most metallic materials including mild steel, aluminium and magnesium alloys is highly sensitive to strain rate. Such materials exhibit an increase in yield and ultimate stresses as the strain rate increases. The strain rate sensitivity behaviour of a material manifests itself as a strengthening effect in a TW component [2]. It has been considered that material strain rate sensitivity is a beneficial phenomenon since it allows the material to achieve a greater energy absorption capacity when it is loaded dynamically [2]. In practice, strain rate effects are usually included in the analysis by using dynamic plastic flow instead of static plastic flow stress. The dynamic plastic flow stress could be calculated using a Cowper-Symonds equation as follows

$$\sigma_d = \sigma_s\left(1 + \left(\frac{\dot{\varepsilon}}{D}\right)^{\frac{1}{q}}\right) \tag{1}$$

where σ_d is the dynamic flow stress, σ_s is the static yield stress, $\dot{\varepsilon}$ is the strain rate, the constants D and q are parameters of the material.

Understanding the dynamic behaviour of material is essential for formulating or selecting a proper constitutive equation which can describe the indispensable relation between the strains and the stresses; and can be implemented in a numerical code for modelling purposes. Various constitutive models for the strain-rate-sensitive behaviour of materials have been proposed in the literature. The main constitutive equations that are applicable to metallic materials include Cowper-Symonds model, Johnson-Cook model, Zerilli–Armstrong (ZA) model, Bodner–Partom (BP) model, Khan–Huang (KH) model. Many experimental tests are required in order to obtain the various coefficients in these constitutive equations. A detailed review of these constitutive