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THE AXIAL CRUSHING OF CIRCULAR TUBE UNDER QUASI-STATIC LOADING

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ABSTRACT

This paper presents the effect of round hole on the peak load and energy absorption of circular tube structure. Circular tube made of mild steel was used to observe modes of deformation and load-displacement characteristics during experiment. Axial crushing tests were carried out on the tubes under quasi-static loading condition. The load-displacement characteristics of tested curves are presented. Experimental results of round hole with 10mm diameter at the middle of samples showed 10.45% decrease of peak load than without hole. Energy absorption experimentally slightly decreased than without hole. It has been found the diameter of round hole has a considerable effect of the collapsed characteristics of tubes. Comparison of theoretical and experimental of crushingbehavior of circular tube under axial quasi- static loading is presented.

Keywords: energy absorption, axial crushing, round discontinuous.

1. INTRODUCTION

Every year, the numbers of deaths increased by vehicle accident to several million deaths [1]. Due to this increase of deaths, the high cost of vehicle repair and road maintenance [2], engineers and the designers of automotive tried to reduction the impact loads through several mechanisms of energy absorption. The use of structural forms as energy absorption devices to protect passengers needs to two conditions: increase the energy absorption and decrease the peak load [3].Tubular forms of energy dissipation units which are often utilized in a lot of implementations as in aircrafts and vehicles. The reason to use the tubular structure is that it has simple geometry, low cost and high energy absorbing capability [4]. Different structures such as circular, square, multi-corner etc., have been investigated by some researchers. Gupta *et al* studied the effect of circle discontinuities through circular tube [5]. In this paper, the effect of round hole in the circular tube under axial loading between two rigid plates on peak load will be studied by using experimental and theoretical approach

2. ENERGY ABSORPTION

The most important parameter due to the impact is energy absorption where it plays the principal role in decreasing the damage and provide the protection of occupant and vehicle.

a) Axial loading

Best energy absorption under axial crushing is achieved by continuous or progressive buckling which contributes to energy absorption through plastic deformation than an Euler-type buckling [6]. The behavior of axial crushing of many shapes of tubes was investigated by some studies. Square and circular tube where seized the attention of researchers. Therefore,Abramowicz and Jones [7] studied the behavior of transfer from initial Euler to continuous buckling of thin-walled square and circular tube under axial loading conditions. They used different cross section and length of square and circular tube, were found the transition depends on length, cross section, type of material, strain rate and strain hardening of the tube see Figure-1.

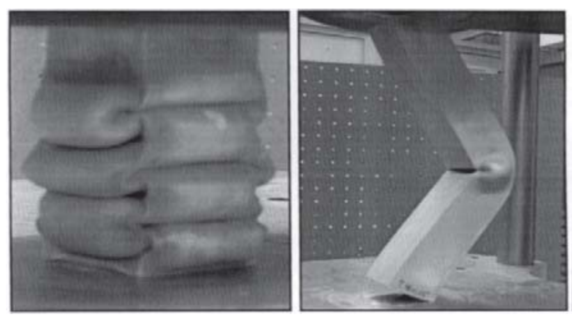

Figure-1. (i) Progressive buckling mode at axial load (ii) global bending mode at axial load [8].

i. Circular tube under axial crushing

The primarily theoretical work on the plastic collapse of tubes and columns by the pioneering work of Alexander [9].He presented a problem of collapse for circular tube under axial compression in experimental work, after that in theoretical assumption and he suggested the method to the determination of the basic parameters of the crushing by a simple formula. Figure-2 explains Alexander model.

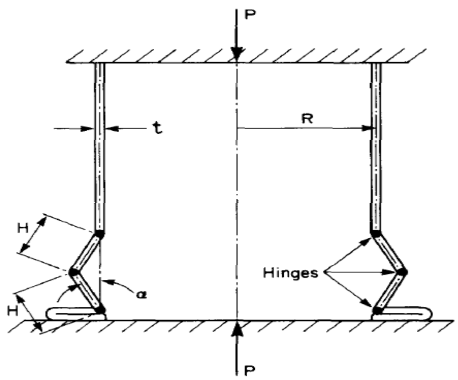

Figure-2. The axial crushing of tube Alexander model [10].

b) The characteristic of load-displacement curve

In axial compression crushing when the first folding start in load-displacement curve clearly hasthe highest value and this value represents the peak load or maximum load (P max). The mean load (medium load) can obtain from the load-displacement curve as illustrated in Figure-3.

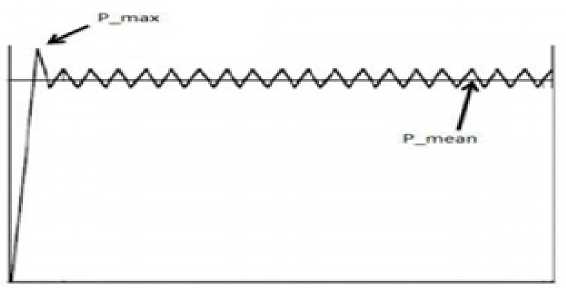

Figure-3. Ideal curves of load-displacement explain the peak load & mean load [11].

From this two values of peak load and mean load can calculate the value of crush force efficiency (CFE) by divided mean load over maximum load as shown in equation (1) [11].

$$CFE = P_{mean} / P_{max} \quad (1)$$

The crush force efficiency is a very important parameter used to evaluate the performance of energy absorbing structures [12]. Therefore, it can get a high value of crush force efficiency by reducing peak crushing load.

The energy absorption of the tubes was evaluated from the area under load-displacement curves that describes the work done by the crushing force [9]. To calculate the energy absorbed as an integration of a load-displacement curve by using equation (2) [8].

$$E_{absorbed} = \int P \cdot d\delta \quad (2)$$

Where;

P = crushing load (N)
δ = the deflection of the tube (mm)

Figure-4 explains the energy absorption as the area under the curve (blue area).

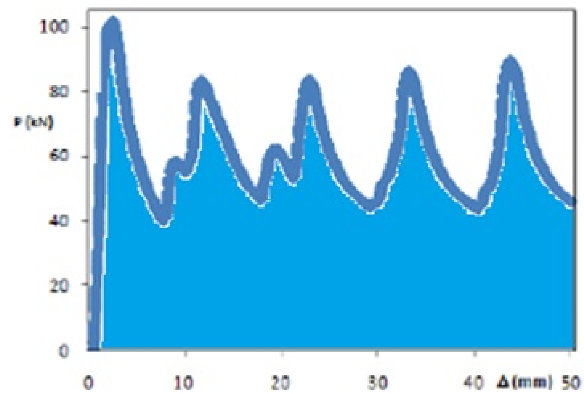

Figure-4. Energy absorption in load-displacement curve [13].

c) Types of modes

There are three types of mode of deformation:

i. **Concertina mode**

The work of Alexander [9] explained the analysis of the concertina mode when he used thin cylinder under axial loading and he put formula for mean load or mean crushing load, equation (3)

$$P_m = 6Yt\sqrt{D/t} \quad (3)$$

Where D is the outerdiameter, Y means yield strength and t represents the thickness of tube. The equation offers a good estimate for often substances when D/t < 30, also consider the greatest celebrated equation of the axial load Figure-5. Other authors [14] improved Alexander's expression that offered mean load's average for the axisymmetric mode to be in the equation (4).

$$P_m = Yt\,(6\sqrt{D/t} + 3.44t) \quad (4)$$

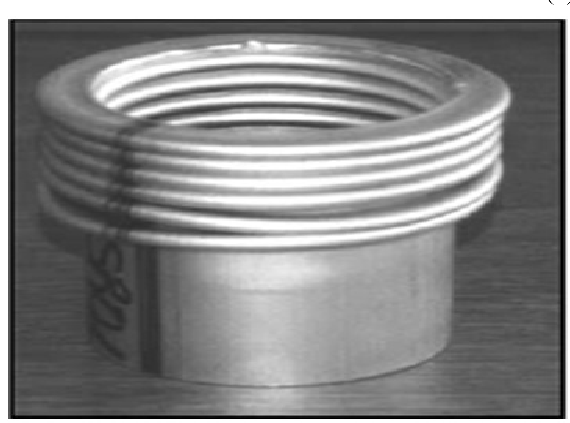
Figure-5. Concertina mode-all fold like ring [15].

ii. Diamond mode

The pioneer studied the diamond mode is Pugsley and Macaulay [16] they used thin cylinder tubes (high D/t) and suggested a theoretical approximation of axially mean load in the formula, equation (5).

$$P_m = Yt\,(10.05t + 0.38D) \tag{5}$$

After that Pugsley [17] suggested another model to the non-axisymmetric mode built on folding or lobes of row Figure-6, and he used the similar analysis of Alexander's plastic hinge [9] the equation (6) in new form,

$$P_m = 2.286n^2\,Yt^2 \tag{6}$$

Where n is the number of lobes, and this number depends on the ratio of D/t. Another study [18] gave an estimated appearance for diamond mode as equation (7).

$$P_m = 18.15Yt^2\,(D/t)^{1/3} \tag{7}$$

Figure-6. Diamond mode-all folds like lobes [15].

iii. Mix-mode (concertina and diamond mode)

The mix-mode crushing of tube under axial load has more interest from some researchers. The transition from axisymmetric (concertina) to non- axisymmetric (diamond) mode when (D/t = 100) observed by Pugsley [17]. The behavior of mix-mode is transfer from fold (ring) to lobe as in Figure-7.

Figure-7. Mix-mode deformation the fold started to ring and transfer to lobes [19].

3. METHODOLOGY

Circular tube with and without round holes was compressed axially quasi-statically in universal Instron machine at a speed of 20 mm/min under maximum load set up was 240 kN at room temperature. The tube material is made of mild steel. The holes drilled laterally on the circular tube in three different location (top, middle, and bottom). The holes diameters are 5 mm and 10 mm. The dimensions of the circular tube are length 200mm, diameter 60 mm, thickness 1.8 mm.

a) Axial quasi-static crushing of circular tube without holes

The bottom rigid plate is movable and the top rigid plate is fixed under crushing at room temperature. Data acquisition software, connected to the load cell and a computer records data and the force-displacement of the crushing event. The deformed specimens without holes are illustrated in Figure-8.

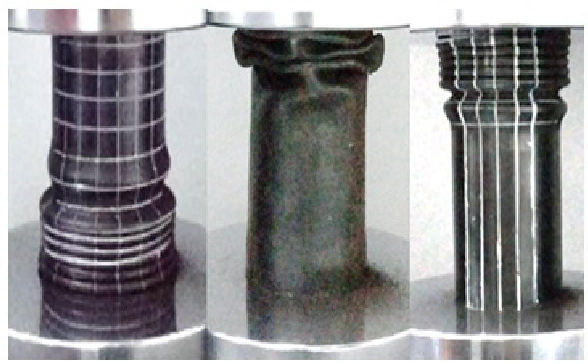

Figure-8. The different mode of buckle for specimens without holes in same geometry after 60 % collapse load.

b) Axial quasi-static crushing of circular tube with holes (5mm, 10mm).

The crushing of tube with holes done is compressed at the same speed which used in the tube without holes. The buckling started at the same location of holes. Figure-9 explains the axial crushing in a tube with holes.

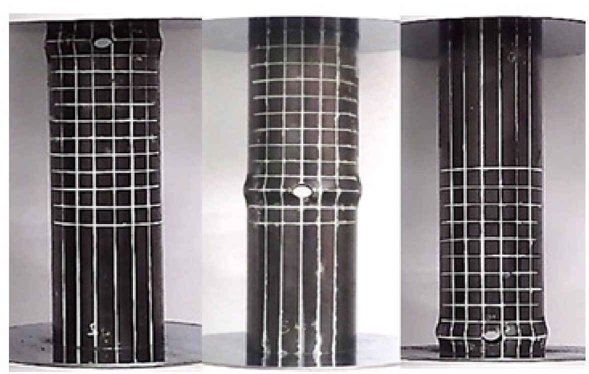

Figure-9. The collapse oftube with holes when the initiator buckling started at the same location of holes.

4. RESULTS AND DISCUSSION

a) Load-displacement characteristics

The differences between theoretical and experimental results of circular tube with and without holes of peak load and energy absorption are summarized in Tables-1, 2. But Table-3 (a,b) illustrates the experimental difference percentage of peak load, mean load, crush force efficiency and energy absorption between tube without holes and tube with 5mm, 10mm holes. In addition, the value of mean load and crush force efficiency of circular tube with holes (5mm, 10mm) in the middle are decreased. This is because no folds formation (irregular deformation) to produce high mean load which proportional directly to the value of crush force efficiency.

Table-1. Different between theoretical and experimental results of peak load.

Peak load theoretical (kN)	Peak load experimental (kN)													
	Without holes	Different %	5 mm hole diameter						10 mm hole diameter					
			top	%	middle	%	bottom	%	top	%	middle	%	bottom	%
99.71	104.3	4.45	102	2.33	100	0.41	98.5	1.15	94	6.07	93.4	6.75	96	3.86

Table-2. Different between theoretical and experimental results of energy absorption.

Energy absorption theoretical (J)	Energy absorption experimental (J)													
	Without holes	Different %	5 mm hole diameter						10 mm hole diameter					
			top	%	middle	%	bottom	%	top	%	middle	%	bottom	%
5440.8	5764.4	5.61	5639.4	3.52	5095.3	6.78	5621.6	3.21	5630	3.36	4934.8	10.25	5649.8	3.69

Table-3. Experimental difference of load-displacement characteristics between with and without holes tube, table (a) with 5mm holes and table (b) with 10mm holes.

Experimental work	Without holes	10 mm hole diameter					
		top	Different %	middle	Different %	bottom	Different %
Peak load (kN)	104.3	94	9.87	93.4	10.45	96	7.95
Mean load (kN)	48.03	46.91	2.33	41.12	14.38	47.08	1.97
Crush force efficiency	0.4604	0.4990	8.38	0.4402	4.38	0.4904	6.51
Energy absorption (J)	5764.4	5630	2.33	4934.8	14.39	5649.8	1.98

Experimental work	Without holes	5 mm hole diameter					
		top	Different %	middle	Different %	bottom	Different %
Peak load (kN)	104.3	102	2.20	100	4.12	98.5	5.56
Mean load (kN)	48.03	46.99	2.16	42.46	11.59	46.84	2.47
Crush force efficiency	0.4604	0.4602	0.04	0.4240	7.90	0.4752	3.21
Energy absorption (J)	5764.4	5639.4	2.16	5095.3	11.60	5621.6	2.47

b) Effect of holes on peak load

Figure-10 illustrates peak load curves for circular tube with and without holes and it shows that the peak load decrease after put holes. In addition, from the same figure can see clearly the reduce in peak load depends on the diameter of holes, where the diameter of holes increases, the value of peak load decrease.

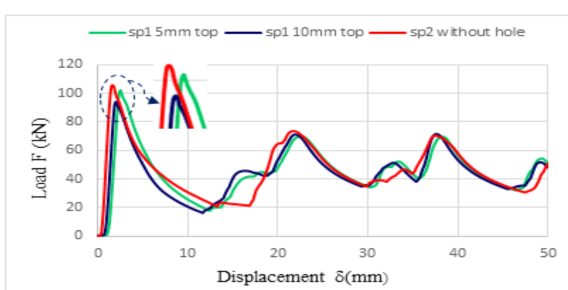

Figure-10. The peak load in load-displacement curve before and after drilled holes on the circular tube.

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c) Effects of holes location on buckling

The deformation of circular tubes with holes (5mm, 10mm) started at the same point of holes location as shown in Figure-10. The deformation in circular tube with holes 5mm and 10mm in the top and bottom was axisymmetric as in Figure-11 while the tube with holes 5mm and 10mm in the middle were buckled in irregular deformation where started ring after that transferred to collapse in random manner Figure-12(a, b).

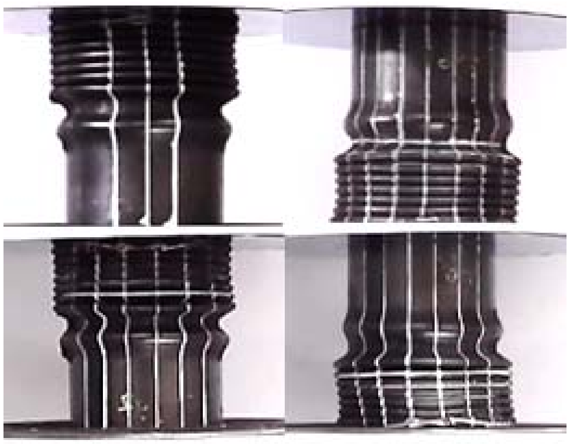
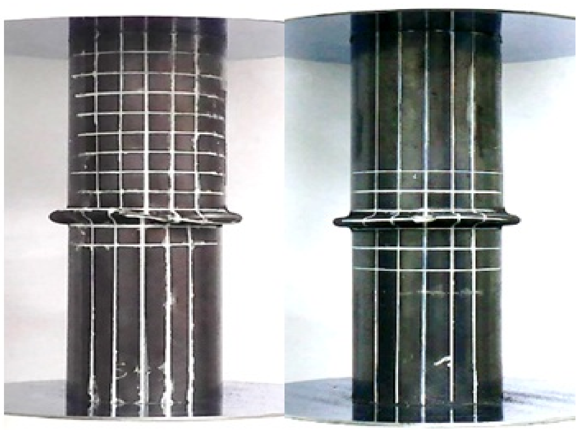


Figure-11. The collapse oftube with holes 5mm, 10mm are axisymmetric.



(a)

(b)

Figure-12. Deformation of the tube with holes in the middle (a) before irregular deformation (b) after irregular deformation.

5. CONCLUSIONS

The effects of round holes on the circular tube are presented. The benefit of holes is to decrease peak load. The location of holes in the midpoint of circular tube shows the best results to decrease the peak load. The experimental work explains the fold start at the same location of imperfection. However, the energy absorption of circular tubes with holes slightly decreases when compared with the tubes without holes. The theoretical and experimental results show close agreement. The decrease of crush force efficiency of circular tube with (5, 10) mm in the middle can be observed because of the drop in mean load value.

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