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Effect of radial clearance and holes as crush initiators on the crashworthiness performance of bi-tubular profiles

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ABSTRACT

The use of bi-tubular structures has gained importance in the design of energy absorption systems for protection of passengers in train collisions. Therefore, it is critical to improve the crashworthiness performance of bi-tubular profiles. For this purpose, the effect of cross-section, bi-tubular clearance and holes as crush initiators is evaluated using finite element simulations. To get reliable outcomes, special emphasis was set on the progressive damage modelling of aluminum 6063-T5 by a Johnson-Cook (J-C) failure model. During the cross-section study, bi-tubular arrangements based on polygonal and circular cross-section were evaluated by quasi-static compression loads. The results indicate that the circular shapes showed better crashworthiness performance or crush force efficiency (CFE) up to 12.28% respect to a square base structure. A 10.72% improvement in CFE was obtained when the non-dimensionalized clearance between profiles is increased from $\lambda = 20$ to $\lambda = 40$. The effect of holes on crashworthiness performance was evaluated by drilling holes at different locations both in the inner and outer profiles. The results show that the use of holes increased the crush force efficiency and energy absorption (E_a) capability even more than the effect of clearance alone. Improvements in the order of 2.50% and 12.96% for E_a and CFE respectively were computed when holes were placed at the top end of a BC-3 profile with a non-dimensional clearance of $\lambda = 40$. Considering all effects simultaneously, an increase of 24.6% and 26.31% for E_a and CFE respectively was calculated. Finally, an application to a crash buffer in a railway transport system is considered. Likewise, its improved crashworthiness behavior is presented.

1. Introduction

The safety of passengers is of critical importance when designing structural components of sea, land and air vehicles [1]. From this reason the use of thin-walled structures is increasing in modern day applications. One of the most important characteristics of thin-walled structures is its large capacity to control external forces by plastic deformation [2]. In order to make improvement in the crashworthiness performance of these structures several arrangements of thin-walled profiles have been analyzed, including single [3], multi-cell [4,5] and honeycomb configurations [6–9]. Recently, a third category of thin-walled structure called bi-tubular arrangement is emerging. This kind of structures are formed by two concentric profiles with the same or different cross-section. Several studies have been carried out to study bi-tubular arrangements. Shafiri et al. [10] evaluated the effect of diameter and thickness on the energy absorption (E_a) properties of circular bi-tubal profiles. In order to reduce the peak load value (P_{max}), different heights and a cut grove were investigated. They indicated the importance of clearance between profiles and its effect on P_{max} and energy absorption. Kashani et al. [11] investigated the energy absorption performance of bi-tubular square tubes experimentally and numerically. The profiles were set in parallel and in a diamond configuration. They observed that the energy absorption of a bi-tubular arrangement is larger than the performance of the individual profiles. Likewise, an improvement of 36% of E_a was obtained for the diamond configuration. Rahi [12] evaluated the effect of cross-section on the energy absorption of mono-tubal and combined bi-tubular profiles. Circular and squares profiles were used to construct bi-tubular arrangements. It was

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concluded that the energy absorption capacity can be increased up to 25% when the external tube of the combined bi-tubular arrangement has a circular cross-section. Vinayagar et al. [13] carried out a crashworthiness analysis of double section bi-tubular structures. The arrangements were formed by an outer circular profile and inner tube with a polygonal cross-section. Their results show that the best crashworthiness performance was obtained with the hexagonal inner tubes. In other recent studies foam has been used as filler between tubes to improve the energy absorption of bi-tubular arrangements [14,15]. Zheng et al. [16] evaluated the energy absorption of foam-filled single and bi-tubal polygonal configurations when are subjected to axial crushing load. They determined that the energy absorbed generally increases as the number of foam filled bi-tubular columns increases. The best crashworthiness performance was computed for foam-filled circular bi-tubal columns. Goel [17] studied the crushing behavior of single, double and multi-wall foam filled square and circular tubes. It was shown that the use of foam filler and concentric configuration modified the crushing behavior of the structure and resulted in an improvement of the energy absorption. Bi-tubular and tri-tubular arrangements showed a better energy absorption performance than single profiles. After comparing square and circular profiles with the same configuration and foam filler, the best performance was computed when circular cross-sections were used. In addition, to foam fillers, a reduction of peak load and an increase in E_a can be obtained if geometrical discontinuities are drilled on the wall of the structures [18,19]. Estrada et al. [20] analyzed the effect of discontinuity shape and aspect ratio on the energy absorption behavior of single square profiles. It was determined that curved discontinuities showed the best crashworthiness performance. However, very few numerical studies regarding discontinuities on structural profiles have considered the use of damage models on their simulations. Arnold [21] analyzed the E_a capacity of aluminum square profiles with circular holes considering Lemaitre's theory. For this purpose, several numerical simulations using LS-Dyna software were carried out. A novelty of this work was the visualization of crack and splitting mechanism. The authors showed the importance of including a model that can describe damage mechanisms. Similarly, Estrada et al. [22] analyzed the effect of location and size of circular discontinuities on the crashworthiness performance of aluminum square profiles using a ductile, shear and Müschenborn-Sonne Forming Limit Diagram (MSFLD) damage initiation criteria. Their results showed that the best location for the discontinuities is at the top of the structure where an increase of 12.67% in crush force efficiency (CFE) was obtained. Additionally, they presented a rule for the effective sizing of the hole diameter. As possible to see we can find both bi-tubular and discontinuities researches. However, the implementation of discontinuities on bi-tubular structures considering damage theoretical models is barely reported.

In this paper the effect of cross-section geometry, radial clearance and holes as crush initiators on the crashworthiness performance of bi-tubular aluminum profiles is analyzed. For this purpose, the Johnson Cook (J-C) failure model with evolution was implemented into the discrete model. The progressive damage and fracture were accurately captured under quasi-static load of the aluminum profiles. Finally, the study of an improved crash buffer system for a railway application is presented.

2. Lightweight structures and material modelling

When a lightweight structure is impacted (e.g. railway crash) the large amount of energy, and large deformations involved in the process increase the complexity of the structure's mechanical behavior. The behavior of the material suddenly changes from elastic to plastic regime ending with failure and fracture of the structure (see Fig. 1). The material failure refers to the complete loss of load carrying capacity due to degradation of the material stiffness [23]. In practice, structural failure occurs by shear and ductile mechanism including compressive and tensile effects. In order to get a realistic outcome, numerical simulations of crashworthiness behavior should consider the failure theory that models the progressive damage of the structure.

In this paper the phenomenological Johnson-Cook (J-C) failure model is used to model the progressive damage behavior of a structure. The J-C model is based on the value of the equivalent plastic strain ($\bar{\varepsilon}^{pl}$) at the element integration points. Failure is attained when the damage parameter (ω) exceeds 1, where $\Delta\bar{\varepsilon}^{pl}$ is an increment of the equivalent

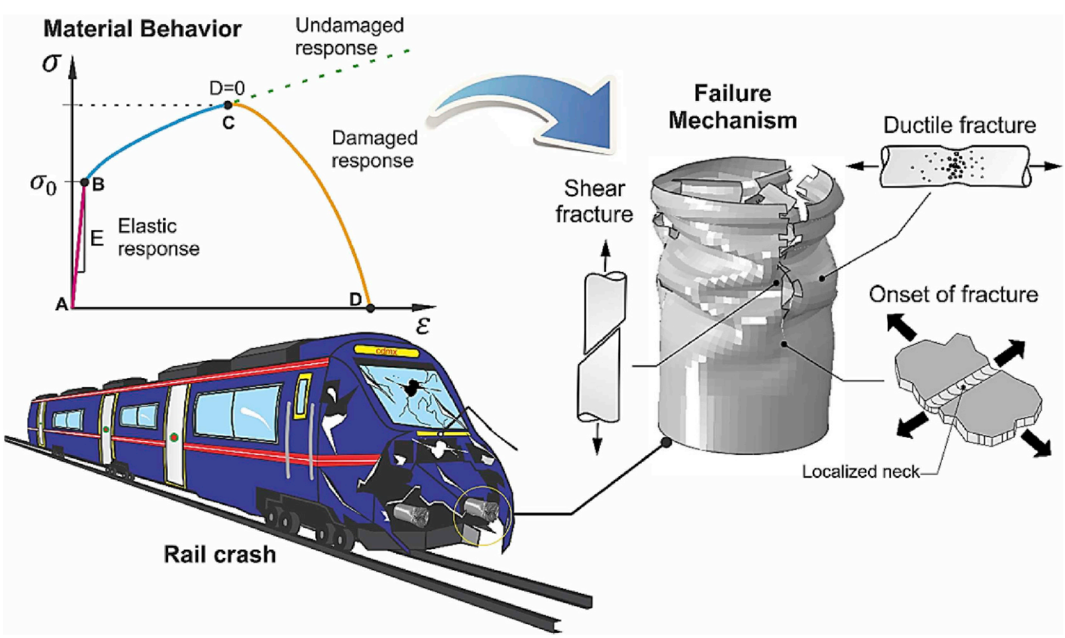

Fig. 1. Crash buffer system under a train crash scenario, material modelling and failure mechanisms, based on [24].