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Lateral Crushing of Square Aluminium Tubes Filled with Different Cores

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Thin-walled tubular structures are widely used in industries such as automotive, aerospace and military because of their lightweight and excellent performance under different loading conditions. This study aimed to investigate the lateral crushing performance of square aluminium tubes filled with different cores (honeycomb, polyurethane foam and mixed of these two fillers). Different failure modes of tested structures have been observed and they are progressive failure with plastic hinges formed in the middle of the tube wall, cracks at the corners of some tested tubes and fractures in the mixed foam and honeycomb core. Results show that the lateral crushing performance of aluminium tubes was significantly improved when using mixed filler (honeycomb and foam). The average load, energy dissipation and specific energy absorption of mixed core filled tubes increased up to 638%, 451% and 177% respectively when compared to those for hollow tubes.

Keywords: *Aluminium, Honeycomb, Polyurethane foam, lateral crushing, square tube.*

1. Introduction

Thin-walled tubes are structurally efficient sections and have been significantly used as energy absorbing structures in many industries and applications such as aerospace, transportation, and construction. The energy dissipation performance of laterally crushed tubes is important because tubes can be applied in crushing systems in a vehicle to dissipate kinetic energy during a transverse collision by producing plastic hinges. One of the earlier studies on the laterally crushable tube was conducted by DeRuntz and Hodge[1]. They derived an analytical equation to predict the lateral crushing load of circular steel tubes for a range of tube thickness to diameter ratios. This theoretical model was modified by Reid and Reddy[2,3] by considering the strain hardening effect of plastic hinges formulation to minimise the discrepancy between the theoretical model suggested by DeRuntz and Hodge[1] and the experimental lateral loads of crushed tubes.

Lateral crushing tubes have also been used in crash cushions on freeways. The crash cushions made of stacking steel circular tubes were investigated by Reid[4] and found that the assembled tubes decelerated the serious damage to the vehicle by reducing the effect of dynamic lateral loads in wave damage. Gupta and Sinha[5-8] have been very active in developing the lateral crushing of aluminium and mild steel square and circular tubes and a system of orthogonal arrangement tubes. They revealed that the lateral loads and deformation modes were affected by the width of the platen, tube length, tube diameter, side length and diameter to thickness ratio. The no-orthogonal system of square and rectangular metal tubes is also experimentally and theoretically investigated and considered the energy dissipated by moved and stationary plastic hinges of the tube[9-11]. The tubes with small diameters and thick walls were found to have high lateral specific energy dissipation[12,13]. Bennbaia and Mahdi[14] investigated the effect of interior angles of aluminium hexagonal rings subjected to lateral crushing and found a significant effect of the interior angles on the energy dissipation performance and deformation mode of hexagonal rings. Thus, a hexagonal honeycomb with interior angles of 120° was considered in this study to fill tubes to be laterally crushed.

Researchers have attempted to enhance the lateral energy absorbing capabilities of thin-walled metallic structures by increasing the number of tubes. Circular and elliptical nested tubes where tubes with different diameters were placed inside each other under lateral impact with different impact velocities were analysed[15-18]. It was found that the nested tubes dissipated more energy than a single tube. Subsequently, Sofi et al.[19] investigated multi-cell circular aluminium tubes stacked together and noted that the dissipated energy increased with an increase in the number of cells which means increasing the number of plastic hinges configuration for each cell. Lohith Reddy et al.[20] discussed the impact of transverse crushing of multi-cells stiffened cylindrical tubes and they noticed that the transverse energy dissipation increased with an increase in the number of cells or ribs.

Several studies have focused on trying to improve the efficiency of laterally crushed thin-walled metallic tubular structures by using lightweight aluminium foam. For instance, aluminium foam-filled aluminium, brass or titanium circular tubes had higher specific absorbed energy than empty tubes under quasi-static and high strain transverse loading[21,22]. Furthermore, the aluminium foam-filled aluminium circular tubes had the highest energy absorption of other tested tube configurations and there was no obvious effect of bonding

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foam to tube on the lateral crushing performance[21,22]. On the other hand, Shen et al.[23] observed that the crushing patterns and energy absorption of tubes were affected by bonding aluminium foam to sandwich tubes. Square aluminium tube filled with aluminium foam was also examined by Zhang et al.[24] and found the lateral crushing load of tubes was lower than the load of specimens under axial loading. Sandwich and packed tubes filled with aluminium foam under dynamic and quasi-static lateral loading were investigated[25-29] and observed three failure modes, symmetric, sequential, and symmetric failure mode with a fracture in foam core. Djamaluddin and Mat[30] numerically analysed the transverse crushing response of aluminium foam-filled ship fenders with different geometric dimensions. The results showed that the foam-filled sandwich circular fender had better performance than a conventional fender.

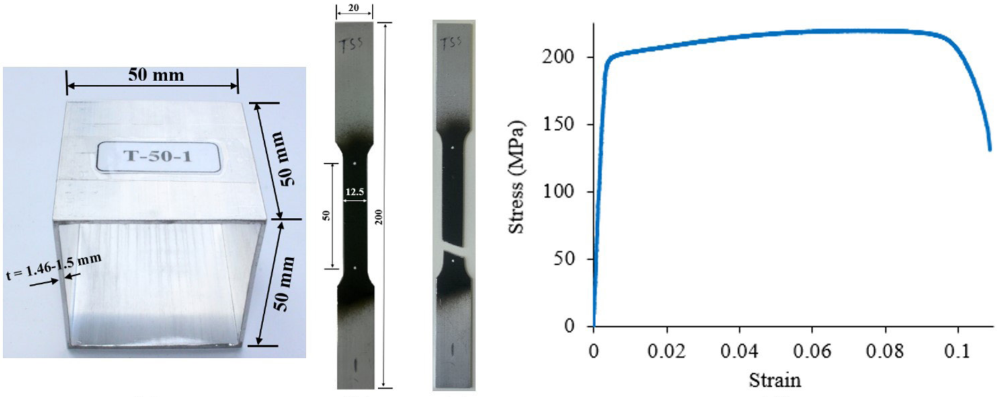
Some studies have examined the polymeric foam-filled tubes subjected to lateral crushing. Aluminium square tubes – filled with different cores: honeycomb, polyurethane foam and mixed of them under axial loading had been investigated and found that the energy dissipating of the tube was improved, and the deformation mode was changed depending on the strength of filling[31-33]. Niknejad and Rahmani[34] conducted an experimental and theoretical investigation of hollow and polyurethane foam-filled hexagonal tubes and found that the foam and tube geometry affected the lateral crushing performance of tubes.

Other studies were focused on composite CFRP tubes filled with honeycomb under lateral and axial compression[35,36] and found improvement in dissipated energy of composite tubes when using honeycomb core. Subsequently, the dissipated energy of filled hybrid CFRP/aluminium circular tubes was affected by foam density, tube wall thickness and CFRP layers[37]. Mahdi and El Kadi[38] examined analytically and experimentally glass fibre/epoxy elliptical tubes subjected to lateral crushing and observed a good agreement between the results. Woven glass/epoxy hexagonal rings with different angles and arrangements were experimentally examined by Mahdi and Hamouda[39]. It was found that the failure mode and crushing performance of composite rings were significantly affected by the geometry and arrangement of rings, where the energy absorption of rings increased with the increase of the internal angles. Subsequently, Sun et al.[40] conducted an experimental test on circular aluminium, GFRP and CFRP tubes under lateral compression with different loading angles. The deformation mode was found to be comparable, and the initial lateral crushing load decreased with the increase of loading angle. Mahdi and Sebaey[41] also assessed the crashworthiness of six hexagonal/octagonal CFRP cells packed inside aramid rings and filled with polyurethane foam. They noticed that the stroke efficiency, average load and energy dissipation of CFRP cells packed inside aramid/epoxy ring were improved compared with those of cells packed inside CFRP/epoxy ring. However, the investigation of an aluminium tube filled with different cores or combined different multi cells and foam core under lateral crushing loads is still lacking and need more investigation.

In the present study, an examination of the lateral crushing of aluminium square tubes with different cores such as honeycomb, polyurethane foam (Pu) and mixed honeycomb and foam was conducted. The failure mode and crushing parameters were analysed. The capability of honeycomb filled with Pu foam core to improve the dissipating energy of aluminium tubes is assessed. The lateral load-displacement curves, energy dissipation and specific energy absorption of hollow and filled tubes with different cores are investigated.

2. Specimens and Experimental Setup

The square tubes used in this study were manufactured from aluminium AA6060-T5. The approximate tube wall thickness was 1.46 mm, the outer side length was 50 mm and the height of the tube was 50 mm as shown in Figure 1a. A previous tensile test of five coupons cut from the same sidewall of the tube tested in this study was conducted by Hussein et al.[33] by following the ASTM E8/E8M standard[42]. Photographs of one tensile coupon before and after failure with dimensions are presented in Figure 1b and c respectively. The engineering stress-strain curve of the tube wall material obtained from the previous tensile test is presented in Figure 1d. The ultimate tensile stress and proof yield stress were found to be 220 MPa and 202 MPa respectively at a strain of 8.6%.

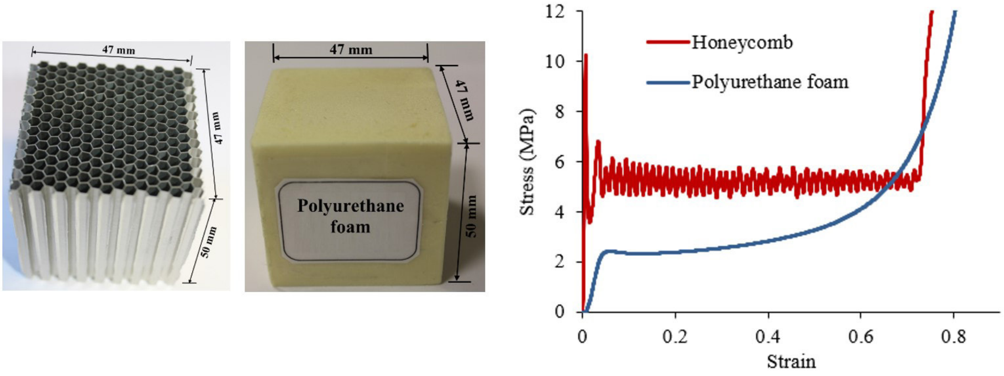


(a) (b) (c) (d)

Figure 1. (a) A photograph of aluminium tube with dimensions; (b) tensile test coupon before the test with dimensions by following ASTM E8/E8M standard; (c) coupon after tensile test; (d) engineering stress-strain curve of the aluminium coupon from tensile test[33].

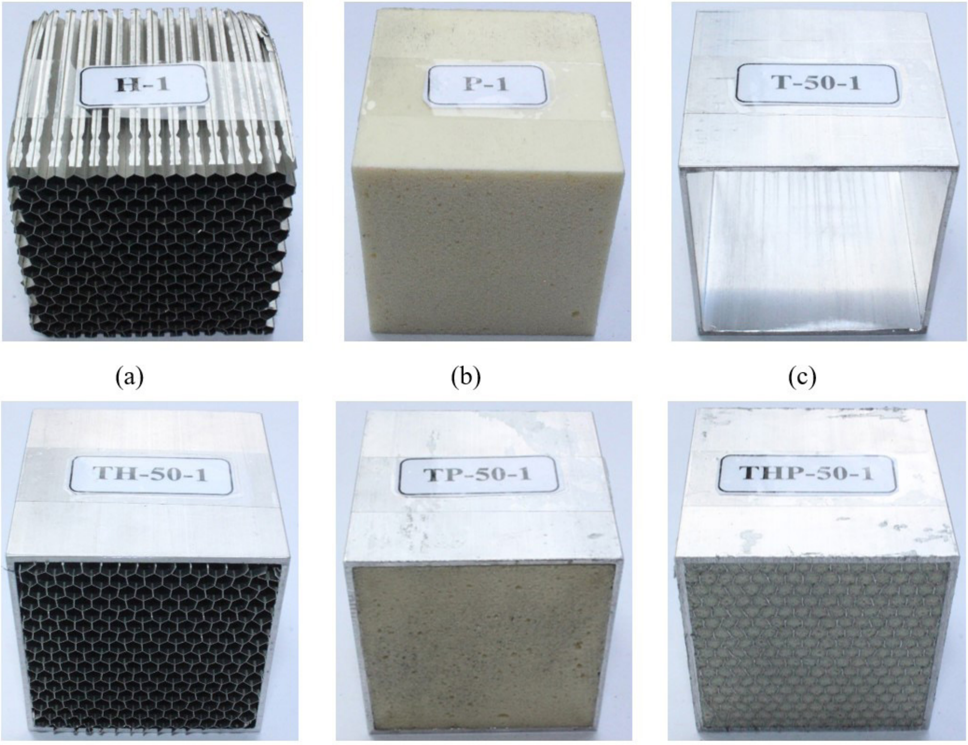
HexWeb® CRIII 8.1-1/8-5052-.002N aluminium alloy honeycomb cores were used. The cell length of this honeycomb, the wall thickness of the cell and density are 3.175 mm, 0.0508 mm and 129.75 kg/m^3 respectively. Figure 2a shows a photograph of a honeycomb that was used to fill the aluminium tubes. Figure 2b shows polyurethane foam (Pu) that was used as a core to fill the tube as well as the honeycomb. This foam is rigid foam with a density of 180 kg/m^3 and consisted of two liquid chemicals (Isocyanate and Polyol). Figure 2c shows the engineering stress-strain curve for this honeycomb tested at a velocity of 0.05 mm/s with corresponding plateau stress was 5.21 MPa[33]. Figure 2c also shows the engineering stress-strain curve of foam[33] and the plateau stress of this foam was determined to be 2.8 MPa.

Photographs of typical test samples are presented in Figure 3. The side length of all tested specimens was 50 mm. A 250 kN MTS computerized machine was utilized to apply lateral compression at a quasi-static velocity of 0.05 mm/s to study the failure modes and obtain the load-displacement curves of tested specimens.



(a) (b) (c)

Figure 2. (a) a honeycomb photograph; (b) a photograph of Pu foam; (c) engineering stress-strain curves obtained from compression tests of honeycomb in out-of-plane direction and Pu foam[33].



(a) (b) (c)

(d) (e) (f)

Figure 3. Photographs of typical test specimens: (a) honeycomb; (b) Pu foam; (c) empty tube; (d) tube filled with honeycomb core; (e) tube filled with Pu foam core; (f) tubes filled with mixed core (Pu foam and honeycomb).

To check the accuracy of the testing machine, hollow aluminium tube specimens subjected to lateral crushing were repeated three times and the curves are presented in Figure 4. It was observed that the lateral load-displacement curves of the three specimens match very well. Thus, it was conducted two lateral compression tests for each similar group of specimens and the two representative lateral load-displacement curves for each group of these specimens are presented in the following sections.

The magnitudes of lateral compressive characteristics were determined directly from the corresponding load-displacement curves such as maximum load (P_{max}), average load (P_{ave}) and energy dissipation (E). Specific energy absorption (SEA) is also calculated by dividing energy absorption by the mass of the specimens. These parameters were calculated at the range of displacements of 5 mm to 30 mm from the lateral load-displacement curves.

3. Results and Discussions

Figures 5-10 show photographs of the deformation history for each of the six specimens. Figure 11a-f illustrates load-displacement curves for specimens laterally crushed.

3.1. Failure mode

The failure mode of honeycomb placed in-plane direction experimentally tested is shown in Figure 5. The V-shape formulation is obvious in lateral crushed honeycomb. This direction of honeycomb is weak compared with the out-of-plane direction of honeycomb. The lateral compression was continued until the final failure of the honeycomb as shown in Figure 5. For polyurethane foam, the failure mode is illustrated in Figure 6. It was noticed that the Pu foam deformed progressively and after removing the applied load, the crushed foam sprang back for approximately 10 mm of the distance between machine platens at the final crushing of foam. This phenomenon occurred due to the elastic nature of the foam and its resistance to compressive load.

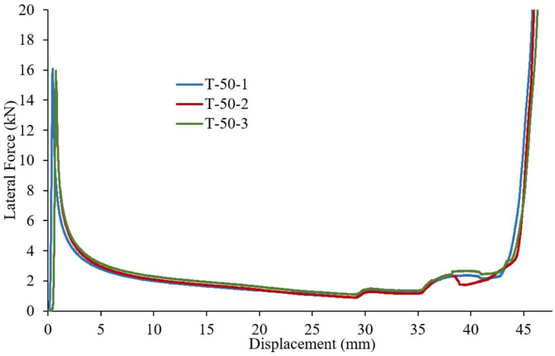


Figure 4. Lateral load-displacement curves for hollow aluminium tubes of three repeated tests.

Figures 7-10 illustrate the deformation history of hollow and filled aluminium tubes with honeycomb, foam, and mixed filler respectively. At the beginning of lateral crushing, the formulation of plastic hinges that occurred in the middle of tube side length required a high lateral load to form and this load is called peak crushing load. Furthermore, it was observed that the filler (foam or honeycomb) was individually deformed without fillers interacting with the tube wall. The failure mode can be considered as the progressive plastic hinges formulation mode for the tubes. Subsequently, it was found some cracks at the folding position of hollow tubes and mixed fillers (honeycomb and foam)-filled tubes as well as some cracks in honeycomb and foam core as shown in Figure 10. Honeycomb or foam core did not fill the gaps between folds of the tube (Figures 8 and 9), while mixed filler (honeycomb and foam) was filling part of the fold of the tube (Figure 10).

3.2. Effect of different cores on lateral crushing loads

Figure 11 shows experimental load-displacement curves of lateral crushing for different tested specimens. The honeycomb specimens have smooth plateau loads and the maximum load seems to be similar to the average load as shown in Figure 11a. After 35 mm of displacement, the lateral loading starts to increase sharply at the end of the tests. For the polyurethane foam, the lateral crushing loads to displacement curves of two repeated tests are presented in Figure 11b. It was observed that the lateral crushing loads increased slightly until 30 mm of the crushed displacement, after that the load increased quickly. Figure 11c-f shows

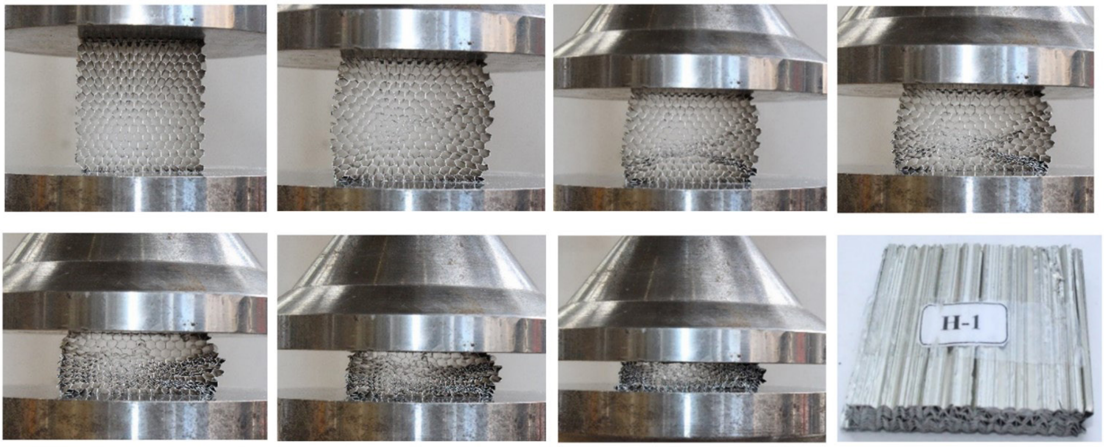


Figure 5. Stages of the failure mode of honeycomb specimen laterally crushed.

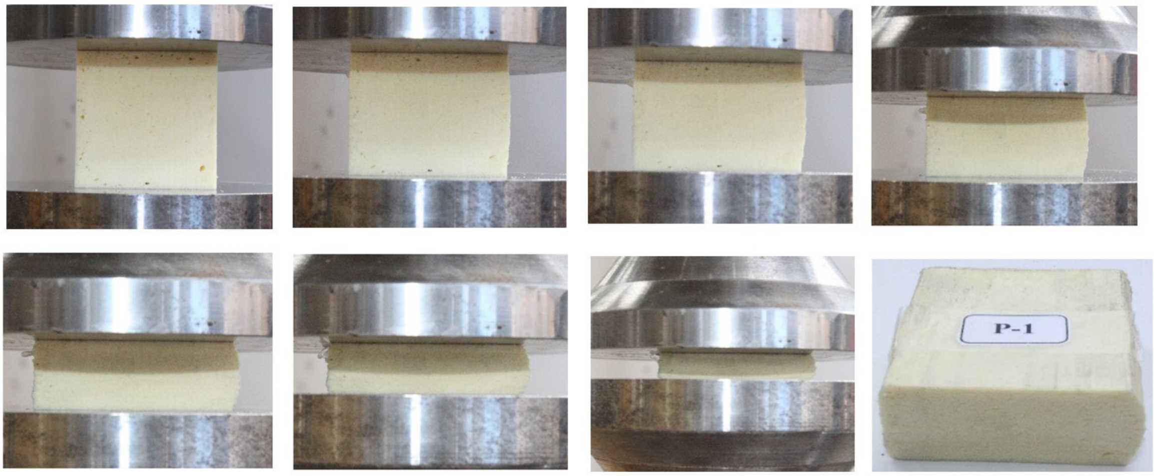


Figure 6. Stages of the failure mode of polyurethane foam laterally crushed.

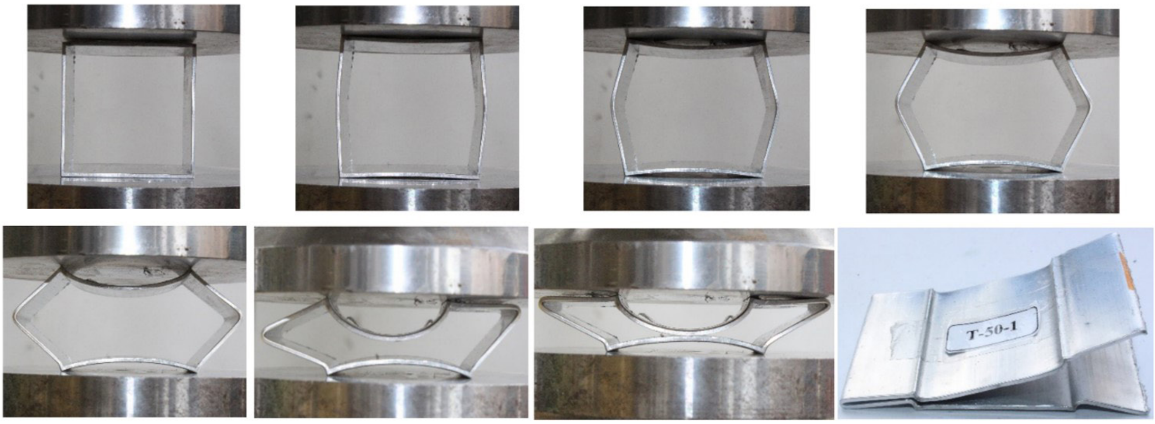


Figure 7. Stages of failure mode of hollow tube laterally crushed.

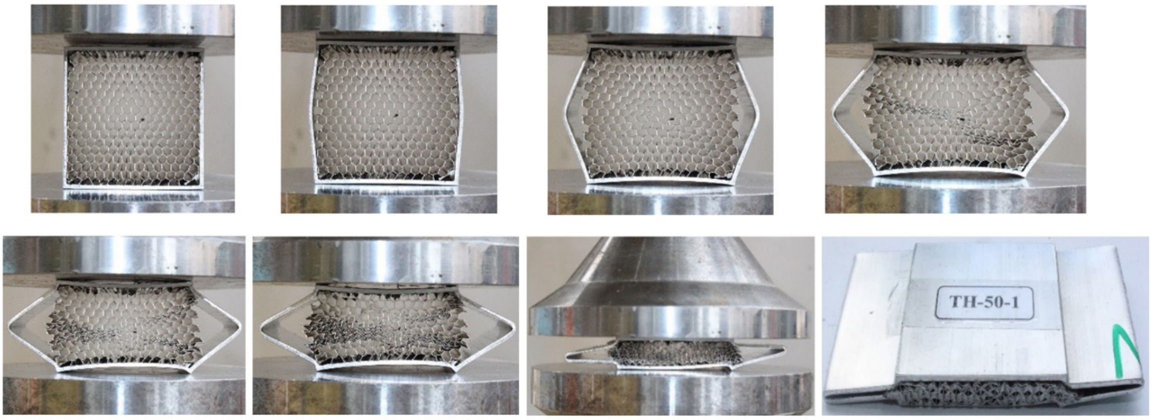


Figure 8. Stages of failure mode of a tube filled with honeycomb laterally crushed.

the lateral crushing load-displacement curves of hollow and filled tubes. It is evident from these curves that there are initial peak loads (maximum loads) at the beginning of applying loads. These maximum loads were required to form plastic hinges in the middle of the tube wall of hollow and filled tubes with a different core. Then, the loads drop to be plateaued until the end of the tests where the loads increase sharply at a certain displacement depending on the strength of fillers.

Figure 12 presents a graphical comparison of the maximum loads and average loads of all tested specimens. It was found that the interaction effect between honeycomb

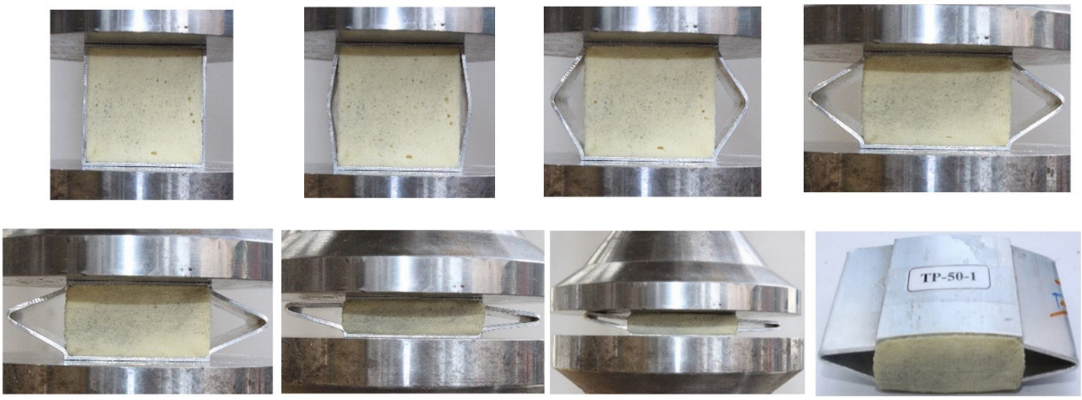


Figure 9. Stages of failure mode of a tube filled with polyurethane foam laterally crushed.

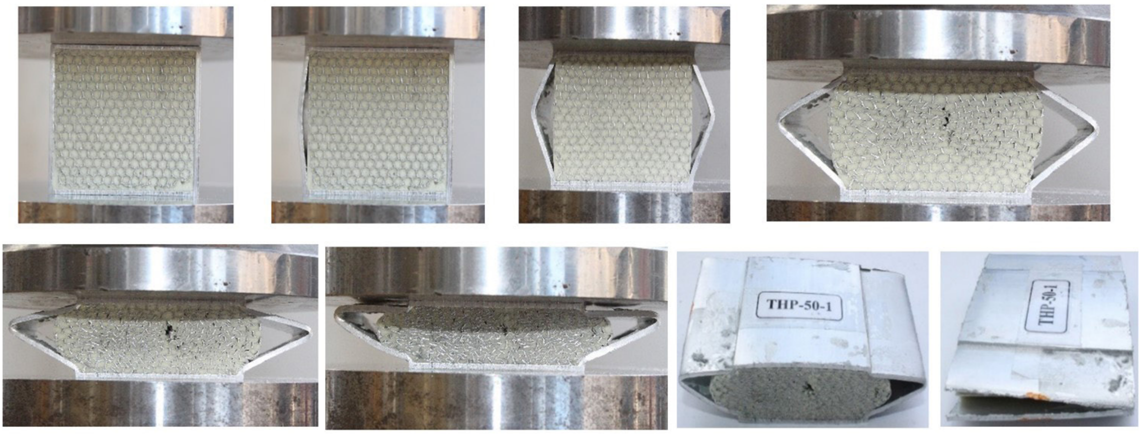


Figure 10. Stages of failure mode of a tube filled with mixed core (Pu foam and honeycomb) laterally crushed.

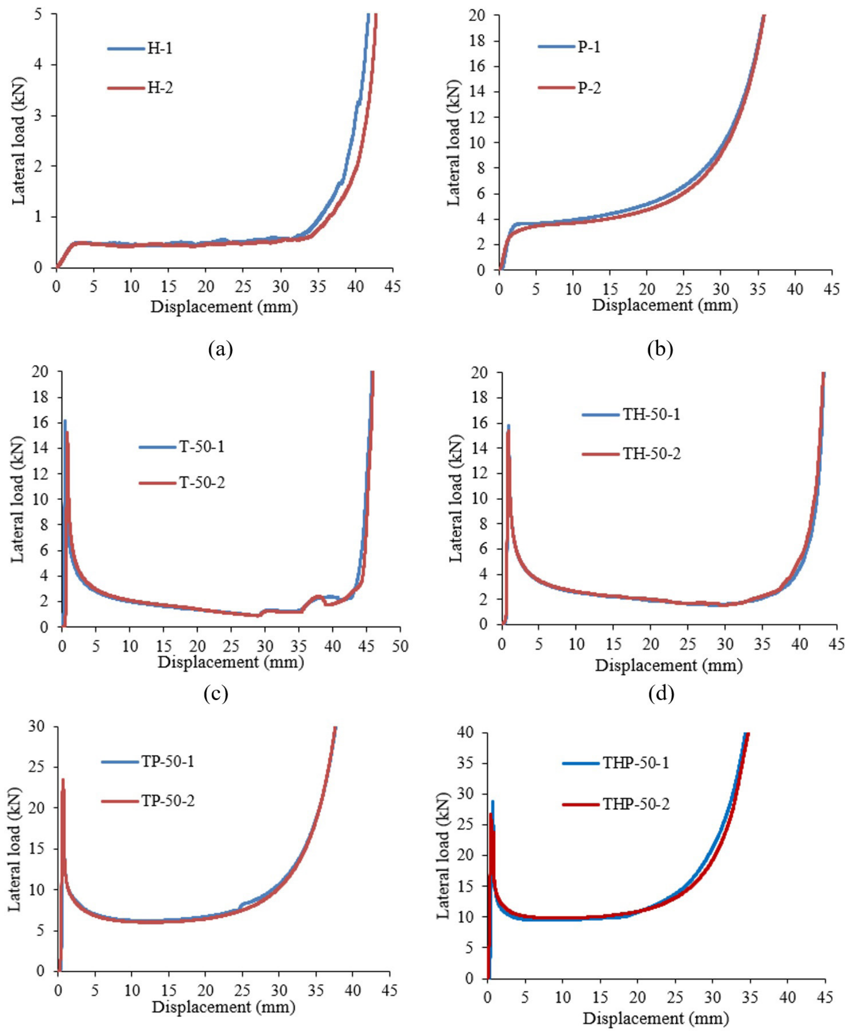
core or polyurethane foam and tube walls under lateral crushing was inadequate. It was observed that the average load of the honeycomb-filled tube and foam-filled tube increased by only 3.7% compared with the sum of average loads of its components; honeycomb or foam and tube were tested separately. That is because every component deforms lonely without an interaction effect between two different materials. It can be improved if bond materials of using different geometry than a square tube.

The average load for a honeycomb-filled tube was approximately 2.2 kN, while for a hollow tube was around 1.6 kN, where the average load increased by up to 36% of that of a hollow tube. For tubes filled with Pu foam, the increase of average load was approximately 350% compared with that of the hollow tube. Thus, the average load of foam-filled tubes increased remarkably compared with that of tubes. This indicates that the interaction between foam core and tubes' walls is excellent. This definite increase in lateral loading of foam-filled tubes was because the foam had an excellent resistance in its lateral direction to the applied loads. Furthermore, the average load of foam-filled tubes was up to 230% more than the average load of honeycomb-filled tubes. It can be concluded that using polyurethane foam to fill tubes is better than using honeycomb as a core in lateral compression.

It can also be seen from Figure 12 that the average load of the mixed core filled tube of one tested specimen is 11.6 kN, while it is 1.6 kN for the hollow tube. Furthermore, the average load of tubes filled with mixed core (honeycomb and foam) is 58% higher than the sum of the average loads of its components (tube, honeycomb, and foam). If the average load of the mixed core filled tube compared with the hollow tube, the increase was up to 630% higher than that of the hollow tube. In addition, the average loads of mixed core filled tube were 442% and 64% greater than the average loads of honeycomb filled tube and foam-filled tube respectively. That indicates a very strong interaction between foam and honeycomb during lateral compression. A large force was required to fold the tubes and fold cells of honeycomb because of foam filling these honeycomb cells. Thus, filling tubes with honeycomb and foam was found to be very effective in improving the lateral crushing performance of tubes.

3.3. Energy dissipation and specific energy absorption

The energy dissipated by test specimens is shown in Figure 13a. It was observed that the absorbed energy of all tubes with core was higher than that of hollow tubes. The energy dissipation of mixed core filled tube was



(a) (b)

(c) (d)

(e) (f)

Figure 11. Typical lateral crushing load-displacement curves of: (a) honeycombs; (b) polyurethane foam; (c) hollow tubes; (d) honeycomb-filled tubes; (e) foam-filled tubes; (f) honeycomb and foam filled tubes.

approximately 346 J, while it was 63 J for empty tube with an increase of 451%, which is a significant improvement in energy absorption. This high energy dissipation was due to the resistance of the core (honeycomb and foam) as well as some cracks were noted in the specimen which required more energy dissipation to form these cracks (Figure 10). Another filler that improves the energy dissipation of the tube is polyurethane foam with an increase of 249% compared with that of the hollow tube. For honeycomb filled tubes, the increase in energy dissipation was 26% compared with that of the hollow tube.

Figure 13b shows a comparison of specific energy absorption (SEA) for all tested specimens. It is obvious from Figure 13b that the SEA of polyurethane foam is greater than the SEA of other specimens. Where the average SEA of repeated Pu foam specimens is approximately 7.6 J/g while the average SEA of mixed core (honeycomb and Pu foam) filled tubes is 4.6 J/g. However, the SEA of mixed core-filled tubes was 177% greater than the SEA of empty tube. Furthermore, the amount of absorbed energy of a mixed core filled tube is much higher than that of Pu foam as shown in Figure 13a.

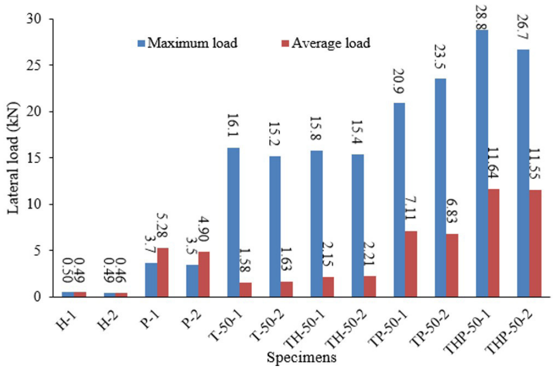
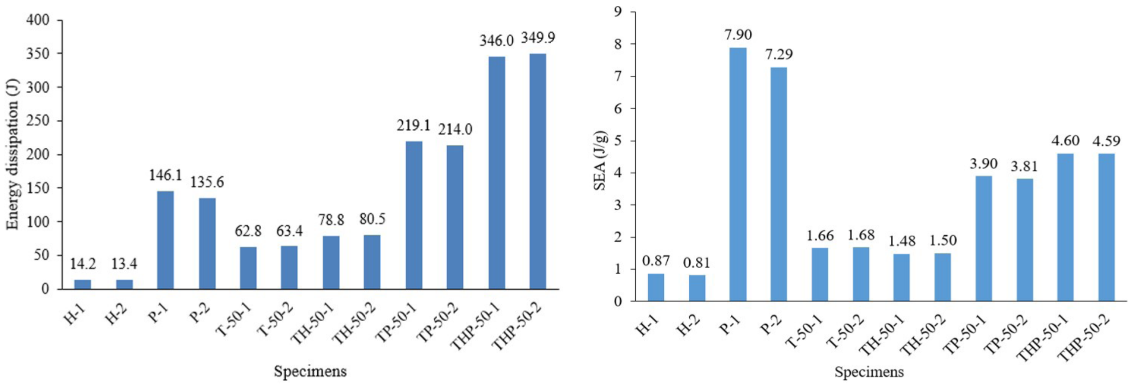


Figure 12. A graphical comparison of maximum and average lateral loads of tested specimens.



(a) (b)

Figure 13. A graphical comparison of: (a) energy dissipation of tested specimens; (b) specific energy absorption (SEA) of specimens.

4. Conclusion

Experimental tests were performed to investigate the lateral crushing performance of hollow square aluminium tubes, tubes filled with honeycomb core, tubes filled with polyurethane foam and tubes filled with mixed core (honeycomb and foam). Based on the experimental observations and results, it was noticed that a progressive failure mode of honeycomb and Pu foam. Furthermore, the failure mode of the hollow tube and the filled tube was a progressive failure with plastic hinges formed in the middle of the tube wall, as well as some cracks observed in some tubes' corners and mixed core (honeycomb and Pu foam).

The crashworthiness parameters of tested specimens are analysed in this study. It was observed that the average load and energy dissipation increased significantly depending on the strength of the filler. The following cores order of highest effective to least effective in increasing the energy dissipation of square tube: mixed core (honeycomb and foam), polyurethane foam, and honeycomb. Therefore, the mixed core filled tube was found to be effective to improve the energy dissipation of the tube with an increase of up to 451% compared with that of the hollow tube. The specific energy absorption (SEA) of honeycomb and foam-filled tubes was approximately 4.6 J/g, and it is lower than the SEA of Pu foam which is 7.6 J/g. However, the energy absorption of Pu foam is significantly lower than that of the mixed core filled tube. Thus, honeycomb and foam-filled tubes are effective in dissipating energy and have excellent specific energy absorption, which is 177% higher than the SEA of hollow tubes.

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