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Innovative solution for strength enhancement of metallic like-composite tubular structures axially crushed used as energy dissipating devices

A. Abdul-Latif[a,b,*], A. Ahmed-Ali[a,c], R. Baleh[a,d], M. Ould Ouali[c]

[a] *Laboratoire Quartz, Supméca, 3 rue Fernand Hainaut, 93407 St Ouen Cedex, France*
[b] *Université Paris 8, France*
[c] *Laboratoire LEC2M, University Mouloud MAMMERI of Tizi-Ouzou, BP17RP, 15000 Tizi-Ouzou, Algeria*
[d] *Ens. Sup. La salle Passy-Buzenval, Rueil-Malmaison 92500, France*

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ABSTRACT

This work presents the milestones of the underlying of a patented work [1] (Abdul-Latif, 2014) which aims to enhance the plastic buckling resistance of thin-walled right-circular cylindrical mild steel tubes deformed axially under the quasi-static compressive load. The proposed concept can be described by producing a metal like-composite where a hard phase incorporates in these tubes made by case-hardening of 15% of tubes outer surface with different geometrical shapes and a constant depth along the tubes thickness. To study the effect of case-hardening configurations, several forms were designed, made and tested. They were four ring forms (with 2, 3, 4 and 5 rings), two vertical strip forms (2 and 3 strips) and, six helical strip forms with three tilt angles of 30°, 45° and 60° (2H30, 3H30, 2H45, 3H45, 2H60 and 3H60). The total energy absorption of conventional tubes could be increased up to 46%. The effects of the case-hardened zone, quasi-static strain rate and the crush force efficiency were investigated. Moreover, the deformation modes of these case-hardened tubes were analyzed. The effect of the case-hardened forms could be classified into three categories by the gain percentage (low, intermediate and high gains). Especially in the high gain category, the material behavior seems to be directed by complicated local strain induced by the metal like-composite tube, where a triaxial strain state was encouraged particularly within the tube wall of 3H30. For this reason, the collapse load became the function of case-hardened forms.

1. Introduction

For several decades, the passive safety concept related to crashworthiness has received a significant attention in designing energy dissipating systems and devices. These systems should be able to answer the high requirements for crashworthy design of different transport vehicles with the aim of improving their safety and reliability. The role of such devices is to mitigate both structures damaging and human injuries during vehicles collusion. These devices can be used in many mechanical systems, like road vehicles, railway couches, aircraft, ships, lifts, machinery, satellite recovery, aircraft soft-landing, etc. One of these passive safety devices is one that use large deformations as a basic concept. This will be considered in the present work.

The extensive crashworthy structural elements commonly used in these devices are different: circular and square tubes, honeycomb structures, spherical shells, frusta, taper tubes, s-shaped tubes, composite tubes, foam-filled tubes, wood-filled tubes, etc. The cylindrical tubes attract much more attention due to an optimized combination of several key factors of high stiffness/high strength/low weight together with its manufacturing process simplicity, i.e., low cost product. This leads therefore to economical energy-dissipating devices (e.g., [2–6]).

Understanding the behavior of collapsed structures (modes of deformation and the resulted failure) and its materials behavior is essential to evaluate the energy absorption ability. According to the relevant literature, a strong conviction is emerging that the response of structures to a large extent depends on several factors such as the structural geometry, its material properties particularly strain hardening behavior, boundary and loading conditions, strain rate, etc. (e.g., [2,7–9]).

It has been recognized that thin-walled components are widely used in these devices under compressive loading. Several deformation modes can be recorded. Actually, it can be plastically turned inside-out or outside-in. This is so-called *tube inversion* (e.g., [10–13]). It provides a favorable constant crush force, but with relatively low stroke efficiency. This is because only half of the tube length contributes in plastic deformation. Also, it has a strong sensitivity to external loading condition which makes its application limited as energy-dissipating system.

On the other hand, tubes can be made to *split* and *curl up* (for

* Corresponding author at: Laboratoire Quartz, Supméca, 3 rue Fernand Hainaut, 93407 St Ouen Cedex, France.
E-mail address: aabdul@iu2t.univ-paris8.fr (A. Abdul-Latif).

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example, [14–17]). It is found that axial splitting and curling of tubes provide low crush load and low stroke efficiency. Therefore, these devices provide us with low specific energy absorption.

To the authors knowledge, the first reported work on the *plastic buckling* of thin-walled tubes under axial compression has been pioneered by Mallock in 1908 [18]. Currently, this concept is largely used in developing energy dissipation devices. Note that the goal of this work falls into this category. Circular, square and rectangular sectioned tubes are the most widespread and efficient means of dissipating energy (e.g., [19–25]). The recorded load-deflection curve has an oscillatory nature with a first maximum peak load. The latter is considered in determining the crush force efficiency (ρ) as a factor for evaluating the crashworthiness of an energy absorber device. Its definition and role will be discussed later. For a given tube, the peak load is affected by initial imperfections over the tube. To minimize its value, several solutions have been developed, like holes near the tube ends, chamfering, grooving, etc. The concept of a buckling initiator is successfully developed reducing this peak load up to 30% [24,25]. This device, in the process of large plastic deformations, provides one of the best due to: (i) the stability of the average collapse load throughout the entire crushing process and (ii) the available stroke per unit mass, i.e., a high percentage of tube material contributes to the plastic deformation of the tube wall. The bending and stretching strains combination and its progress along the buckled tube guarantees the participation of material in the absorption of energy by plastic work. Three principal collapse modes could be observed: axisymmetric mode, diamond mode and mixed one. The main geometrical parameters controlling these modes are: the η (= R/t) ratio of diameter (R) to thickness (t) and the λ (= R/L) ratio of diameter to length (L) [21,26,27]. For $\eta < 15$ [2], the mode axisymmetric becomes predominant for most engineering materials. Nevertheless, the diamond fold mechanism (or mixed one) tends to occur for larger values. Favorable crashworthiness characteristics could be achieved when the tube deforms in axisymmetric mode, i.e., the energy absorbed is gaining more recognition in the axisymmetric mode than that in the diamond or mixed one [27]. Together with η ratio, the λ ratio can also play a significant role in controlling the plastic flow mechanism. Few investigations have been carried out to determine the effect of this parameter on the axial collapse of tubes (e.g., [21,26,27]).

In the light of this fact, a new solution has been proposed for encouraging the axisymmetric mode. In fact, the developed solution consists of cutting a tubular structure in several portions. These portions are coaxially assembled together and separated by non-deformable discs. The number and the length of portions effects (i.e., λ ratio) on the flow mechanism have been investigated [27]. Besides, other solutions have been already proposed with the purpose of not only maximizing the energy absorbed but improving the stabilization of the collapse process. The idea is always based on the concept of encouraging the axisymmetric mode. These developments deal with either introducing *corrugations* over the tube to force the plastic deformation to occur at predetermined intervals along the tube length (e.g., [28,29]), or introducing circumferential *grooves* which are cut alternatively inside and outside of the tube at predetermined intervals. This offers an effective solution to orient the plastic deformation occurring at these predetermined intervals along the tube [30–34]. These methods provide a reasonable increase in crush force efficiency of the developed shock absorber, but with relatively limited stroke efficiency. This is due to the fact that part of the tube length cannot contribute in plastic deformation especially of the circumferential grooves solution and non-deformable discs. In general, limited research programs have been conducted for controlling the deformation mechanisms. Therefore, this field still requires more attention.

Contrary to these standard passive systems, a relatively new concept has been developed to generate a plastic biaxial buckling regime via a patented rig [9,35,36]. The solution deals with creating a particular combined biaxial complex loading condition of compression-torsion. Hence, this provokes an enhancement in strength properties of the loaded structure due to changes in local deformation mechanisms [37]. The reported results of copper circular shells buckling revealed an increase in the energy absorption up to 60% compared to the classical uniaxial case.

Whatever the energy dissipating device type, especially for these devices used the plastic buckling basis, a well-grounded question is worthy to be answered. This is regarding the possibility to further increase the energy absorbed in a tubular structure crushed axially. In this work, the performance of axially crushed mild steel tubes could be enhanced using an innovated idea [1]. It consists of creating steel like-composite with different geometrical configurations. The steel like-composite could generate complex straining conditions within the structure through the combination of local heterogeneities dictated by the composite and the external load. Undoubtedly, mild steel tubes are employed due to its ability to be case-hardened up to a certain depth along the tubes thickness. In this work, the targeted case hardening involves surface and subsurface modification without any increase in tube dimensions. Hence, it is a technique by which the outer surface hardness of steel alloys part is improved by a carburizing or nitriding process without affecting the tough interior of the part. A carbonaceous or nitrogenous atmosphere is used at elevated temperature to treat any steel part at its outer surface level by atomic diffusion. With this diffusion, the chemical composition of the surface is modified by adding hardening elements such as carbon, nitrogen, or boron. The thickness of case hardened zone is usually on the order of 1 mm which is harder than the inner core of material. Selective a surface-hardening zone, as in this study, allows localized hardening. One of the important advantages is the compressive residual stresses which are induced at the surface of the case-hardened part. Such a stress type reduces the crack initiation probability that helps prevent crack propagation at the case-core interface particularly in fatigue [38]. Likewise, this combination of hard surface and tough case-core is helpful for several mechanical elements such as cams, gears, bearings, shafts, automotive elements to resist the impact that occurs during operation. Several carburizing processes have been already developed which are: gas carburizing, vacuum carburizing or low-pressure carburizing, plasma carburizing, salt bath carburizing, pack carburizing. Such methods have their limitations and advantages. However, gas carburizing is now considered as the most effective and widely used method for carburizing steel parts in high volume.

In this study, 15% of tubes outer surface was chosen and heat treated with several shapes. A key point that emerges from this study is related to the structure response (i.e., plastic flow mechanism, the energy absorbed and crush force efficiency) which is largely influenced by the treated shape. To study the geometrical effect of case-hardened forms, they are: four different ring forms (2, 3, 4 and 5 rings), two configurations with 2 and 3 uniformly distributed vertical strips parallel to the tube axis and finally 2 and 3 helical strips with three tilt angles of 30°, 45° and 60°. The behavior of the crushed materials demonstrates the dependence of the plastic buckling behavior on the composite type.

2. Originality and general scoop

In these tubular structures, as demonstrated before [e.g., [9,35,36,39]], enhancement the material performance through the loading complexity is a concept that requires further development henceforth beside the common structural design requirement. In the same state of mind, the originality of this study deals with the enhancement of the energy dissipating capacity of thin-walled cylinders loaded axially by modifying the mechanical behavior of the material in some targeted zones starting from the outer surface of the tubular structures up to a certain depth. This can be made using a specific case-hardening process. Afterwards, the obtained tubes are considered as a steel like-composite (i.e., increase the tube strength in selected zones for certain depth and form). It is so-called steel like-composite, since the product cannot be a conventional composite material. Designing