Thin-Walled Structures 119 (2017) 820–827

Contents lists available at ScienceDirect

Thin-Walled Structures

journal homepage: www.elsevier.com/locate/tws

Full length article

Analytical study on functionally graded thickness tubes under external inversion process

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ARTICLE INFO

Keywords:
Inversion tube
Theoretical model
Functionally Graded Thickness (FGT)
Finite element
External inversion

ABSTRACT

The axial crushing of Functionally Graded Thickness (FGT) tubes under external inversion process is studied analytically, and their results have been checked with experimental and Finite Element (FE) simulation results. Employing doubly curved shell theory and using rigid-perfectly plastic (R-PP) material idealization, a theoretical solution is derived for the crushing inversion load of a variable thickness distribution tube. Experimental tests are carried out by employing tubes with linearly variable thickness distribution, and their results compared with analytical model. It is seen that the obtained results from experiments and theoretical model show excellent agreement. To evaluate nonlinear thickness patterns behavior, numerical simulations are carried out using the explicit FE code LSDYNA. It was found that FE simulations and theoretical analysis have reasonable correlation. Finally, the study was extended to find out the most accurate loads of thickness functions that the proposed theoretical model is predicted. The results show that the predicted theoretical loads of concave and linear thickness distribution have more precision with respect to convex function based on the FE and experimental results.

1. Introduction

In modern structural design, energy absorption components and structures have many applications in automotive, aircraft, military, civil, and transportation engineering. In practice, there are different kinds of energy absorbers which could be employed in various situations based on their applications, such as in nuclear engineering [1], vehicle design [2–6], and collision protection for highway safety [7,8]. Thin-walled metal tubes widely used as energy absorbers, since they are relatively cheap and efficient for absorbing energy. During axial crushing, a circular tube can deform in an axisymmetric (concertina) mode, non-symmetric (diamond) mode, mixed mode or global Euler buckling mode [9]. This depends primarily on the geometrical dimensions of the tube, namely length, diameter and thickness. Numerous efforts have been made in the past decades to improve the crashworthiness performance of the tubes such as foam filler [10–14], introducing patterns [15], grooves [16,17], multi-cells [18,19] and functionally graded structures [20–35]. Also, Sun et al. derived the theoretical models to predict the mean crushing forces and energy absorption of axial functionally graded thickness and lateral functionally graded thickness tubes [36].

There are many energy absorption mechanisms such as folding, tube inversion, splitting, flattening and tearing. Among these axial compression modes, the inversion tube has a constant operating load and a high specific energy absorption capacity, which both of them are ideal characteristics of an impact energy absorber [37–39].

Guist and Marble [37] have reported the first experiments and analysis on the free inversion of tubes. The rigid-perfectly plastic material idealization (R-PP) was employed in their two dimensional deformation model. The inverted tube in this case assumes a natural shape in the bent region connecting the two concentric cylinders. It was found that the calculated knuckle radius was about twice that observed experimentally. This model was improved by subsequent studies; for example, the strain hardening of material was considered by Reddy [38]; a two-stage deformation assumption was proposed by Colokoglu and Reddy [39].

A theoretical analysis of the tube inversion process was presented by Miscow and Al-Qureshi [40], based on the slab method. The aim of their work was to propose a method to predict inversion load based on the quasi-static experiments. The method employs the principle of conservation of energy of the body which is totally dissipated through plastic deformation of the tube under inversion process, without considering the curl at the free end. A high peak force predicted in their study is not in agreement with the experimental data in transient stage. This model was improved by Niknejad and Moeinifard [41], in which the free end of tube was assumed to be curled up 360°. Their theoretical

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http://dx.doi.org/10.1016/j.tws.2017.08.002
Received 18 February 2017; Received in revised form 1 August 2017; Accepted 4 August 2017
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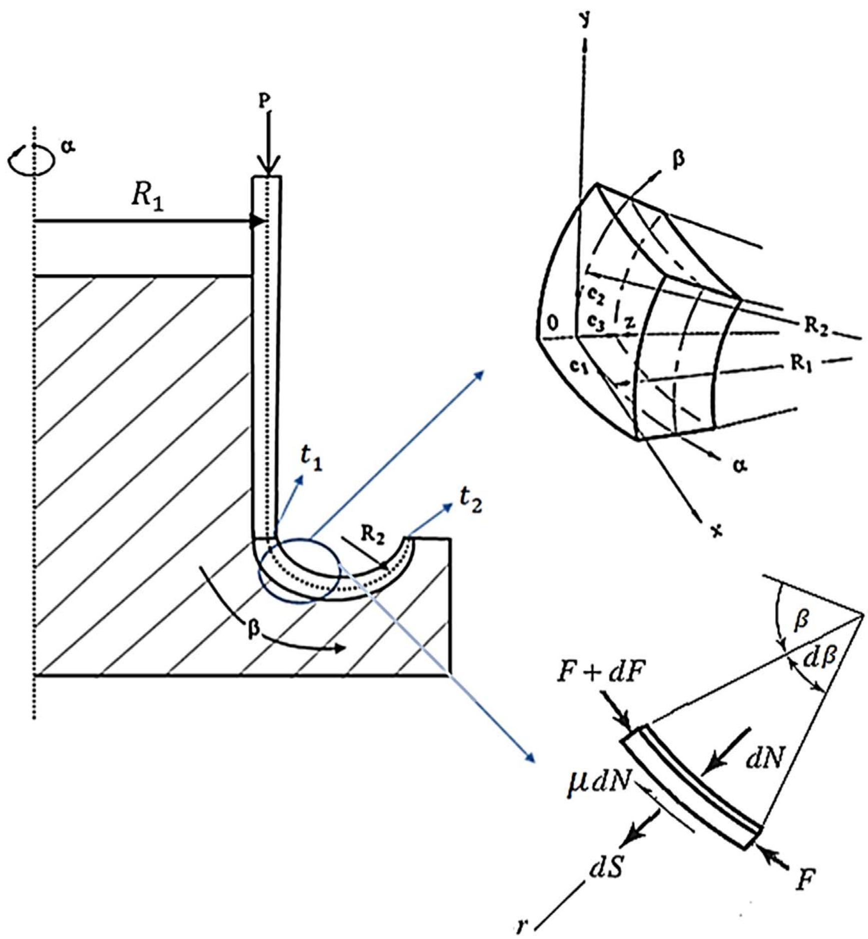

Fig. 1. The external inversion process of FGT tube over a circular die.

analysis shows that the absorbed energy in the axial load during the inversion process depends on the tube diameter and its material type, and the die radius. Their work only considers uniform thickness tubes.

Our literature review indicates that there is not a theoretical study for inversion process in the thin-walled tubes with distributed variable thickness, until now. This paper studies the characteristics of force external FGT inversion tube, theoretically. Therefore, a new theoretical model is presented and an analytical formula is derived to predict the instantaneous inversion load during the external inversion process. Then, the results obtained from theoretical model are validated by experimental and numerical simulation results. Finally, the effect of thickness distribution on energy absorption characteristics was investigated as a parametric study.

2. Theory for FGT tubes under external inversion process

In this section, a theoretical model is derived for the external inversion process of FGT tube over a circular die (Fig. 1). A circular tube with variable thickness $t(\beta)$ and undeformed average radius R_1 crushes along its axial direction under force P, over a circular die with radius r_d. As depicted in Fig. 1, the whole inverting length lies in a length in which the thickness varies from t_1 to t_2. When this inverting region is completed, t_2 will updated as t_1. This process will continue until the inverted length reaches to the specified inversion length which in this article is selected as 40 mm.

The energy dissipation in each region in the inversion process is analyzed as bellow.

The mathematical expression for grading thickness distribution of FGT tube is presented by

$$t(\beta) = t_1 - (t_1 - t_2)\left[\frac{\beta}{\pi}\right]^m 0 \le \beta \le \pi \tag{1}$$

According to Eq. (1), in FGT tube, the thickness of the tube decrease from maximum valuet_1 to minimum value t_2 and the distribution function is concave for the value of exponent gradient $m > 1$ and is convex for the value of exponent gradient $m < 1$ (Fig. 2).

Considering Δx as total displacement of compression load P during the inversion deformation, and defining F_{fri} as friction force between the tube and die, the total plastic dissipation U according to energy

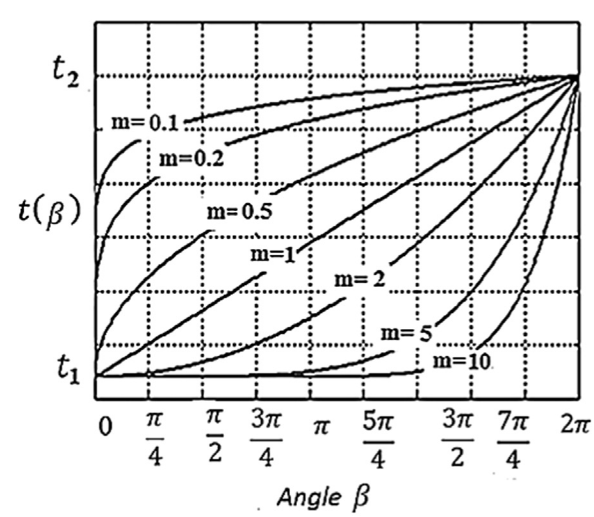

Fig. 2. Variation of thickness vs. inversion angle.

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