Thin-Walled Structures 47 (2009) 1469–1477

Contents lists available at ScienceDirect

Thin-Walled Structures

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

Energy absorption of longitudinally grooved square tubes under axial compression

Xiong Zhang, Hoon Huh *

Department of Mechanical Engineering, Korea Advanced Institute of Science and Technology, Science Town, Daejeon 305-701, Republic of Korea

ARTICLE INFO

Article history:
Received 13 January 2009
Accepted 14 July 2009
Available online 5 August 2009

Keywords:
Square tube
Thin-walled structure
Groove
Energy absorption

ABSTRACT

This paper investigates the energy absorption characteristics of longitudinally grooved square tubes under axial compression by using explicit nonlinear finite element code LS-DYNA. The grooves are fabricated by stamping and the distributions of the effective plastic strain and the thickness variation from the stamping process are considered in the following crash analyses. From the simulation results, we find that when grooves are introduced on the sidewalls, the specific energy absorption of conventional tubes can be increased by up to 82.7% and the peak force can be reduced by up to 22.3%. The influences of several parameters, including the width of the tube, the length of the groove and the number of the grooves, are analyzed and the features of the deformation modes of grooved tubes are described. The introduction of groove is found to be an effective way to improve the crashworthiness of thin-walled structures.

1. Introduction

Tubular thin-walled structures with different shapes of sections are widely used in various transportation systems as energy absorbing components to dissipate the kinetic energy during accidents of collision and crash. To design these structures with less weight and excellent crashworthiness performance is a significant task for the sake of public safety, energy saving and environmental protection. Light and efficient energy absorbing devices should have high specific energy absorption (SEA, that is energy absorption per unit structural mass) values and low maximum reaction forces during the impact processes. Researchers and engineers have proposed a variety of methods to achieve these goals and great progresses have been made.

Filling tubular structures with appropriate lightweight materials such as foam or honeycomb materials is one of the options to improve the energy absorption characteristics and has been studied extensively [1–8]. Designing the columns with internal webs is one other way to increase the energy absorption efficiency. Both the energy absorption and weight efficiency could be significantly enhanced when the single cell cross section was replaced by multi-cell profile, according to Chen and Wierzbicki [9], Kim [10] and Zhang et al. [11,12]. Introducing a group of regular patterns to the face sheet of thin-walled structures is another method recently suggested by Zhang et al. [13] to control and change the deformation modes of them under compression. Two types of patterns were introduced to square tubes and performed very well.

Grooves or corrugations can be very easily produced on metal sheets by a stamping process. As shown in Fig. 1, a groove is stamped on the front side member of a car. The influence of grooves or corrugations on the energy absorption of components has been studied by many researchers. Experimental researches were carried out by Singace and El-Sobky [14] to investigate the effect of introduction of corrugations on the load-displacement and energy absorption characteristics of circular aluminum and PVC tubes. Mild steel die blocks were used to form the corrugations on straight tubes. Daneshi and Hosseinipour [15] experimentally studied the effect of introducing grooves to circular steel tubes under axial crushing. Alternately inside and outside annular groove patterns were scratched on the tube surface. They all found that corrugations or grooves could control the energy absorption of the tubes to some extent and improve the uniformity of the load–displacement curve. The energy absorption capacity of the tubes, however, was reduced in comparison with conventional tubes. Experimental tests and numerical simulations conducted by Lee et al. [16] and Mamalis et al. [17,18] for the effect of dents on axially compressed square and circular tubes showed similar results. After review of previous literatures, it was found that grooves are all generated transversely rather than longitudinally on the surface of the tubes when the tube is loaded axially. However, the grooves along the loading direction may greatly increase the ability of tubes to resist crushing and their capacity of energy absorption. Recent

* Corresponding author. Tel.: +82 42 350 3222; fax: +82 42 350 3210.
E-mail address: hhuh@kaist.ac.kr (H. Huh).

0263-8231/$ - see front matter
doi:10.1016/j.tws.2009.07.003

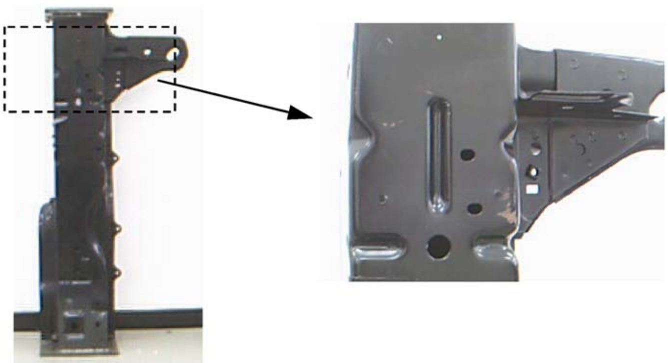

Fig. 1. Groove introduced on front side member of a car.

investigation conducted by So and Chen [19] and Chen et al. [20] showed that the critical crushing loads and energy absorption of plates under axial compression were enhanced by several times by stamping with V-grooves.

In this paper, the influence of longitudinally distributed grooves on square tubes under axial compression was investigated with numerical simulation. Grooves are fabricated by stamping and the whole metal forming process is simulated by using a commercial explicit nonlinear finite element code LS-DYNA [21]. Distribution of the effective plastic strain and the thickness variation from simulation of sheet metal forming are considered in the following crash analyses. The deformation mode and energy absorption characteristics of grooved tubes are investigated and compared with that of corresponding simple tubes without grooves. The paper is organized as follows. In Section 2, the finite element models for stamping and crash processes are present. Section 3 conducts some preparation work before the investigation of grooved tubes under axial crushing. In Section 4, the energy absorption characteristics of grooved tubes with different configurations are studied. Finally, Section 5 summarizes the present work.

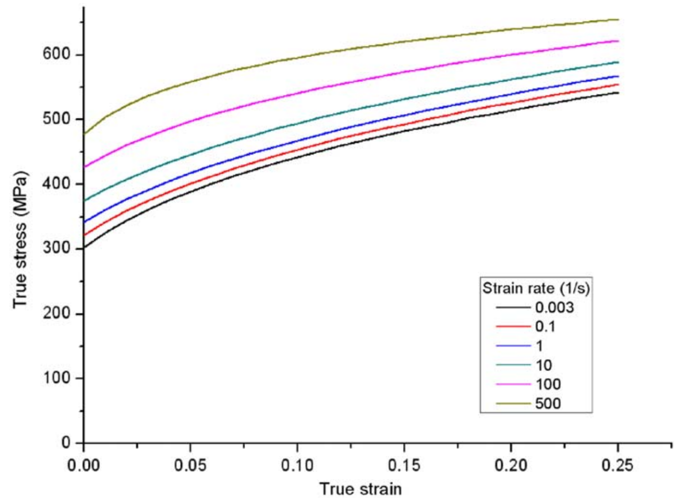

Fig. 2. True stress–strain curves of mild steel SPRC40R.

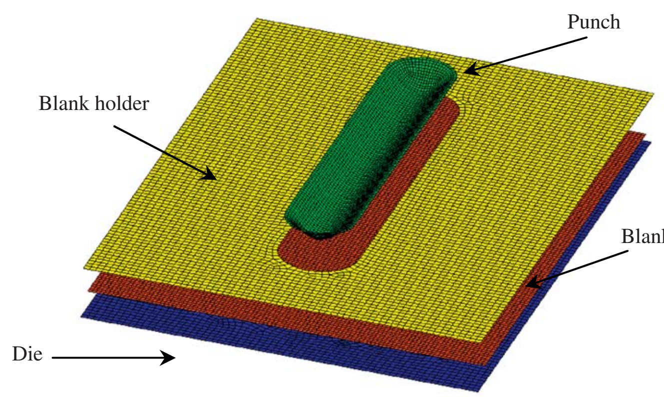

Fig. 3. Finite element models of a stamping system.

2. Finite element modeling

2.1. Material properties

The material of tubes used here is high strength steel of SPRC40R with its mechanical properties: Young's modulus $E = 210$ GPa, the initial yield stress $\sigma_y = 302.2$ MPa, the ultimate tensile stress $\sigma_u = 425.2$ MPa, Poisson's ratio $v = 0.3$ and the power law exponent $n = 0.21$. True stress–strain curves for this material is obtained by experiment and shown with the variation of strain rate in Fig. 2. The strain rate effect can be accounted by using the Cowper and Symonds model that scales the flow stress with the factor $1+(\dot{\varepsilon}/C)^{1/P}$, where C and P for SPRC40R are 42322 s^{-1} and 4.4, respectively.

2.2. Stamping analysis

A representative finite element model for a stamping process is show in Fig. 3. All parts of the stamping system were modeled using the Belytschko–Tsay 4-node shell elements with five integration points through the thickness and one integration point in the element plane. The blank sheet is simulated by material model #24 MAT_PIECEWISE_LINEAR_PLASTICITY in LS-DYNA, while the tools are regarded as rigid. The characteristic size of mesh is 1 mm for the blank sheet and 1 or 1.5 mm for the tools. The loading velocity of punch is controlled by a sinusoidal curve, which ensures the acceleration to be zero in the beginning and end of the analysis. Uniform pressure of 2 MPa is applied in the blank holder before the stamping process. Forming surface to surface contact is employed to consider the contact between the blank and the tools with the Coulomb friction coefficient of 0.15.

The dimensions of the groove region of a punch and die are shown in Fig. 4. The section of the groove was fitted with a B-spline curve which consists of five points. Three points are marked in the figure and the other two points can be obtained by symmetry. The two ends of the groove are formed by rotation of the above spline curve and they are not included in the length of the groove H as shown in figure. The groove located in the middle of the blank with the dimensions: width = 100 mm; length = 130 mm; and thickness = 1.2 mm. The length of the groove H is modified in later section to consider its influence, while other parameters are kept invariable. The effective plastic strain and thickness variation of a blank are given in Fig. 5 when the groove length is 80 mm. After the stamping process, the blank is trimmed and remeshed. Results obtained from stamping are mapped into a new mesh system and square tubes were assembled from grooved sheets.

2.3. Crash analysis

Crash models of square tubes with and without grooves are shown in Fig. 6. For conventional tubes without groove, the