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Experimental study on thin-walled grooved tubes as an energy absorption device

G. H. Daneshi & S. J. Hosseinipour
Department of Material Science and Engineering
Sharif University of Technology, Tehran, Iran.

Abstract

Axial crushing behavior and crashworthiness characteristics of thin-walled steel tubes containing annular grooves are experimentally studied. The grooves determine the position of the folds and control the buckling mode of deformation. The aims are improving the uniformity of the load-displacement behavior and predicting energy absorption capacity of the tubes. Grooves are cut circumferentially and alternately inside and outside the tubes at predetermined intervals. Quasi-static axial crushing tests are performed with different groove distances. Photographs are taken during axial buckling and the specimens after crushing are sectioned axially to carry out the measurements. The deformation modes and load-displacement curves are described and energy absorption and mean post-buckling load are determined. In almost all the specimens the convolutions are achieved by folding in an axisymmetric concertina mode about circumferential grooves. The results show that the load-displacement curves and the energy absorbed by the axial crushing of the tubes could be controlled by changing the distances between the grooves. It is also found that grooves can stabilize the deformation and thus grooved tubes are good candidates for controllable energy absorption element.

1 Introduction

The use of thin-walled tubes collapsing plastically in axial compression is one of the most efficient means of energy absorption. These tubes are light in volume and weight, easy to fabricate and cheap, and stable during crushing. They have been the subject of numerous investigations into the crumpling mechanisms of components made from different materials and various geometrical shapes. Experimental results show that axial crushing load-displacement curves in tubes are highly non-uniform in character. The height of the first peak (collapse load),

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which is associated with the first hinge, is much bigger than the other peaks. The uniformity of the crushing load and deceleration pulse could be obtained by introducing grooves along the tube to guiding the maximum plastic moment to occur in certain position. Studies on the ways of controlling the deformation mechanisms by introducing geometrical discontinuities are few. Mamalis *et al.* [1-3] report the crumpling of thin-walled grooved tubes. They examined PVC and steel tubes with two kinds of groove patterns; external circumferential grooves and internal axial grooves. They reported non-axisymmetric diamond mode of deformation in both cases. Singace *et al.* [4] have carried out different axial crushing tests on aluminum and PVC corrugated tubes. Effect of circular holes on axial collapse behavior of circular tubes was investigated by Gupta *et al.* [5].

In the present paper the crashworthiness characteristics of thin-walled tubes with alternately inside and outside annular groove patterns are experimentally investigated. The aim is to achieve a method to control the buckling mode and the energy absorption characteristics and to improve the uniformity of the load-displacement curves. Different axial quasi-static crushing tests on steel tubes are performed and the deformation behavior, load-displacement curves and energy absorption characteristics of the tubes are studied.

2 Experimental Procedure

Seamless mild steel tubes of commercial quality with 60 mm outside diameter and 5 mm wall thickness are machined to the required size, as shown in Table 1. Annular grooves are cut alternately inside and outside the tube surfaces. The grooves are 3 mm wide and 1 mm deep. To achieve symmetry of deformation, the numbers of grooves are chosen to be odd and the first groove is inside the tube wall. The lengths of the specimens are chosen to be proportional to the distances between the grooves (1). One specimen is without groove for comparison purposes. Details of the specimen dimensions are given in Fig. 1.

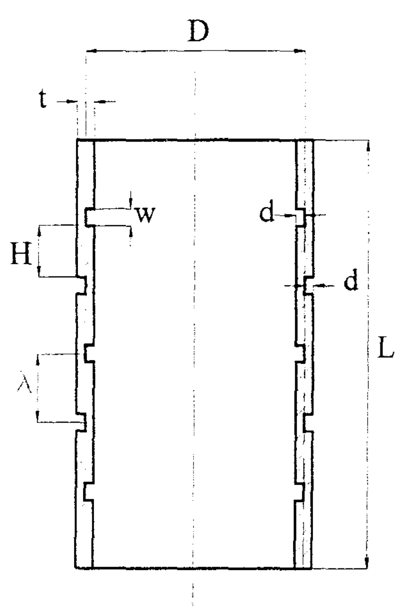

Figure 1: Details of the specimen design.

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Table 1: Specimens dimensions and experimental results after axial crushing.

Specimen No.	Mean diameter **D** (mm)	Wall thickness **t** (mm)	Length ratio **L/1**	Groove distances **1=H+w** (mm)	Number of grooves **N**	Crush length **D** (mm)	Buckling mode **	Fold length **F** (mm)	Eccentricity factor **m**	Collapse load $\mathbf{P_i}$ (KN)	Energy absorbed **E** (J)
A *	54	2	*	-	-	70	2C→D	-	-	146.5	5688
B1	54	2	20	5	19	61.7	10C	5.3	0.66	26.4	2469.3
B2	54	2	18	6	17	73.4	9C	5.95	0.62	24	2125.8
B3	54	2	16	7	15	76.4	8C	6.75	0.67	47.2	3617.7
B4	54	2	12	9	11	80.7	6C	8.49	0.68	50.4	3112
B5	54	2	10	11	9	85.7	5C	11.4	0.60	70.4	4570.9
B6	54	2	8	13	7	81.4	4C	12.66	0.69	85.6	4752.4
B7	54	2	6	16	5	71.3	3C	15.75	0.65	92.8	4842.7
B8	54	2	6	18	5	83	1C→D	-	-	93.6	5449.2
B9	54	2	4	21	3	54	1C→D	-	-	95	4994

* Simple specimen, L=100 mm
** C: Concertina, D: Diamond

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Quasi-static axial compression tests are performed in a 20 tons AMSLER hydraulic testing machine at a nominal crosshead speed of 5 mm/min. The specimens are crushed, in as-received condition, between parallel steel platens of the test machine without any additional fixing. Photographs at different stages of the axial buckling, are shown in Fig. 2. Figure 3 shows the specimens after crushing. The crushed specimens are sectioned axially Fig. 4 and the curved lengths of the folds at both sides of the original diameter of the tube are measured after magnifying the image suitably. Load-displacement curves are plotted in Fig. 5. Energy absorption and mean crushing loads are calculated by measuring the area under the load-displacement curves. A summary of the results is shown in Table 1.

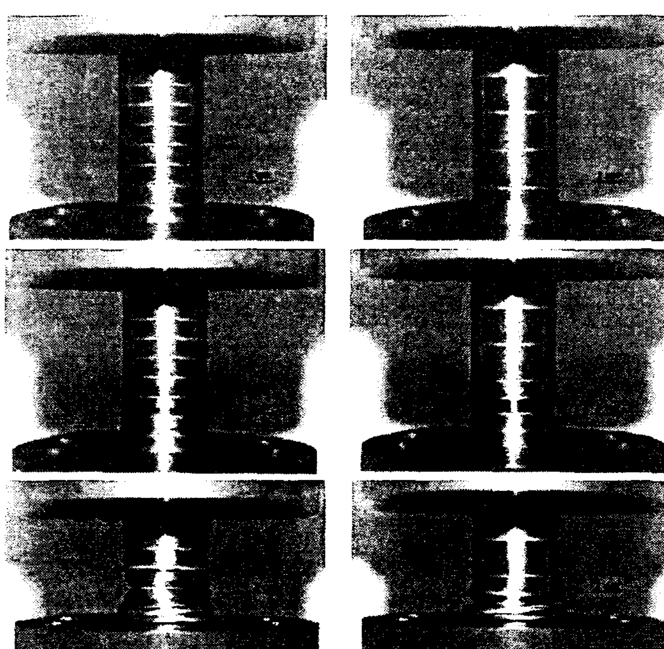
3 Results and Discussion

Figure 2 shows grooved specimens during axial buckling. It can be seen that, after an initial elastic deformation, the first plastic hinge is formed in the grooves, usually near one end of the tube. The mechanism of traveling hinges of constant radius around the circumference can be clearly observed. The plastic hinges in internal grooves move towards the outside of the tubes, and the plastic hinges associated with external grooves move towards the inside of the tubes. This leads to the formation of convolutions in concertina mode.

(I)

(II)

(II)



(a) (b)

Figure 2: Specimens (a) ***B2*** and (b) ***B5***, (I) before axial loading (II) during initial buckling (III) during axial crushing.

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Photographs of the crushed tubes are shown in Fig. 3. It is seen that for specimen *A* the deformation begins in concertina mode and after formation of two rings changes to diamond mode. The shift from one mode of deformation to another depends mainly on D/t ratio and material properties. Grooved specimens ***B1*** to ***B7*** buckle completely in concertina mode. Each convolution is between two external grooves and each folding is between two consecutive grooves. The number of folds is equal to ratio of initial tube length to groove distances (L/l) and the fold length is equal to groove distances l. As the distance between the grooves increases the stretching between the grooves increases too. At higher distances the concertina mode of deformation cannot be sustained and hence the buckling mode is changed to diamond mode. For specimens ***B8*** and ***B9***, where the groove distances are 18 and 21 mm the deformation begins in concertina mode and after the formation of one convolution changes to diamond mode. In this case the grooves have no important role in controlling the deformation. In both specimens the diamond buckling is continued with the formation of a double lobe elliptical type folding.

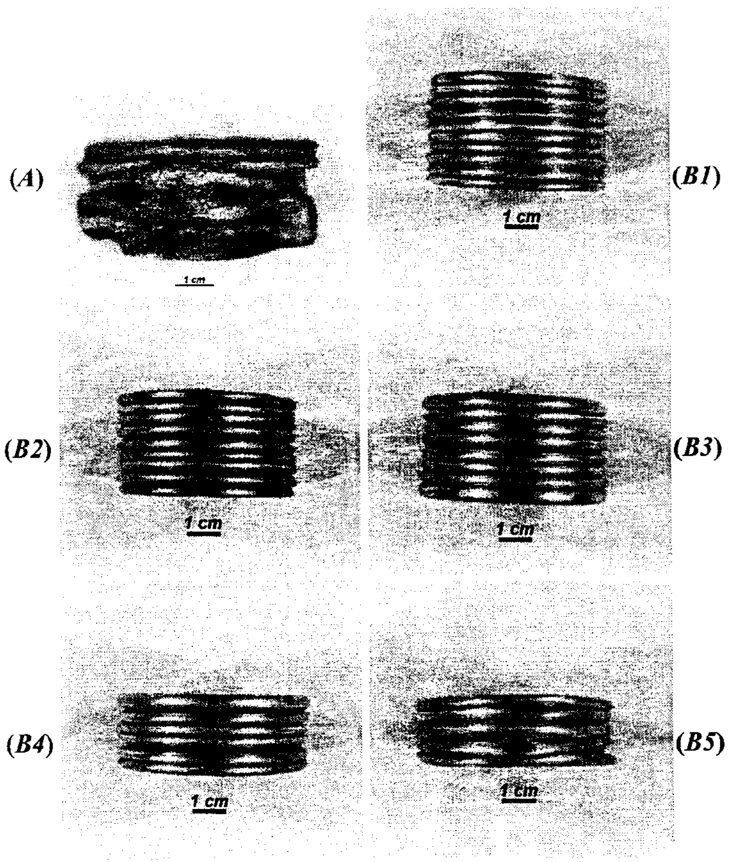

Figure 3: Specimens after axial crushing.

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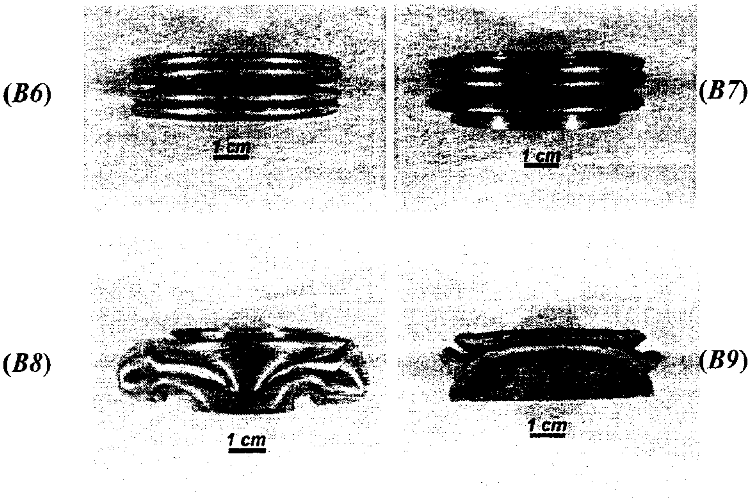

Figure 3: Continued

In all grooved specimens the convolutions are flattened approximately into discs and there is not any curved regions in plastic hinges Fig. 4. This is due to the reduction effect of the grooves on strain hardening in plastic hinges and leads to an increase in crush length. The fracture, which is observed in some cases along the grooves, is thought to be the result of the stretching of the grooves. Stress concentration in the grooves and notch effect of the sharp corners may be responsible for this effect too. The eccentricity factor (**m**) is presented in Table 1. Their value of about 0.65 is comparable to results given by Singace *et al.* [6,7]. The results show that the grooves with different distances have no important effect on the eccentricity factor.

The load-displacement curves are shown in Fig. 5. Initially, the shell behaves elastically and the load rises at a steady rate to a maximum value. Then the material yields and the first circumferential plastic hinge is developed. After that the load falls and the deformation becomes unstable until a fold is developed. The load fluctuations in the grooved specimens are much less than those of the simple specimen (*A*). The grooves reduce the overall wave amplitude and the mean crush load, a property that is favorable in an efficient energy absorption device. It is seen that the collapse load (first peak) decreases with decreasing groove distances (Table 1). Mamalis *et al.* [2] have mentioned this result for steel tubes with external circumferential grooves.

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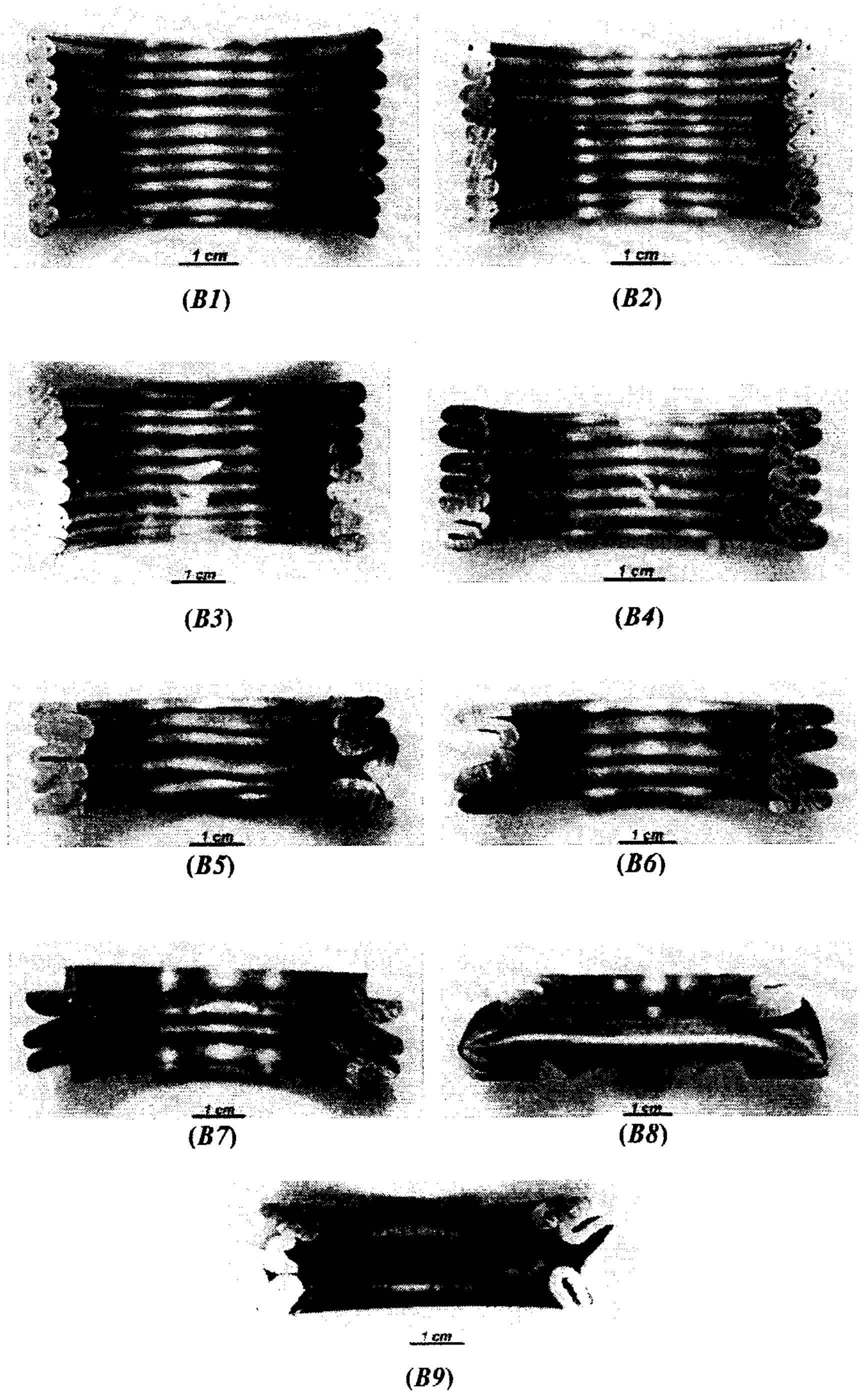

Figure 4: Axially sectioned specimens after axial crushing.

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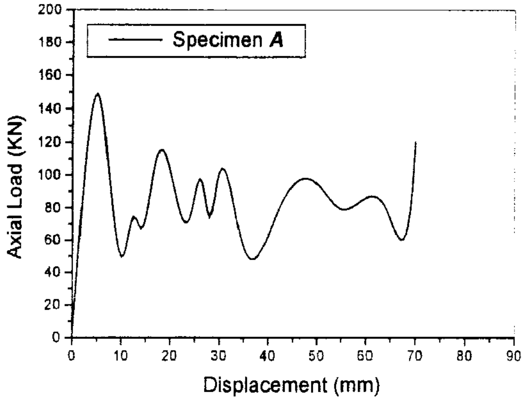
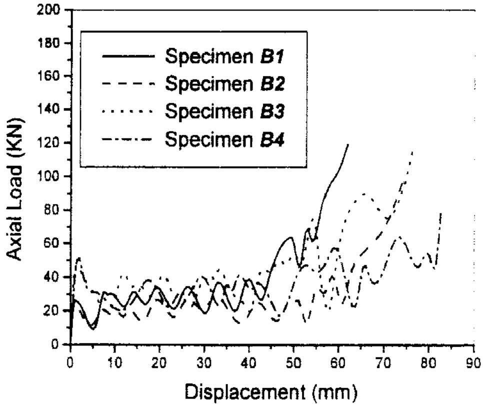
(a)



(b)



(c)

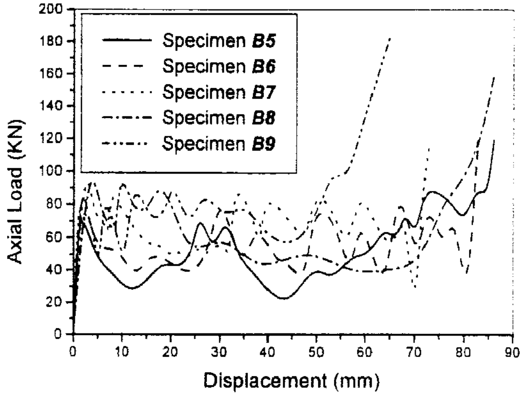


Figure 5: Load-displacement curves, (a) specimen *A*, (b) specimens ***B1-B4***, (c) specimens ***B5-B9***.

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Figure 6 shows the specific energy absorption of the tubes versus groove distances. It is seen that the introduction of the grooves reduces the energy absorption capacity of the tube as compared to those of the simple tubes. This is due to the fact that in simple tube, part of the applied load is dissipated during the formation of the plastic hinges. The introduction of the groove helps in directing the failure along the groove trough, thus the amount of work required for a complete crush is reduced. However work is still necessary for bending about and stretching between plastic hinge lines. The same behavior is observed in Fig. 7 where mean crushing load is plotted versus groove distances.

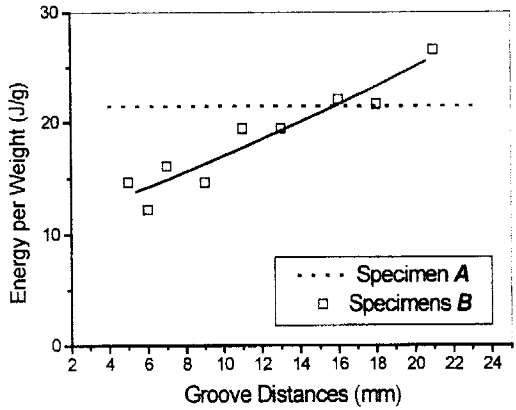

Figure 6: Specific energy versus groove distances.

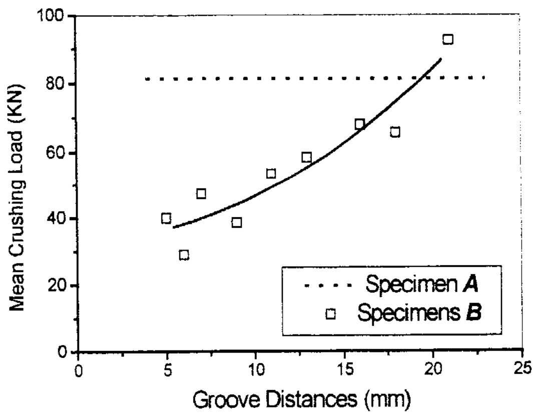

Figure 7: Mean crushing load versus groove distances.

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4 Conclusions

The deformation mechanisms and the crashworthiness characteristics of the grooved tubes subjected to axial loading and based on experimental observations are described. Experimental results indicate:

- The axial crushing behavior of tubes can be controlled by the introduction of grooves through which circumferential plastic hinge lines are forced to develop at certain positions along the grooves.
- Grooves at short intervals force stable deformation in concertina mode, but they have no significant role in controlling deformation modes at longer intervals.
- Grooved tubes show favorable characteristics as energy absorption elements. Load uniformity and low deceleration pulses are observed in these tubes.
- Introducing the grooves with different distances results in smoother load-displacement curves and predictable energy absorption capacities. Thus for a controlled behavior of energy absorption device, grooved tubes are a favorable choice.

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