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Effects of elastic–plastic behaviour on the axial crush response of square tubes

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ABSTRACT

Axial crushing of square tubes is widely studied for their energy absorption characteristics that are similar to automotive structural components. In this paper, the effects of the elastic–plastic behaviour of lightweight alloys on the steady state crush force, peak crush force, energy absorption and crush efficiency response of the axial crushing of square tubes are studied. Axial crush simulations are performed on square crush tubes where the yield stress and strain, ultimate tensile strength, hardening rate, and failure strain of the material are varied. New definitions and analytical equations for crush efficiency and energy absorption are developed and calibrated with the axial crush simulations to develop a framework for optimal material selection for axial crush. This work shows that the yield stress increases the energy absorption, peak crush force and steady state crush force, while tending to decrease the crush efficiency. After sufficient increase in the hardening capabilities, positive gains are obtained in the crush efficiency when increasing the yield stress. The ultimate tensile strength, hardening rate and the yield stress of the material have a strong effect on improved energy absorption. Lightweight alloys with a low yield stress that have significant work hardening capabilities outperform materials with a high yield stress and very little work hardening in terms of energy absorption when a constraint is imposed on the peak crushing force.

1. Introduction

Fuel economy requirements and other government regulations to reduce the carbon footprint of a vehicle has driven vehicle mass reduction strategies as manufacturers balance cost, mass and performance with innovative technologies in design, engineering and manufacturing [1]. Lightweight alloys offer a distinctive mass advantage that can translate to performance gains over automotive structural steels while the later offers design, engineering and manufacturing flexibilities. Use of new design and engineering approaches can enable lightweight alloys to successfully compete for potential applications in vehicle structural components, such as front rails, bumpers, and B-pillars. These structural components that contribute significantly to the mass of the vehicle without directly interacting with the use of the passenger on an everyday basis must be engineered to perform under automotive collision conditions to offer safe vehicles. Passenger safety is a key element in a vehicle design [2]. In 2011, the standards for deceleration limits and crashworthiness set by the National Highway Traffic Safety Administration (NHTSA) in North America and the European New Car Assessment Program (Euro NCAP) have become even more stringent to further drive occupant safety [3]. Automakers, challenged with the problem of making vehicles lighter and safer at the same time, have interest in developing advanced lightweight alloys and designs that can offer superior performance without added cost penalties.

In the last three decades, significant advances have been made to understand energy absorption mechanics of thin-walled structures for their versatility. Extensive literature reviews have been performed by Alghamdi [4], Olabi et al. [5], and Yuen and Nurick [6] on the various applications of these structures. In particular, simple crush tube geometries, such as square, circle and rectangle, have been widely studied for their energy absorption characteristics due to their similar behaviour of automotive structure components during an impact [7–13]. Wierzbicki and Abramowicz [14–16] performed pioneering work to develop models for the mechanics of axial collapse. They used rigid-perfectly plastic material behaviour models to analytically understand the fundamental mechanics behind the crushing of thin-wall structures. Wierzbicki, Abramowicz and Jones later validated the analytical models through quasi-static and dynamic crush experiments on square and circular tubes with reasonable accuracy [17–22]. Abramowicz and Wierzbicki continued their work to improve on the mechanics of crushing and collapse by introducing local deformation effects in their macro element model [23]. Abramowicz later extended the collapse mechanics from rigid-perfectly plastic to rigid-plastic by

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calculating the equivalent flow stress with a Power Law Plasticity constitutive model [24]. This resulted in improved accuracy energy absorption predictions. Yamashati et al. [25] further extended the work to analytically relate the crushing strength response to the tensile strength of the material. More recently, Najafi et al. [26] have incorporated advanced deformation mechanisms to improve analytical axial crush predictions.

With the development of commercial non-linear finite element software, such as LS-DYNA, PAM-CRASH and ABAQUS, numerical simulations were performed to model axial crushing of tubes. These simulation tools were able to model the non-linear influences of contact and elastic–plastic constitutive models that were not considered in the previous analytical work of axial crush [27–29]. Langseth et al. [30,31] began to study the behaviour of aluminum and steel thin walled structures during axial crush using LS-DYNA, and validated their results with experiments. In their work, the conventional definitions of crush efficiency and energy absorption are introduced for crashworthiness analysis of axial crush tubes. Williams et al. [32] used a similar approach to perform numerical and experimental analysis of the effects of material anisotropy, hardening and strain on the mean crush force of hydroformed tubes.

In recent years, a renewed interest has arisen towards the investigation of crashworthy elements. In the work of Nagel and Thambiratnam [33–35] a systematic analysis was performed to calibrate an analytical equation to numerical results produced by finite element simulations of tapered rectangular tubes. Jones [36] performed a dimensionless analysis on the ratio of crush structure energy absorption to the total energy absorption during uniaxial tension to differentiate between materials for efficiency. It was found that an aluminum alloy was more efficient than conventional steels because the higher rupture strain of steel was classified as an inefficient use of material. While a significant amount of work has been performed to understand the behaviour of axial crush [37], very little research exists that provides direct insight into the effects of the elastic–plastic behaviour of the material on the axial crush response for lightweight alloys. Additionally, the conventional definitions of crush efficiency and crushing force do not adequately capture the actual loading to a vehicle passenger during an impact. Currently, no work has been performed to relate the peak crush force to material properties. Thus, no analytical equation for crush efficiency has also been proposed in terms of material behaviour.

Furthermore, no work has focused on investigating the relationship between energy absorption characteristics and how they interact with each other through the material behaviour. For example, there is no study on the implications of peak crush force constraints on the steady state crushing force, energy absorption and crush efficiency of crush tubes when comparing different lightweight alloys. With a wide variety of available lightweight alloys with different large strain behaviour, automakers have been challenged to design and select materials that offer superior crashworthiness performance without additional cost or significant development time. Currently, automakers use commercial numerical simulation tools to accurately simulate and predict the effect of lightweight alloys for frontal crash scenarios, which requires a significant amount of time and resources. A structure for optimal material selection for axial crash and energy absorption to reduce front rail development time is required.

In this paper, the effects of the elastic–plastic material behaviour on the energy absorption characteristics of axial crush are studied. In order to investigate the effects of the elastic–plastic material behaviour, axial crush finite element simulations are performed on a simple square front rail crush tube. The geometry of the crush tube remains constant for all simulations during the study. The yield stress and strain, ultimate tensile strength, hardening rate, and failure strain of the material are varied in each simulation. The objective of this study is to develop a new framework that can be used to select a set of material properties to achieve optimum energy absorption and crush efficiency. In this framework, new concepts are introduced for energy absorption and crush efficiency metrics. Furthermore, a new set of analytical equations, based on numerical simulations, are developed for the framework to predict the steady state crushing force, maximum crushing force, crush efficiency and energy absorption behaviour due to various elastic–plastic material responses. The analytical equations are derived from the macro-element formulation to separate geometric and material effects [14–16] and calibrated from the results of numerical simulations. Constraints are imposed on the peak crushing force and energy absorption to develop the material selection framework. Validation simulations are performed to compare the set of analytical equations and the FE model to experimental work found in literature.

2. Energy absorption and crush efficiency

Fig. 1 shows a typical front rail crush tube force–displacement response during an axial crush. At a component level, the front rail crush tube experiences an initial peak crushing force, $F_{peak,1}$, due to elastic loading of the structure. Once the structure yields due to compression, the structure enters an instability mode of deformation that leads to bending and creates a plastic hinge. This results in a drop in the crushing force that is now required for the bending mode of deformation. As the fold completes, the structure begins to stiffen and triggers subsequent folds. As folding progresses, the force–displacement response of the front rail crush tube transitions to an oscillatory steady state behaviour of plastic hinging. The oscillation of the crushing force in the steady state region is typically bounded by the steady state crushing peak, $F_{peak,2}$. A time delay is present between the initial impact and resulting passenger deceleration [38]. During the initial crushing, the passenger compartment experiences a damped response due to additional vehicle components, such as the bumper and foam absorbers [39].

In the work of Hanssen et al. [40,41], the classical definitions of energy absorption characteristics and crush efficiency were introduced. In their work, they defined energy absorption as the total integral of the force–displacement curve with respect to displacement, which is defined as

$$E_{abs} = \int_0^d F(x)dx \tag{1}$$

where d is the total displacement. Furthermore, they defined the average crush force as the total energy absorbed divided by the total displacement:

$$F_{ave} = \frac{\int_0^d F(x)dx}{d} \tag{2}$$

They also introduced the conventional concept of crush efficiency, which is the ratio of the average crush force, F_{ave}, to the initial peak crushing force, $F_{peak,1}$:

$$\eta_{classical} = \frac{F_{ave}}{F_{peak,1}} \tag{3}$$

This definition of average crushing force and conventional crush efficiency is a very simple performance metric of determining the energy absorption characteristics. However, the average crushing force would tend to over predict the average crushing force observed by a passenger in the steady state regime. This is due to the averaging of the large energy absorption that occurs in the initial folds that a passenger may not fully observe during an impact. In this study, a new definition of crush efficiency is defined, which is called the steady state crush efficiency.