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Novel strategy using crash tubes adaptor for damage levels manipulation and total weight reduction

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ABSTRACT

Absorbing energy by crash tubes has been extensively employed in many applications to improve the crashworthiness of the structure. This paper proposes Piecemeal Energy Absorption (PEA) as a novel proposed strategy to perform crashworthiness in a gradual way. PEA is implemented by crash tubes adaptor, whilst this adaptor is composed of nested pieces. Based on geometrical dimensions of the nested tubes, PEA strategy generates lower damage under lower impact velocity and higher energy absorption under high impact velocity to improves the crashworthiness of the protected structure. The novel strategy is validated by numerical and experimental methods. Furthermore, PEA flexibility and capability are illustrated by implementing the strategy in two popular applications (subway buffer and UAV landing gear). Due to the generality and applicability of the proposed PEA strategy, it is recommended to replace existing vehicles absorbers in order to manipulate the damage levels, along with considering PEA roles in new crashworthy designs leads to redistribute and reduce the whole internal protected structure masses.

1. Introduction

Crashworthiness can be defined as the ability of a structure to protect itself and its occupants from serious damage, injury or death when subjected to an impact load. More recent attention has been paid to the provision of crashworthiness as an essential requirement in the design of vehicles structure. Crash tubes that absorb kinetic energy through plastic deformation have been extensively employed in many applications to improve the crashworthiness of the structure [1–3]. The literature has emphasized the widespread use of crash tubes as energy absorbers is due to their good performance under dynamic loading, availability, low manufacturing cost, and efficiency [4–7]. Although circular shaped crash tubes have been used for a long time, a significant amount of research has been conducted recently on the energy dissipated by circular crash tubes in addition to studying the corresponding mechanisms such as corrugated and sinusoidal circular crash tubes subjected to axial loading [8–12], reinforced circular crash tube [13–16] and, circular crash tubes subjected to lateral loading [17–21].

There is an unambiguous recent appearance of nested crash tubes as a special case of multi-cell crash tubes for their outstanding performance as potential energy absorbers [22–26]. According to many observations in this field, nested tubes configuration is easier in manufacturing compared with other multi-cell sections. The efficient dynamic behavior of internally nested tube systems subjected to lateral loading has been investigated by Wang et al. and, Baroutaji et al. [27,28]. Traditionally, it has been observed that nested tubes have good capability in energy absorption (EA) under axial loading [29,30]. System comparison of single and two concentric tubes with equal mass structures has been done by Nia, and Khodabakhsh, showing that energy absorption in two-tubes system is more than single-tube system [31]. Azarakhsh et al. have used the polyurethane foam in filling bitubular tube to increases the energy absorption capacity [32]. A similar study in this area is the work of Gao et al., it has been found that the energy absorption capability per unit mass of the foam filled double ellipse tubes is larger than the empty tubes [33]. However, a comprehensive work in studying the behavior of nested multi-tubular structure has been developed recently by Nia, and Chahardoli [34,35]. They have defined the interaction ratio as the ratio between tube thickness over the distance between two successive tubes. The important conclusion of these publications from the current work point of view, is that the interaction between the nested tubes can be considered as an added-value for absorbing energy. To further reveal the superiority of the interaction mechanism, the more increase in the interaction ratio the more increase in specific energy absorption.

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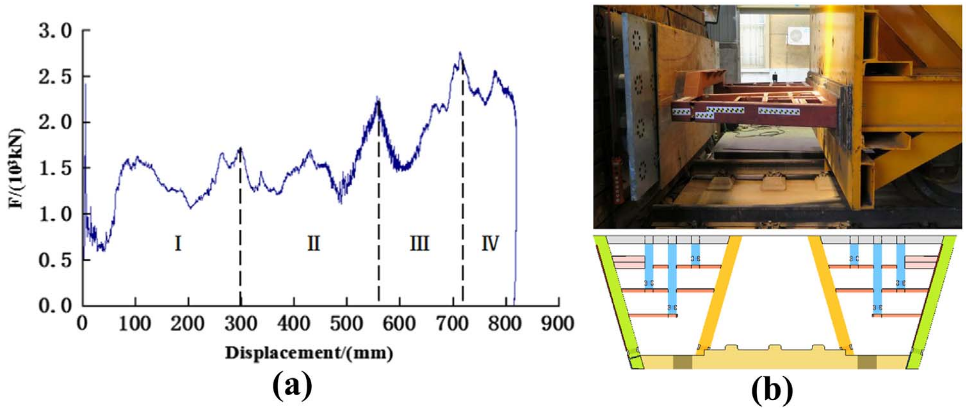

Fig. 1. Gradual energy absorption concept for certain subway vehicle [32,33] (a) GEA force-displacement curve (b) Absorber layout: real and schematic drawing.

Gradual Energy Absorption (GEA) is a novel expression that has been used by Xu et al. to express obtaining the energy dissipation stage by stage as shown in Fig. 1[36,37]. These stages have been generated by the entire structure developed orderly deformation. A serious weakness of this argument, however, is that the employed structure is an energy-absorbing structure for a certain subway vehicle application with specific dimensions and conditions, thus this applied application is relatively complicated and cannot be generalized to replace other employed crash tubes, whilst it will be more efficient for other absorber devices whether they gain GEA characteristics. Furthermore, GEA can be generated by any simple structure starts with relatively weaker element/s and ends with stronger element/s passing through in-between element/s. Over the past decade, many researches have emphasized the occurrence of GEA even that has been done as an indirect objective. Tapered tubes with/without graded thickness [38,39], conical/cylindrical tubes with/without graded thickness [40–42], functionally-graded structures [43] and, nested tubes with multi-levels can be employed to generate GEA but more simple than other complicated absorber devices.

Emergency actions refer to unknown parameters. During the emergency conditions, even the action reasons are not controlled but for safety, the reaction results must be under controlled. The history of vehicles accidents can give an expectation range for the initial impact velocity. It is very important to study the generated force corresponding to different expected ranges of initial impact velocities. However, the absorber device will be more efficient if it contains a mechanical force-adaptor technique. The shortage in studying force adaptors availability is a major drawback of the most of EA publications, hence there is a need for a mechanical adaptor that is in charge of manipulating the corresponding force with the expected initial impact velocity during the EA process. The most efficient adaptor must be able to manipulate lower force with lower initial velocity and reasonable force with high initial velocity.

Recent trends in multi-objective optimization have led to a proliferation of studies that have probed optimum crashworthy designs [44]. Liu et al. have improved crashworthiness of sandwich structure with star-shaped tube in the center by using multi-objective optimization [45]. Li et al. have applied crushing analysis and multi-objective optimization to improve the crashworthiness of a railway vehicle driver's cab [46]. Maximum specific energy absorption capacity and minimum collapse load have been combined inside the optimum crashworthy design by Baroutaji et al. for crash tubes under lateral loading [21,47]. Furthermore, the present design of the questionnaires was based on crashworthy requirements through multi-input parameters, multi-parameters relationships, and multi-objectives, thus Adaptive Multiple-Objective Optimization [48] (AMO) is an efficient method to investigate the mechanical adaptor architecture.

The current work proposes Piecemeal Energy Absorption (PEA) as a novel strategy. The proposed PEA strategy has the same concept of GEA but it extends to various structures and applications as it occupies almost the same filling form of the employed absorber. As explained in the introduction, it is clear that one of the challenges of most employed energy absorption techniques is the dependency on the system architecture and application specs. However, the present work aims at proving the generality and applicability of PEA. Due to the generality and applicability of the proposed PEA strategy, it can replace the existing absorbers in order to manipulate the damage level for impact cases, moreover, PEA redistributes and reduces the total structure weight for new designs of protected vehicles. The current work studies two popular applications (railway buffer, and UAV landing gear) to prove the implementation flexibility of PEA strategy.

This paper is organized as follows. Section 2 highlights the PEA strategy. PEA implementation results are presented in Section 3. Section 4 is the discussions about PEA behavior. Finally, conclusions are drawn in Section 5.

2. PEA strategy

2.1. PEA strategy description

PEA is a strategy aims at manipulating accidents feedbacks (reactions/damages) depending on accidents initial impact velocities.

In reviewing the database of different vehicles accidents, a lot of data can be found in the association between accidents and their initial impact velocities. Initial velocities of accidents can be categorized into the following:

- Accidents are relatively controlled (even emergency conditions) that have been initiated with relatively low impact velocities ($V_{ini.1}$).
- Accidents are partially controlled that have been initiated with higher impact velocity ($V_{ini.2} || V_{ini.1} < V_{ini.2}$).
- Accidents are relatively out of control that have been initiated with relatively high impact velocities ($V_{ini.max} || V_{ini.1} < V_{ini.2} \ll V_{ini.max}$).
- Accidents are unconscious that have been initiated with unexpected impact velocity, however, this case cannot be considered at the most of vehicle designs.

This accidents database is used by structural designers in their Crashworthy design to expect the maximum initial impact velocity as an essential input parameter even the maximum value ($V_{ini.max}$) happens rarely.

Stable crushing with constant force of crash tube has been considered as the best choice by crashworthy designers [12]. Actually, the accidents that frequently happen are mostly expected to be initiated with relatively low impact velocities ($V_{ini.1}$). However, the response of the most of crash tubes suffers from some serious limitation in manipulating the difference between relatively low impact velocities ($V_{ini.1}$) and, relatively high impact velocities ($V_{ini.max}$). Furthermore,