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A novel tailor-made technique for enhancing the crashworthiness by multi-stage tubular square tubes

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ABSTRACT

State-of-the-art studies of the energy absorption systems reveal various techniques for enhancing the crashworthiness of a structure, and each technique has its benefits and drawbacks. For crashworthy designers, it is a challenge to design an efficient energy absorbing system which fulfills its requirements in terms of crashworthiness. Therefore, this paper proposes tailor-made technique for crashworthiness design by performing a combination of two or more energy absorption techniques to fulfill the crashworthy designer requirements. The tailor-made technique is adapted to have the ability of implementation by different structural configurations; thus, tubular square tubes configuration has been utilized as an example. Tailor-made technique implementation is validated experimentally and numerically under quasi-static and axial impact loading, afterwards, its merits are discussed through conducting a comparative study. Results show that the novel tailor-made technique provides the designers the flexibility in designing of the protected structure. Furthermore, tailor-made technique improves the crashworthiness of the energy absorbing system in terms of crushing performance and energy absorption capacity. Moreover, it leads to energy absorbing systems applicable to a wide range of impact velocities through generating low reaction force under low impact velocity and logical crushing force under high impact velocity.

1. Introduction

Vehicle designers keep in mind a lot of considerations during their design, one of the most important is assuring the safety of passengers and reducing the risk of being injured or killed in deadly crashing accidents. Resistance to the effects of a vehicle collision, yet protecting its occupants from the outcomes of an accident is caller Crashworthiness [1–4]. Studying the behavior of crashworthy elements is the best way to improve their efficiency along with studying their interactions on the whole structure, taking the automotive engineering as an example, the vehicle structural elements consist of front rails, bumpers, pillars and rockers [5,6]. Among those elements, the front rails are the structural components which play a main role in the energy absorption and can be considered as the most effective parameter in the design of vehicle's safety because it absorbs approximately up to 55.3% of the kinetic energy of the vehicle in case of frontal crashes, as shown in Fig. 1(a) [6].

Using a thin-walled tube as an energy absorber is one of the efficient techniques for enhancing the crashworthiness of vehicle's elements such as, crash boxes which are fixed on the front rail, as shown in Fig. 1(b). Thin walled tube has high energy absorption characteristics as it dissipates the kinetic energy in various forms such as plastic deformation, friction, fracture, shear, bending, tension, torsion, and metal cutting [1,4,9]. The axial loading (frontal collision) is the most famous test used in experimenting the vehicle structure due to the deformation process occurs progressively, thus, a high-energy absorption can be obtained with a high crush efficiency [10,11]. They can be manufactured with various cross sections such as square, circular, oblong, taper, hexagonal, octagonal, frusta, corrugation and S-shaped [1,12–15]. Amongst these, square thin-walled tubes have been used extensively as a light weighted crashworthy component in vehicle structural elements like crush boxes due to their high stiffness, high strength, lightweight, low cost, ease of manufacturing, and excellent crashworthiness characteristics, as mentioned in Fig. 1(b) [1,2,16]. Under axial collision, square thin-walled tubes deform in different deformation modes which are investigated by the basic folding corner elements theory. Generally, the corner elements experience two progressive collapse modes: extensional mode and in-extensional mode, or

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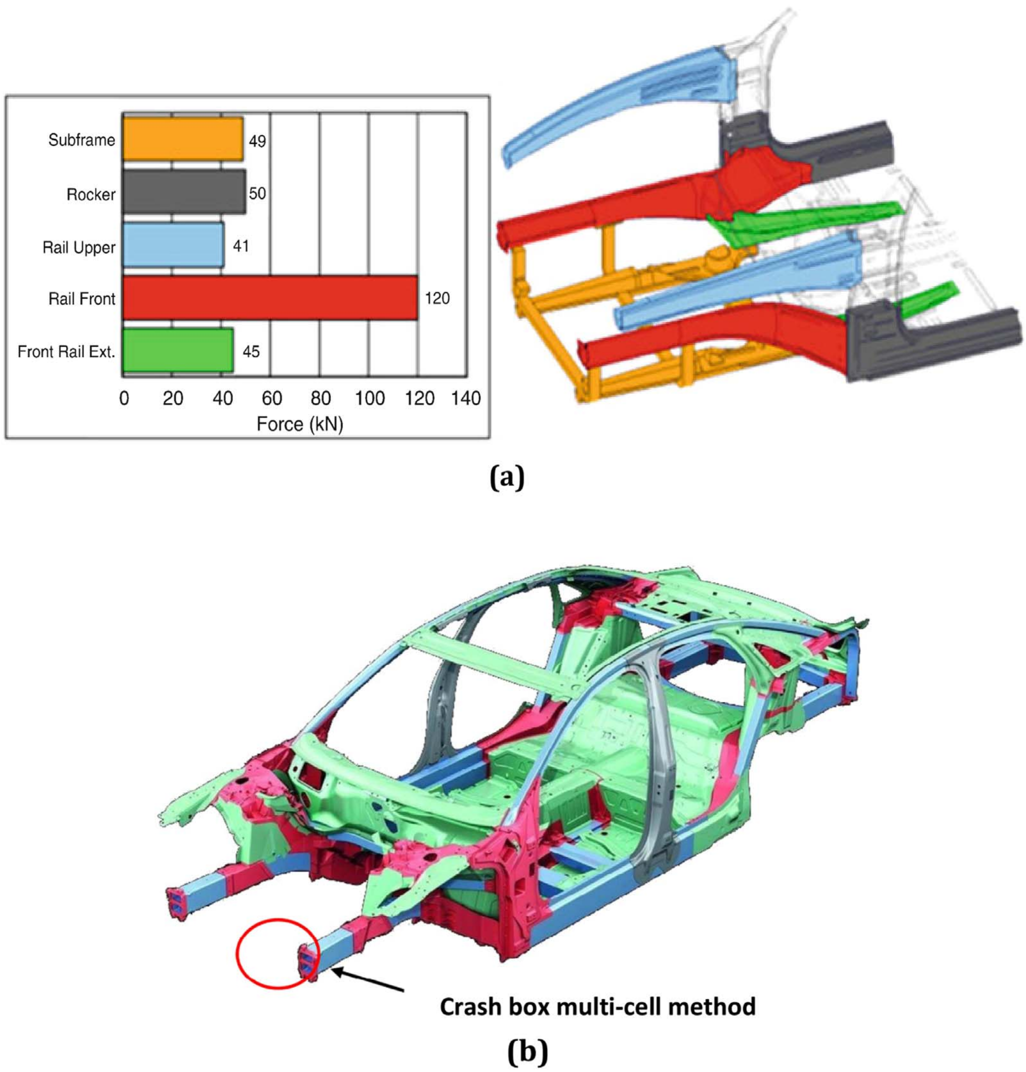

Fig. 1. Structural components of a passenger vehicle (a) load efficiency path [6], (b) crash box fixed on the front rail [7,8].

mixed mode [17,18]. A series of experimental, numerical, theoretical studies have been conducted to study the mechanical characteristics, crash performance and impact response of simple square thin-walled tubes [19–26].

State-of-the-art studies of square thin-walled tubes (square crashing tubes) reveal several methods with various configurations/arrangements to improve the energy absorption characteristics under axial loading [27,28]. Such as, filling with foam material (uniform density – functionally graded density) which was used to enhance the energy absorption characteristics of these tubes through increasing the strength and the crash resistance of the tubes. For instance, Yin et al. [27] studied the crashworthiness design of functionally graded foam-filled multi-cell thin-walled structure. The results showed that the functionally graded foam-filled structure possessed better crashworthiness than the traditional uniform multi-cell thin-walled structure with the same weight. Another method of using functional graded or various thickness, adding external or internal stiffeners and composite hybrid tubes (reinforcement by stacking composite layers) which were proposed to improve the energy absorption characteristics and the crush performance of these tubes [29–31]. For example, Fang et al. [29] designed new extrudate multi-cell tubes with functionally graded thickness and studied the crushing behavior under impact loading. They found that the thickness gradient parameters in different regions have significant effects on the energy absorption characteristics.

Recently, using multi-cell thin-walled tubes have gained comprehensive attentions and have been put forward as an effective method to increase the energy absorption capacity while at the same time maintaining the weight efficiency of crashworthy structures [12,32–38]. The tubular/nested structure is considered as a special arrangement of multi-cell tubes. It is one of the most widely used in the energy absorption system especially in the axial impact cases as it is simple in manufacturing, has excellent energy absorption characteristics, and the ability for deforming in a progressive way. Several investigations have been performed experimentally, theoretically and numerically to study the crushing behavior of the tubular (nested) tubes [39–43]. For instance, A series of investigations have been performed by Nia et al. [41–43] to investigate the crashworthiness characteristics of the nested multi-tubular structures. These investigations showed that multi-tabular structures had a better crushing performance for absorbing impact energy compared to single-tube structures with same conditions. In general, the most of the aforementioned methods can increase the energy absorption capacity in compared with the simple thin-walled tubes but, the disadvantage of these methods is keeping a high value for the initial peak load which is undesirable for occupant safety [1,4].

On the other hand, applying imperfection methods (trigger technique) with the aim of reducing the initial peak loads such as holes, patterns, grooves, corrugation, diaphragms, saw cutting, and buckling initiator were introduced by numerous investigations [44–47]. For instance, Khalkhali et al. [45] carried out multi-objective crashworthiness