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Energy absorption capacities of square tubular structures

A.M.S. Hamouda [b,*]
co-operating with
R.O. Saied [a], F.M. Shuaeib [a]
[a] Mechanical Engineering Department, Faculty of Engineering Garyounis University, Benghazi, Great Social People Libyan Arab Jamahiriya (GSPLAJ), Libya
[b] Mechanical Engineering Department,
College of Engineering Qatar University, Doha-Qatar, Qatar
* Corresponding author: E-mail address: hamouda@qu.edu.qa

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Materials

ABSTRACT

Purpose: The purpose of the paper is to presents a study of the energy absorption of square tubular structures.
Design/methodology/approach: Tubes of three materials namely, mild steel, glass reinforced composite and Kevlar reinforced composite were used to observe their deformation and energy absorption characteristics. The tubular structures energy absorption characteristic was reviewed from both the materials and structural points of view. Axial crushing tests were carried out on the tubes under quasi-static loading condition.
Findings: The load-displacement curves of the tested tubes were presented and described. In addition, the deformation processes of the tubes was analyzed and evaluated. Several fracture modes of the crushed tubes were observed in most cases.
Research limitations/implications: It has been found that parameters such as thickness, type of fiber and length of tubes has a considerable effect on the crushing characteristic of collapsed tubes
Originality/value: Description of crushing behavior of the energy absorption characteristic of glass/polyester and Kevlar/polyester thin-walled composite square tubes under quasi-static axial crushing load.
Keywords: Energy absorption; Composite materials; Kevlar fibre; Glass fibre; Crushing mode; Mean load carrying capacity

1. Introduction

The box tubular structures are among the energy absorbing devices which can be used in many applications such as cars, ships, and aircrafts and so on. The advantage of the tubular is that it has simple geometry, low cost and high energy absorbing capability. Crashworthiness studies have attracted much attention in recent years particularly to analyzing the deformation characteristics and determining the energy absorbing efficiency of various thin wall crashworthy components of different materials. For example, metals, plastic, composite, etc and for various geometrical shapes, cylindrical tubes, cones, conical frusta, square tubes, square frusta and pyramids all grooved or un-grooved when subjected to axial crushing/compression loading [1,2].

The crushing behavior and energy absorbing capability of thin metal tubes of circular, rectangular or square cross-section have been investigated by many researchers. Rawlings and Shapland [3], Meng et al [4], Wierzbicki and Abramowitz [5] and Abramowitz and Jones [6] undertook axial crushing tests on such tubes to study their collapse modes and evaluate their mean crushing loads. Mamalis et al [7] studied experimentally the crushing behavior of thin-walled octagonal steel tubes. They considered the tube as an in-between shape exhibiting some behavior of both cylindrical and square tubes. Wierzbicki and Huang [8] studied the post buckling and post failure responses of a thin–walled prismatic column under axial compressive loading. They developed a simple mode of an imperfect column to describe the transition of deformation from post buckling to post failure stage. Reid et al [9], studied experimentally and theoretically the effect of the polyurethane foam filling on the crushing behavior and energy absorption of square metal tubes. Wierzbicki [10] investigated basic, kinematical, admissible, global deformation mechanisms of thin walled tubes comprised of flat plates. Fold mechanism in which large portions of the tube undergo in-extensional deformation and extensive extensional mechanism have been described. These models have been applied to the crushing of both square and rectangular tubes. It have been demonstrated that plastic deformations caused by local stretching at edge of the fold, bending of the horizontal fixed hinges and bending of inclined hinges each dissipate equal amount of energy. Expressions for mean loads, fold length and fold radius were derived by equating the external work needed to completely collapse one fold to the plastic work done in deformation regions. Recently Mohr and Wierzbicki [11] performed experimental and analytical studies on crushing of soft-core sandwich profiles. They found that the folding mechanism of sandwich profiles is very different from that of solid thin –walled structures. In particular, the shear behavior of the core material was found to strongly influence the mechanics of energy absorption. Marzo et al [12] investigated the collapse and steady flow of thick –walled flexible tubes in three-dimension using finite-element approach. Their model results were in excellent agreement with published numerical values based on thin-shell elements.

Composite materials are being proposed for application to aircraft and automotive structures to meet strength, weight and cost constrains. Although composite materials can exhibit crushing modes significantly different than the crushing modes of metallic materials, enormous studies have shown that composite materials can be efficient energy absorbing materials.

Many researches have been conducted to investigate how the constitutive material properties and architecture of composite materials affect energy absorption capability. Thornton [13] investigated the specific energy absorption capability and collapse characteristic of glass, graphite and Kevlar reinforced composite tubes. Farley [14] studied the energy absorption of graphite/epoxy, Kevlar/epoxy and glass/epoxy composite tubes and compared their result with equivalent aluminum tubes. Russell et al [15] undertook axial quasi-static and dynamic tests on glass/polyester, Kevlar/polyester and carbon/polyester composite square tubes to study the effect of parameters such as compression rate, thickness, type of fiber and filling the tubes with foam on crushing behavior and energy absorption capability. Farley [16] undertook static crushing tests on graphite composite tubes to examine the effect of fiber and matrix strain on energy absorption. He concluded that to achieve maximum energy from composite materials, a matrix material that has a higher strain at failure than fiber reinforcement should be used. Farley [17] has studied the effect of crushing speed on the energy absorption capability of graphite/epoxy and Kevlar/epoxy composite tubes and he found that the energy absorption characteristic of the tubes was affected by the crushing speed.

In this paper crushing behavior of the energy absorption characteristic of glass/polyester and Kevlar/polyester thin-walled composite square tubes under quasi-static axial crushing load will be studied using the experimental approach. Comparison of energy absorption and deformation behavior of the crushed square composite and metal tubes will be performed. Effect of parameters such as thickness and l/w ratio will be investigated.

2. Experiments

2.1. Metallic tubes

Mild steel sheets of 1mm thickness were used to form square (100×100) sectional tubes. The edges of the sheet were joined by arc welding along the length of the tube. Specimens were cut and prepared according to the L/W ration of 0.25, 0.5, 1, 2 and 3.

Quasi-static axial crushing tests were performed at room temperature on the specimens using an Instron universal testing machine at cross head speed of 10 mm min^{-1}. The test results in terms of crushing load-displacement were obtained for each crushed specimen. Also in some tests, the deformation process was photographed using video camera.

2.2. Composite tubes

A series of thin-walled composite square tubes (FRP) with dimension of 100×100×1000 mm were manufacturing by collapsible wooden mandrel using hand lay up method. E-glass 290 m^2, Kevlar 190m^2 woven roving cloth and polyester resin were used to manufacture the tubes. The glass/polyester (GRP) and Kevlar/polyester (KRP) tubes were made of two, four and six layers with angle orientation of 0/90^o and 45^o for GRP and 0/90^o for KRP tubes as shown in Table 1. Test specimens with length / width ratio (L/W) of 0.25, 0.5,1,2 and 3 were cut and prepared from each tube of GRP 0/90^{o,} GRP 45^o and KRP 0/90^o for two, four and six layers. Ends of each specimen were carefully machined to keep them perpendicular to the sidewall of the tubes.

3. Results and discussion

Table (1) a-c shows the experimental results of the metal tubes and the four layers FRP composite tubes. It can be seen that the maximum and mean load carrying capacity are much higher than the composite tubes having the same thickness due to high strength and rigidity of the steel. Furthermore, the energy absorbing capability of the metal tubes is two to three times higher than that of the composite tubes. However, the specific energy of the composite tubes, which is related to the increase in the stability of the tube, is higher than the specific energy of the metal tubes. The higher value of the specific energy was exhibited by Kevlar tube (9.048 kJ/kg) whereas the lowest value exhibited by the metal tube was (2.57 kJ/kg). This is related to the lightness of the composite materials which is about five times less than the metal tubes. The specific energy is considered to be a very important feature in term of saving energy especially in aerospace applications.

Table 1.
Experimental result of the crushing tests on the metal and composite tubes

Table 1a.
Tubes with L/w = 0.5

Properties	Metal tube	GRP ±45°	GRP 0° /90°	Kevlar 0°/90°
Mass (g)	190	46.19	40.17	39
Thickness (mm)	1.5	1.35	1.5	1.54
Compression (%)	86	94	94	94
Maximum load (kN)	41.5	0.0182	0.148	0.015
Mean load (kN)	18	0.00486	0.0039	0.006
Energy absorption (kJ)	0.49	0.221	0.166	0.270
Specific energy (kJ/kg)	2.57	4.700	4.13	6.90

Table 1b.
Tubes with L/w = 1

Properties	Metal tube	GRP ±45°	GRP 0° /90°	Kevlar 0°/90°
Mass (g)	400	46.19	100	98.4
Thickness (mm)	1.5	1.65	1.53	1.6
Compression (%)	87	93	92	90
Maximum load (kN)	33.5	0.019	0.021	0.024
Mean load (kN)	18.6	0.00405	0.0052	0.00965
Energy absorption (kJ)	1.52	0.374	0.471	0.861
Specific energy (kJ/kg)	3.80	8.09	4.71	8.75

Table 1c.
Tubes with L/w =2

Properties	Metal tube	GRP ±45°	GRP 0° /90°	Kevlar 0°/90°
Mass (g)	900	207	189	185
Thickness (mm)	1.5	1.6	1.57	1.6
Compression (%)	86	94	95	92
Maximum load (kN)	32.7	0.019	0.021	0.020
Mean load (kN)	18.3	0.0065	0.00427	0.09
Energy absorption (kJ)	2.9	1.22	0.8	1.674
Specific energy (kJ/kg)	3.22	5.89	4.23	9.048

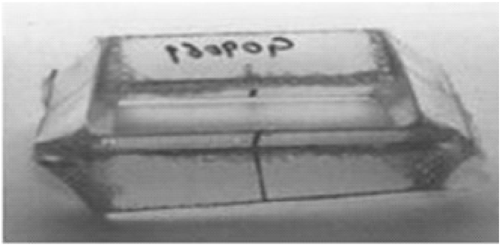
Table 1d.
Tubes with L/w =3

Properties	Metal tube	GRP ±45°	GRP 0° /90°	Kevlar 0°/90°
Mass (g)	1100	277	300	256.7
Thickness (mm)	1.5	1.44	1.57	1.6
Compression (%)	86	44	61	92
Maximum load (kN)	36.6	0.0138	0.0126	0.0159
Mean load (kN)	23.5	0.0036	0.0044	0.07
Energy absorption (kJ)	5.77	0.473	0.811	1.93
Specific energy (kJ/kg)	5.24	1.707	2.70	7.518

3.1. Collapse modes of the crushed tubes

The collapse modes for metal and composite tubes under crushing load varied with material, thickness and L/w ratio. Three different collapse modes were observed experimentally during the crushing of the tubes. These three modes are: 1) regular, 2) mixed and 3) irregular. The regular mode was identified as when the tube deformed with inextensional collapse mechanism described by Wierzbicki and Abramowitz [5]. In each fold of deformation, there are effectively four horizontal and eight inclined hinges formed around the circumference at middle length of the tube where two opposite sides folded inwards, while the two other opposite sides folded outwards. Figure (1) shows typical examples of the regular mode of a crushed metal and composite tubes respectively. Figure (2) show the stages of crushing process of a six layer KRP composite tube with L/w = 3. It can be seen that the first fold starts at the bottom end and then continuous to deform in a uniform manner.

a)



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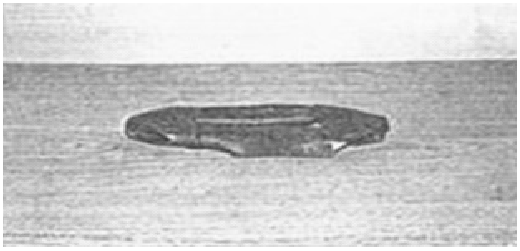


Fig.1. The regular fracture modes of (a) composite tubes and (b) metal

The irregular collapse mode was identified by the tubes which deformed in random manner due to instability. This mode was exhibited by thin and long tubes with L /w > 1. Figure (3) shows the deformation process of a metal square tube which is deformed in irregular manner. It can be seen that the tube first collapsed from the bottom end to form the first fold and then buckled to form another fold from the top end. Finally it was buckled again and became unstable between the compression plates of the machine. Another example of the irregular collapse mode is shown in Figure (4) which illustrates the crushing process of a four layer GRP 0/90^o tube with L/w = 2. It can be observed that the tube starts to buckle with half sine waves on each of the faces and then it collapsed at the middle length to form circumferential fractures leads to interpenetration failure mechanism and finally the tube broken into two halves which enter into each other followed by disintegration of the tube. Figure (5) shows collapsed metal and GRP tubes which exhibited the irregular deformation mode.

The mixed collapse mode was identified by the tubes which were in-between the regular and irregular modes. This mode was exhibited by most of the composite short tubes with L/w < 1 and by metal tubes with L/w = 2. Figure (6) shows a mixed collapse mode for six layer 45^o GRP tube with L/w = 0.5. It can be seen that the deformation is affected by three fixed horizontal hinges moving bodily inward and the hinges in the other side moving in an opposite direction.

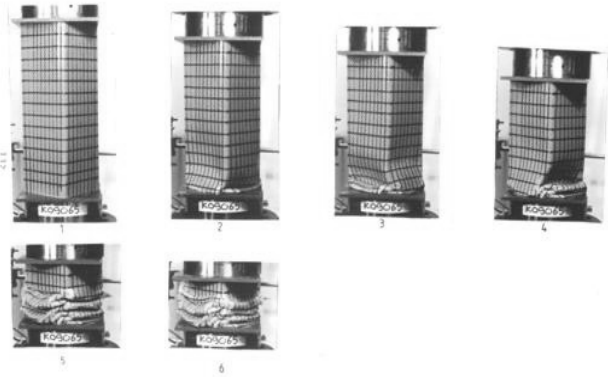


Fig. 2. Crushing process for six layers Kevlar 0/90˚ a square tubes with L/w=3

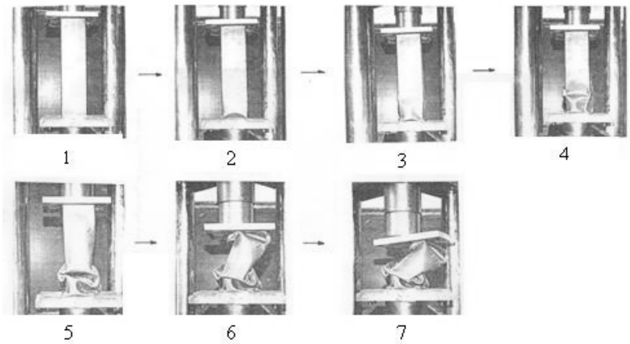


Fig. 3. Crushing process for a metal square tube with L/w=3

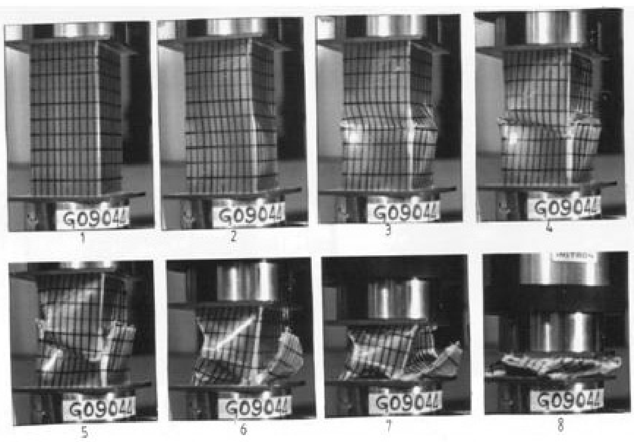


Fig. 4. Crushing process for six layers GRP 0/90 a square tubes with L/w=2

a)

b)

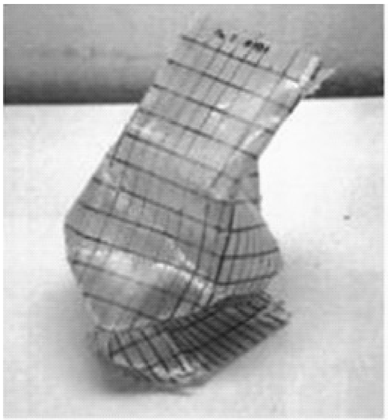
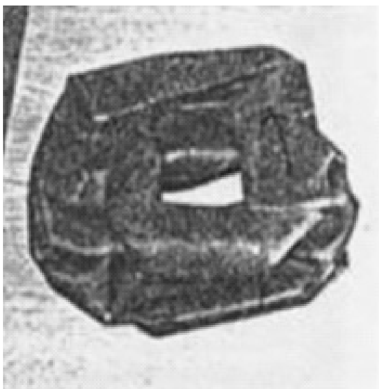


Fig. 5. Shows the irregular modes of (a) metal tubes and (b) GRP tubes

a)



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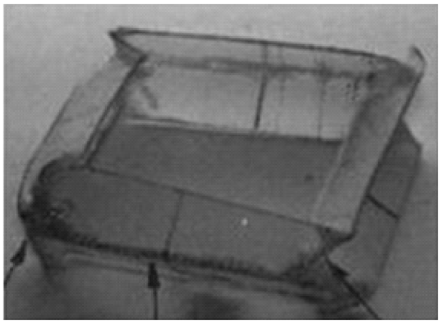

Fig. 6. Shows the mixed modes of (a) metal tubes and (b) GRP

3.3. Effect of the material on the crushing behavior

Figures (7) and (8) show the load- displacement curves for metal and composite tubes with L/w = 0.5 to 3 respectively. It can be observed that there is no significant difference in their general characteristic. All the curves show a large initial peak load corresponding to the initial collapse followed by rapid decrease in load due to instability of the tube. After this stage the load reduced gradually and the curves become nearly flat. As the ratio of L/W increases, the curves exhibit a series of fluctuations about the mean load. The fluctuations consist of peaks and troughs corresponding to the deformation and folding of the tubes. It can be observed that the load-displacement curve for the metal tube with L/w =3 shows large flatten after the first peak due to the instability of the tube under the crushing load.

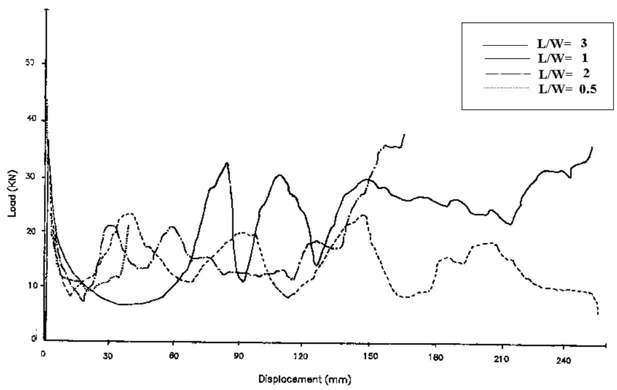

Fig. 7. The load –displacement curves for metal and composite tubes

3.2. Effect of the wall thickness

Because the thickness of the metal tubes was constant, the effect of the thickness on the crushing behavior was considered only for composite tubes.

The energy absorption, the maximum load and the mean load carrying capacity is considerably affected by the wall thickness of the tube. Figure (9), shows the effect of thickness on the crushing behavior of GRP 45^{o} and KRP 0/90^{o} tubes respectively. The 45^{o} GRP tubes exhibited irregular modes of deformation. The two layer tube shows few collapse hinges and delamination at the corners, whereas the four layer tubes showed more irregularity and enhanced collapse and delamination at the bottom and the middle. In the six layer tube, the tube shows complete collapse resulting in large fragments. For KRP 0/90^{o} tubes it can be observed that the tow layer tube exhibited irregular mode, whereas, the four and six layer tubes exhibited regular mode. It can be concluded that as the thickness increased, the collapse mode become more stable, uniform and exhibited a greater degree of fracture at corner and horizontal hinges.

Energy absorption and maximum load carrying capacity were observed to increase with increasing the wall thickness of the tubes for all L/w ratios. Figure (10) shows the thickness versus specific energy and crushing stress of the tubes respectively. These curves demonstrated that the specific energy and crushing stress increases with increasing wall thickness. These results are consistent with the results of Russell et al [15].

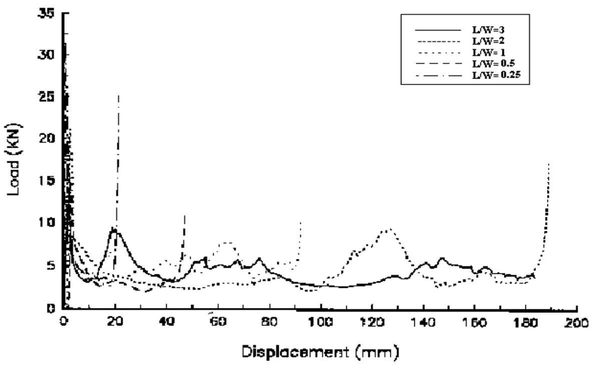

Fig. 8. The load-displacement curves for four layers G0^{o} /90^{o} square tubes with L/W = 0.25, 0.5, 1, 2, and 3

4. Conclusions

Energy absorbing characteristic of metal and composite square tubes with different l/ w ratio have been examined experimentally. Three types of deformation modes were observed during the crushing g of the tubes. These are regular, irregular and mixed modes. Most of metal and GRP 0/90 and 45 tubes crushing ended to exhibit the mixed and irregular modes whereas most of Kevlar tubes crushing ended to exhibit the regular mode. The maximum load carrying capacity and energy absorbing of the metal tubes were higher than those of the other tubes. However, the specific energy of the composite tubes was about four times higher then the specific energy of the metal tubes. Also, it has been found that parameters such as thickness, type of fiber and length of tubes has a considerable effect on the crushing characteristic of collapsed tubes

a)

b)

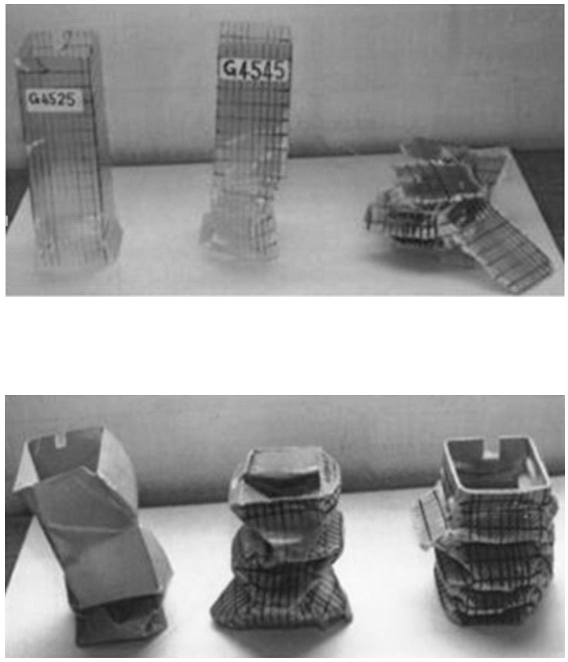

Fig. 9. Thickness effect on the collapse modes for (a) GRP tubes and (b) Kevlar tubes

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