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Original Research Article

Experimental and numerical investigation of the effect of the combined mechanism of circumferential expansion and folding on energy absorption parameters

Mostafa Abolfathi, Ali Alavi Nia [*], *Ali Akhavan Attar, Mohammad Abbasi*

Department of Mechanical Engineering, Bu-Ali Sina University, Hamedan, Iran

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ABSTRACT

In this research, in order to increase energy absorption of thin-walled tubes, a combined deformation mechanism is proposed which involves the simultaneous combination of circumferential expansion and folding. Such a combined mechanism was not concerned in the literature. The study is carried out both experimentally and numerically. A special device was designed and made to conduct experimental tests on tubes. The samples were made of aluminum, and quasi-static loading was applied at two different speeds of 10 and 200 mm/min. Energy absorption parameters including specific energy absorption (SEA), crushing mean force, initial peak force, the deformation mode and crush force efficiency (CFE) were studied. Experimental results showed that combined mechanism (without lubrication) could increase absorbed energy up to 123% compared to the folding mechanism. If the lubricant is used, the increase will be up to 97%. The combined deformation mechanism (without lubrication) increases absorbed energy up to 94% compared to the circumstantial expansion. This value will be 107% with lubrication. In addition, the initial peak force in the combined mechanism decreases between 8% and 36% relative to the folding mechanism. The circumstantial expansion in the proposed mechanism is complete and the expansion stroke length is 100%, while this stroke was less in the previous researches due to design restrictions. Numerical simulations were conducted using LS-Dyna software and there is good agreement between the numerical results and experimental data.

1. Introduction

Today, a variety of thin-walled structures are used as energy absorber in order to protect structures and withstand the destructive effects of impact under different conditions. Extensive research in this context has so far been carried out through analytical, numerical and experimental methods. These parts absorb the impact energy in different ways including lateral collapse [1–3], inversion [4,5], bending [6] and

* *Corresponding author.*
E-mail address: alavi495@basu.ac.ir (A. Alavi Nia).

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splitting [7]. Among the various types of collapse, two methods of axial collapse or folding and circumferential expansion are considered in this research.

In the study of energy absorption by circumferential expansion, an expansion mechanism with rigid die and ductile tube was suggested for the first time by Eddins [8] for the aircraft landing system.

Deformation in the form of circumferential expansion of cylindrical thin-walled tubes as an energy absorber was experimentally and numerically studied by Shakeri et al. [9]. In this work, a rigid tube is plunged into the thin-walled tube under axial pressure load. In this case, the impact energy is absorbed as expansion energy consumed by plastic work done on the ductile tube as well as frictional energy between the contact surfaces of two tubes. They showed that the mean crushing force can be affected by the thickness and tolerance between the rigid tube and the absorber tube, and the amount of friction coefficient. Due to the circumferential expansion, energy absorption of tubes was experimentally and numerically investigated by Yang et al. [10]. According to their results, the contribution of friction in the energy absorption of circumferential expansion was 22% of total absorbed energy. Also, for the tubes with smaller thickness, the expansion process occurs faster; moreover, in this case there is more contact between surfaces. In another work by Yan et al. [11], several mandrels were made with tip angles of 5–40 degrees and friction coefficients were considered from zero to 0.3 to acquire the appropriate angle of mandrel tip and friction coefficient. They proved that the relationship between the expansion angle and the loading force is nonlinear, while the coefficient of friction and the loading force have linear relation with each other. They reported the most appropriate angles for expansion between 10 and 20 degrees. As an energy dissipation mechanism, circumferential expansion of cylindrical tubes was experimentally and numerically investigated by Tavakoli [12].

Some theoretical works have been done in the field of energy absorption due to axial collapse [13–15]. Also, several studies have been conducted to study the effect of geometric parameters of energy absorber [16,17], quasi-static or dynamic loading as well as the effect of impact velocity [18–20] and the use of composites for the production of energy absorbers [21].

In addition, design and geometry of the energy absorber structure have been of interest to improve energy absorption in axial collapse deforestation. For example, changing the geometry of the tube section [22], making tubes with variable thickness [23,24], creating grooves and controlling buckling [25,26], adding internal and external stiffeners to the structure [27], use of glass-epoxy coating for the metal tube [28], the use of multi-cell absorbers [29,30], creation of circumferential and axial folding on the tube [31] and use of nested tubes as an energy absorber structure [32,33] are some of the changes that improve energy absorption in axial collapse.

Experimental investigations on the energy absorption in the process of shrinking–splitting of a cylindrical tube were carried out by Tanaskovic et al. [34]. In their study, energy absorption is performed by plastic deformation and the friction between the tube and the rod. After passing the cone section, the tube changes its way in the opposite direction of the splitter and more energy is lost during the process. The results showed that the combined absorber increases absorbed energy up to approximately 60% relative to shrinking absorber alone. Experimental and numerical study on energy absorption of cylindrical tubes in the expanding–splitting process was performed by Li et al. [35]. According to their research, the deformation involved two phases. The first phase of deformation included tube expansion by cylindrical mandrel and the second phase included the splitting of the expanded tube along with the initial scratches by the conical section of mandrel. Quasi-static compression test indicated that this kind of combined energy absorber increases the absorbed energy 95.34% relative to purely expansion deformation.

The main purpose of the present study is to provide a combined deformation mechanism that has larger energy absorption compared to two the previously introduced combined mechanisms. In previous studies, two mechanisms of shrinking–splitting and expansion–splitting have been discussed. In this research, combined mechanism energy absorption including circumferential expansion and folding was studied. Aluminum tubes with a suitable ductility were used as energy absorbers and axial quasi-static loading of structures was carried out. To do the loading, a special fixture was designed and built to do the two processes together. In addition to experimental tests, a numerical simulation was also done by finite element software LS-Dyna.

2. Experimental tests

2.1. *Specifications of samples*

Tests samples, in the form of a thin aluminum cylinder with an outer diameter of 70, thickness of 0.6, length of 107 mm, and mass of 102 g, were used. Chemical composition of the samples which has been determined by quantometery test based on ASTM E826 standard [36] is presented in Table 1. According to reference [37], the tube material is close to the aluminum alloy of the 1100 series.

To ensure the ductility of the tube, tensile test with a speed of 2 mm/min was performed. Fig. 1 shows tensile test samples according to ASTM E 8M standard [38] before and after the test. Engineering stress–strain curve obtained from the tensile test as well as the true stress–strain curve is indicated in Fig. 2.

2.2. *Design and manufacture of the fixture and the method of its usage*

One of the important parts of this research is designing a device that performs combined process of energy absorption in the desired form. Expected combined process is carried out by a mandrel with a rigid support attached to the end of it. Tubes with specified dimensions were expanded circumferentially at first, then, expanded tube was axially crushed.

The initial design of the fixture was prepared in Solidworks software (Fig. 3) and after ensuring its ability to work properly, designing components were made with proper tolerances. This apparatus has a mass of 24 kg and its overall dimensions are $(280 \times 280 \times 580\ \text{mm})$. Components of the device are shown in Fig. 4.

Making mandrel both in terms of expansion diameter and cone angle requires high precision. Moreover, its material