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Numerical investigations on a new type of energy-absorbing structure based on free inversion of tubes

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ABSTRACT

A new type of structure, called retractable tube, is introduced in the present work to overcome the drawbacks of two traditional types of invertubes. The inversion processes of the proposed tubes under axial compression are simulated by using the non-linear finite element code LS-DYNA and the features of the force–displacement curves and the deformation modes of the proposed tubes are analyzed. A comparative study is conducted to compare the energy absorption characteristics of the new proposed tubes with the plain circular tubes based on the performance indices used most commonly for energy-absorbing devices. The results show that the whole efficiencies of the new proposed tubes are significantly higher than those of the corresponding plain circular tubes. In addition, a parametric study is carried out to investigate the effects of geometric parameters on the behavior of retractable tubes.

1. Introduction

Circular tubes are widely used as structural components in industry applications due to their excellent load-carrying capacity and energy-absorbing characteristics. When acting as energy-absorbing elements, they show a variety of deformation modes under axial or bending loads and their behaviors have been studied by numerous researchers [1–10]. The progressive crushing of thin-walled circular metal tubes under axial loading conditions received most attentions. During axial crushing, a circular tube can deform in an axisymmetric (concertina) mode, non-symmetric (diamond) mode, mixed mode or global Euler buckling mode. This depends primarily on the geometrical dimensions of the tube, namely length, diameter and thickness.

Under certain conditions, circular tubes can show a simple and special type of deformation mode: tube inversion or invertube. The invertube has a nearly constant operating load, which is an ideal characteristic of an impact energy absorber. A circular tube can be inverted either externally or internally and there are basically two types of tube inversion [12–13]: free inversion and inversion with a die. The former method requires suitable pre-forming of the tube at one end and employing attachments to fix the formed end. The latter process requires no pre-forming operations, but a radiused or conical die must be used. Free inversion can happen if the material of the tube is ductile enough and is not highly strain hardened, while the occurrence of inversion with a die requires satisfaction of stricter conditions [14]. Tube geometry, the strength and ductility of the tube material, die radius and the condition of the contact surfaces are all influencing factors.

Experimental studies and theoretical analyses on tube inversion have been conducted by many researchers in the past four decades [11–19]. A simple expression was derived by Guist and Marble [11] to predict the inverting load for free inversion of tubes. Perfectly plastic material and constant thickness and tube length were assumed. Experimental results of the inversion load agreed well with their analytical predictions. Their theory was revisited by Reddy [13]. A rigid, linear, kinematic, strain-hardening material model obeying the Tresca yield condition with its associated flow rule was adopted in his analysis. The Bauschinger effect was included. The difference between the experimental and theoretical optimum radius during free external inversion was bridged by realizing the influence of material parameters on the natural knuckle radius. The effects of strain rate and inertia during dynamic free inversion process were further investigated by Colokoglu and Reddy [14]. However, the prediction process is very complicated and the agreement between the predictions and experiments is not very good. The predicted quasi-static inversion load is significantly lower than the experimental value while the predicted dynamic mean loads are overestimated. Experimental investigations and analytical studies on the inversion of tubes using dies were carried out by Al-Hassani et al. [12]. The external and internal inversions of tubes of different materials, loaded with different speeds and using different die angles were experimentally studied. In addition, by using power-law-type strain-hardening

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material models, expressions for the steady inverting load and the optimum die radius for the inside-out inversion of tube were given. Other studies on the tube inversion using a die were conducted by Reid [15], Chirwa [16], Rosa et al. [17], Sekhon et al. [18] and Reid and Harrigan [19] among others.

Although the tube inversion has some ideal characteristics of an impact energy absorber, such as constant operating load and high specific energy absorption (SEA) [13], there are drawbacks that limit its industry applications as energy-absorbing elements. As mentioned above, there are two types of tube inversion and their external inversion sketch is given in Fig. 1. Free inversion requires some pre-forming and necessitates attachments to fix around. In addition, more space is needed to contain the deformed tube as shown in Fig. 1(a). For inversion with a die, along with the strict conditions mentioned above, the short crushing distance feature is unsatisfactory. As shown in Fig. 1(b), when it is crushed to half the tube length, a double-walled tube is formed and a very high crushing load is foreseeable. This way of invertube has been recently utilized extensively to produce double-walled tubular parts, which are difficult to be fabricated by any other manufacturing process [17,20].

In the present work, a new type of structure based on the free inversion of circular tubes is introduced to overcome the drawbacks of the above two types of tube inversion. The sketch of the proposed structure is shown in Fig. 2. No pre-forming processes or attachments are needed and a long crushing distance can be achieved. For convenience, the structure is called retractable tube or telescopic tube here, since the shape of the tubular structure is like an antenna or a telescope. The structure is not necessarily constituted only by cylindrical tubes as shown in Fig. 2(a); it can be formed by the combination of cylindrical tubes and tapered tubes as given in Fig. 2(b). The former is called straight retractable (SR) tube and the latter is named tapered retractable (TR) tube. The length of each part is not given randomly. For the SR tube in Fig. 2(a), the lower cylinder tube has a bigger diameter and is predicted to have a higher inversion load by theoretical analysis. Therefore, the length of the upper tube is designed to be twice that of the lower tube in order to derive a high crushing distance up to two third of the whole length. For the TR tube in Fig. 2(b), the upper tube is predicted to have a higher inversion load since the lower tapered tube has a shorter inversion angle. Consequently, the length of the lower tapered tube is designed to be

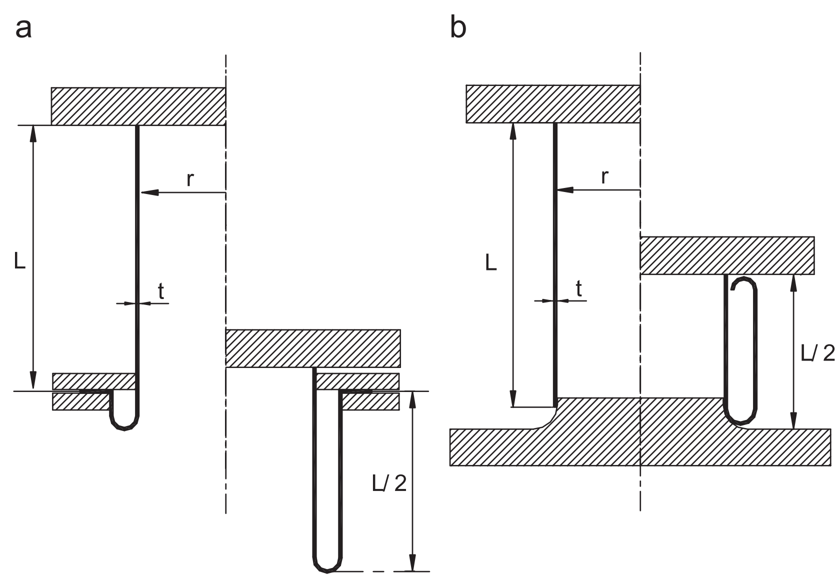

Fig. 1. Sketch for two types of tube inversion: (a) free inversion and (b) inversion with a die.

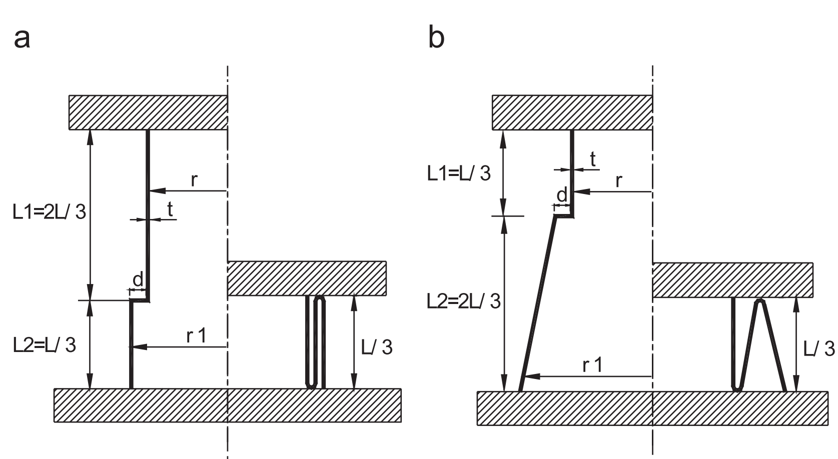

Fig. 2. Scheme of the new type of invertubes: (a) SR tube and (b) TR tube.