Axial Crush Response of Aluminium Square Tube with Origami Patterns

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Abstract. Thin-walled square tubes are widely used as impact energy absorber in automotive structures due to their ease of fabrication and installation, high energy absorption capacity in terms of progressive plastic deformation and long stroke. However, the main drawback of square tube is its high initial peak force during the initial stage of crushing. An origami pattern on the faces of the tube is proposed to reduce the high initial peak force and increase the energy absorption of the tube. Static and dynamic axial crushing were performed using finite element analysis to determine the initial peak force (IPF), crush force efficiency (CFE) and plastic specific energy absorption (SEA) of tubes with origami pattern. The results of simulations were validated by experimental data. Then, various combinations of origami patterns were studied using finite element simulation only. It was found that the origami pattern significantly enhanced the tubes crush performance. Comparison between plain square tube and tubes with various origami patterns was carried out and it was found that the origami patterns reduced the initial peak force and increased the crush force efficiency for both static and dynamic loading conditions.

Keywords: thin-walled, square tubes, origami pattern, plastic deformation, energy absorber

1. Introduction

Energy absorbers in the form of tubular structures of various shapes are mainly used for impact protection of vehicles during collision. Ductile materials such as steels and aluminium are the preferred choice as they exhibit large plastic deformation before total fracture. These materials absorb the excessive kinetic energy during impact by various mechanisms such as friction, fracture, shearing, bending, tension, crushing and plastic deformation. Widely used geometries such as square and circular tubes, frusta and polygons subjected to axial and lateral loadings has been extensively studied for the past six decades [1-3]. The need to further optimise the energy absorption of structures has prompted researchers to explore new geometries, configurations and material combinations.

Zhang X [4] introduced two types of patterns using the basic pyramid elements on to the surface of conventional thin walled square tubes. Type A pattern was aimed at triggering the extensional collapse mode while Type B was planned to fail in a new mode. The tubes were numerically subjected to quasi-static axial crushing using LS Dyna explicit finite element code. Tubes with Type A pattern failed in extensional collapse mode while tubes with Type B pattern failed in octagonal collapse mode. Both patterns resulted in increased specific energy absorption of the tubes. Song J et al. [5] implemented...
origami patterns on to thin walled tubes with square, hexagonal and octagonal cross-sections subjected to axial crushing. Numerical results showed that the patterned tubes exhibited lower initial peak force and more uniform crushing load as compared to the plain tubes. Parametric study has shown that the pre folding angle affected the initial peak force and mean crushing load. A prototype of the patterned tube was then fabricated and tested, and the experimental results validated the simulation results.

Song J et al [6] introduced patterned windows on to thin walled square tubes with the aim to reduce weight while maintaining the mechanical property of the original tubes. Experimental results showed that windowed tubes have lower initial peak force and higher specific energy absorption. Parametric study using finite element analysis was conducted to investigate the effect of window size on the tubes collapse characteristics. Three collapse modes were observed where the symmetric and extensional mode gave an increase in specific energy absorption. Zhou C et al. [7] manufactured origami crash boxes using a customised stamping die. Two types of origami patterns were proposed and subjected to axial impact by using a drop hammer test rig. The origami crash boxes performed better in terms of mean crushing force and energy absorption. Three collapse modes were observed where the complete diamond mode produced the highest energy absorption.

Crushing behaviours of circular tubes with shallow and deep corrugations were experimentally and theoretically investigated under axial loading conditions by Eyvazian A et al [8]. Three types of tube designs were tested and their failure modes and failure history were presented and discussed. The experimental results showed that the corrugated metal tubes provide perfect energy absorbing characteristics in terms of uniformity of load-displacement curve, reduction of initial peak force and controlling failure modes. The theoretical model based on experiment and modified simplified super folding element (MSSFE) theory was proposed to predict the mean crush load. Yang K et al. [9] introduced predesigned ellipsoidal dimples on to the surface of circular brass tubes subjected to quasi-static axial crushing. Finite element analysis was used to investigate the influence of various design parameters of the dimples on the tubes’ crush response. The dimpled brass tubes were fabricated using 3D printing and experiments were carried out to validate the simulation results. The results showed that the dimpled tubes had substantially lowered the initial peak force and produce more uniform mean force as compared to the plain tube.

Cetin E and Baykasoglu C [10] investigated the crashworthiness performance of graded lattice structure filled tubes (GLSFTs) under multiple impact loadings. Results showed that the graded lattice structure designs provide variable stiffness throughout the length of the tubes and enable more folds to be formed without the tubes experiencing global bending. This consequently led to higher energy absorption under axial and oblique loadings. Significant improvement of energy absorption performance can be obtained by appropriate selection of design parameters. Sadeghi A et al. [11] studied circular tubes with different axial corrugations subjected to axial loading. The corrugated tubes were fabricated using forming process. Comprehensive experimental and numerical analysis have been conducted to investigate the effects of various geometrical parameters on the crushing behaviour of tubes. The corrugated tubes showed more uniform force-displacement curves and higher energy absorption. The corrugated tubes deformed in an inversion mode where the additional frictional force between the tube and inverted surfaces resulted in increase of specific energy absorption, mean force and crush force efficiency.

The crush performance indices of a tubular structure under axial loading is expressed in terms of initial peak force (IPF), crush force efficiency (CFE) and specific energy absorption (SEA). The initial peak force is the maximum force experienced by the structure before it collapses. It is desirable to have a low initial peak force so as to reduce the injury level in an event of crash. The crush force efficiency is the measure of the uniformity of the collapse force. It is expressed in term of percentage and is given by equation (1). An ideal energy absorber would have a crush efficiency of 100% which is very difficult to achieve in reality. Typical values of CFE for tubular structures under axial loading are between 30 to 50%.
\[ CFE = \frac{\text{Mean Force}}{\text{Peak Force}} \]  

Specific Energy Absorption (SEA) is the ratio of energy absorbed divided by the total mass of the structure. It allows a direct comparison of similarly shaped structures made from different materials.

\[ SEA = \frac{\text{Energy Absorption}}{\text{Mass}} \]

2. Finite Element Modelling and Simulation

Based on literature review, an origami patterned square tube which has yet to be studied is proposed. The tube geometric configuration is illustrated in Figure 1. The function of the origami pattern is to allow the tube to fail in a predetermined and stable manner. The 3D CAD model of the origami patterned tube was created in Abaqus CAE preprocessor. The tube was modelled as surfaces where it was partitioned into several regions to represent the origami pattern. Also partitioning the surfaces enabled more uniform elements to be created during the subsequent meshing process. Table 1 shows the dimensions of the plain tube and origami patterned tube.

Table 2 shows the detail parameters for the different origami pattern arrangements on the square tube. The tube model was meshed using 4-noded quad S4R deformable elements. Altogether about 13832 elements were used for the origami pattern tube. Prior to that, a mesh sensitivity analysis was carried out to determine the suitable element size for the analysis. The complete assembly model is shown in Figure 2. The top and bottom plates are modelled as surfaces with discrete rigid elements. The bottom plate is fully fixed while the top plate is allowed to move in a vertical direction only. The square tube is made from Aluminium AA6065-T5 and the material mechanical properties is given in Table 3. For the contact and interaction of the multiple bodies, a coefficient of friction of 0.3 was assigned. A point mass of 36.34 kg and impact speed of 6 m/s were assigned to the top plate to simulate the drop hammer property. The values were chosen based on machine capacity.

![Figure 1. Geometric configuration of origami patterned square tube.](image1)

![Figure 2. Complete assembly of the bottom plate, square tube and top plate in the finite element simulation.](image2)
Table 1. Dimensions for the plain square tube and the origami patterned square tube.

| Parameter                  | Plain square tube | Square tube with origami |
|----------------------------|-------------------|--------------------------|
| Length, L (mm)             | 200               | 200                      |
| Width, w (mm)              | 39                | 39                       |
| Thickness, t (mm)          | 1.5               | 1.5                      |
| Width of groove, b (mm)    | -                 | 3,4                      |
| Depth of groove, d (mm)    | -                 | 0.37, 0.75               |
| Pattern angle, Θ (°)       | -                 | 64°, 68.7°               |

Table 2. Detail parameters for origami pattern arrangement of square tube.

| Pattern arrangement | Detail parameters |
|---------------------|-------------------|
| Pattern 1           | The pattern is employed on two opposing surfaces only |
|                     | Width of groove, b = 4 mm |
|                     | Depth of groove, d = 0.75 mm |
|                     | Pattern angle = 68.70° |
| Pattern 2           | The pattern is employed on all surfaces |
|                     | Width of groove, b = 3 mm |
|                     | Depth of groove, d = 0.37 mm |
|                     | Pattern angle = 68.70° |
| Pattern 3           | The pattern is employed on two opposing surfaces only |
|                     | Width of groove, b = 3 mm |
|                     | Depth of groove, d = 0.75 mm |
|                     | Pattern angle = 64° |
| Pattern 4           | The pattern is employed on all surfaces |
|                     | Width of groove, b = 4 mm |
|                     | Depth of groove, d = 0.37 mm |
|                     | Pattern angle = 64° |

Table 3. Mechanical properties of Aluminum AA6063-T5.

| Parameter                  | Value              |
|----------------------------|--------------------|
| Density                    | 2700 kg/m³         |
| Young’s Modulus, E         | 73 GPa             |
| Poisson’s Ratio, ν         | 0.33               |
| Yield strength, σ_y        | 180 MPa            |
| Ultimate tensile strength, UTS | 220 MPa          |
| Plastic strain at UTS, ε_f | 0.1                |
3. Static and Impact Experiments

The fabrication of origami patterned square tubes begins with the cutting of plain aluminum tubes into specified lengths by using an abrasive disc cutter. In order to ensure both ends of the tube are perfectly parallel to one another, the surfaces were finished using the milling machine. The origami pattern was manually machined using the vertical milling machine. The average time to machine the grooves on each surface of the tube was about 15 minutes, hence the total time to completely machine one origami patterned tube was about 40 minutes to one hour. The faces of the tube must be totally flat to ensure proper placement during the experiment. The spirit level ruler was used to check the straightness and flatness of the top and bottom tube faces on the stable table top.

The experiments were conducted to validate the simulation results. Static axial loading was carried out the INSTRON 3382 universal testing machine as shown in Figure 3. The tubes were crushed between the top and bottom compression platens with a loading rate of 5 mm/ min. The tube was crushed until 70% of its original length to ensure complete crushing of the tube. The force-displacement results were recorded using the Instron data acquisition software Bluehill.

An impact test was performed using INSTRON DYNATUP 8250 drop hammer machine as shown in Figure 4. The impact hammer is pneumatically assisted and the impact speed is controlled by the compressor pressure and drop height. Also the machine comes with a safety feature such as automatic locking sensor and impact resistance enclosure to ensure safety during an experiment. The experiment results as such as force, energy and acceleration were recorded using the Instron data acquisition software Impulse.

4. Results and Discussion

4.1. Validation of Simulation Results

Figure 5 shows the experimental and simulation force-displacement curves of the plain square tube subjected to axial static loading. Altogether 5 samples were tested for the experiment. Simulation result showed good agreement with the experimental result where both curves showed high initial peak forces followed by lower fluctuating mean forces. The experimental IPF value was slightly lower than the simulation value. This could be due to the specimen imperfections in the form of tube geometry and material properties.

Figure 6 shows the experimental and simulation force-displacement curves of the square tube with origami pattern subjected to axial static loading. Simulation results showed good agreement with the experimental results. The experimental IPF and mean force were slightly lower than the simulation values due to the specimen imperfections. In addition, machining work to create the origami pattern may result in stress concentrations and residual stress that may further weaken the tube. Both simulation and
experimental results have shown that the tube with origami pattern has lower IPF value compared to the plain tube. The outcome of which demonstrates the effectiveness of the origami pattern in reducing the IPF of the square tube subjected to static axial loading.

Figure 5. Experimental and simulation force-displacement curves for plain tube under axial static loading.

Figure 6. Experimental and simulation force-displacement curves for tube with origami pattern under axial static loading.

Figure 7 shows the experimental and simulation force-displacement curves of the plain square tube subjected to axial impact loading. Figure 8 shows the experimental and simulation force-displacement curves of the tube with origami pattern subjected to axial impact. Simulation results showed a similar trend as the experimental results. The simulation result has higher crushing distance compared to the experimental. This could be due energy lost in the form of heat, sound and vibration in the experimental impact which resulted in the lower crushing distance. Experimental results showed highly fluctuating force which gradually stabilized towards the end of the travel. This could be due to stress wave propagation in the contacting bodies during impact. Tube with origami pattern showed a lower IPF value and longer crushing distance as compared to the plain tube. This indicates that the tube with origami pattern absorbed impact energy in a more gradual and safer manner.

Figure 9 shows the simulation energy-time curves for the tube with origami pattern subjected to axial static loading. Internal energy (IE) is the energy absorbed by the tube by plastic deformation. The artificial energy (AE) indicates the element distortion energy. Since this is a quasi-static loading, kinetic energy is almost negligible as there is no inertia effect. Figure 10 shows the simulation energy-time curves for the tube with origami pattern subjected to axial impact loading. The kinetic energy (KE) is the energy of the drop mass just before impacting the tube. The internal energy is the energy absorbed
by the tube by plastic deformation. As the tube plastically deforms, the kinetic energy of the drop hammer is converted to internal energy absorbed by the tube. For perfect impact energy absorption, the kinetic energy is equal to the absorbed internal energy.

**Figure 9.** Simulation energy-time curves for tube with origami pattern under axial static loading.

**Figure 10.** Simulation energy-time curves for tube with origami pattern under axial impact loading.

Figure 11 shows the final experimental and FE deformed shapes of the plain square tube subjected to static axial loading. Figure 12 shows the final experimental and simulation deformed shapes of the tube with origami pattern subjected to static axial loading. Both experimental and simulation results showed similar failure modes for the plain tube and tube with origami pattern. Failure was progressive buckling mode with similar number of folds. The size and number of the fold of the deformed shapes will dictate the fluctuating mean forces of the tubes crushing after the initial peak forces.

**Figure 11.** Experimental and simulation deformed shapes of the plain square tube under static axial loading.

**Figure 12.** Experimental and simulation deformed shapes of the tube with origami pattern under static axial loading.

Figure 13 shows the final experimental and simulation deformed shapes of the plain square tube subjected to axial impact loading. Figure 14 shows the final experimental and simulation deformed shapes of the tube with origami pattern subjected to axial impact loading. Both experimental and simulation results showed similar failure modes for the plain tube and tube with origami pattern. For the plain tube, progressive buckling failure mode occurred at the bottom of the tube. Due to machine limitations in terms of impact speed and impact mass, only one fold could be achieved which resulted in only one peak recorded in the force-displacement curves. For the tube with origami pattern, the failure mode was similar but at a different location. For the experimental, failure occurred near the bottom of the tube while for the simulation, failure occurred near the top of the tube. This could be due stress wave propagation and stress concentrations on the sample due to machining process of the origami pattern.
4.2. Static and Impact Simulation Results of Tubes with Different Origami Patterns

Figure 15 shows the force-displacement curves for plain square tube and tubes with different origami patterns subjected to axial static loading. Figure 16 shows the failure modes of all tubes with different origami patterns. All tubes failed in progressive buckling mode with different folding size and shape. The plain square tube exhibited the highest IPF while all tubes with origami patterns showed a significant reduction in IPF. From Table 4, it can be seen that Pattern 4 had the lowest IPF, a decrease of 69.1% compared to the plain tube. Pattern 4 also showed the highest CFE with an increase of 134.7% compared to the plain tube. The origami patterns on all four sides of the tubes reduce the resistance to progressive collapse resulting in a lower IPF value and an improved CFE value. In terms of SEA, Pattern 3 showed the highest increase of 27.9% compared to the plain tube. The plain opposing sides of Pattern 3 may result in higher energy absorption due to its higher stiffness. The findings above suggest that the addition of origami pattern on the tube may reduce the IPF and increase the CFE but at the expense of SEA. More parametric study needs to be carried out to optimize the design of origami pattern on the tube for energy absorption under static loading.

Figure 15. Simulation force-displacement curves of plain square tube and tubes with different origami pattern under axial static loading.

Figure 16. Failure modes of tubes with different origami patterns subjected to axial static loading.
Table 4. Changes in crush performance indices of tube with different origami patterns subjected to axial static loading.

| Crush Performance Index | Plain Square Tube | % Change | Pattern 1 | Pattern 2 | Pattern 3 | Pattern 4 |
|-------------------------|-------------------|----------|-----------|-----------|-----------|-----------|
| IPF                     | 39152 N           | -28.5    | -65.5     | -29.8     | -69.1     |
| CFE                     | 40.5 %            | +6.5     | +80.1     | +34.1     | +134.7    |
| SEA                     | 12692 J/kg        | +6.7     | -16.5     | +27.9     | +20.6     |

Figure 17 shows the force-displacement curves for plain square tube and tubes with different origami patterns subjected to axial impact loading. Figure 18 shows the failure modes of all tubes with different origami patterns. All tubes failed in progressive buckling mode where failures occurred at different parts of the tubes. For Patterns 1 and 2, failures occurred near the top of the tubes. For Patterns 3 and 5, failures occurred at the middle of the tubes. The plain square tube exhibited the highest IPF while all tubes with origami patterns showed a significant reduction in IPF. From Table 5, it can be seen that Pattern 2 had the lowest IPF, a decrease of 73.5% compared to the plain tube. Pattern 2 also showed the highest CFE with an increase of 126.9% compared to the plain tube. The origami patterns on all four sides of the tubes reduce the resistance to progressive collapse resulting in lower IPF and better CFE. In term of SEA, all tubes with origami pattern showed slight reduction compared to the plain tube. Among all tubes with origami pattern, Pattern 3 gave the best SEA with a 3.6% reduction compared to the plain tube. The findings above suggest that the addition of origami pattern on the tube may reduce the IPF and increase the CFE but at the expense of SEA. More parametric study needs to be carried out to optimize the design of origami pattern on the tube for energy absorption under impact loading.
Table 5. Changes in crush performance indices of tube with different origami patterns subjected to axial impact loading.

| Crush Performance Index | Plain Square Tube | Pattern 1 | Pattern 2 | Pattern 3 | Pattern 4 |
|-------------------------|-------------------|-----------|-----------|-----------|-----------|
| IPF                     | 42390 N           | -17.1     | -73.5     | -18.4     | -72.2     |
| CFE                     | 41.1 %            | -21.8     | +126.9    | -11.2     | +106.8    |
| SEA                     | 5098 J/kg         | -4.1      | -4.7      | -3.6      | -4.2      |

5. Conclusion

In axial static loading, Pattern 4 showed the lowest IPF which is a reduction of 69.1% compared to the plain square tube. Pattern 4 also gave the highest increase in CFE with an increase of 134.7% compared to the plain square tube. In terms of SEA, Pattern 3 showed the highest increase of 27.9% compared to the plain square tube. In axial impact loading, it can be seen that Pattern 2 shows the lowest IPF, a reduction of 73.5% compared to the plain square tube. Pattern 2 also gave the highest increase in CFE of 126.9% compared to the plain square tube. In terms of SEA, Pattern 3 gave the best performance which is a reduction of only 3.6% compared to the plain square tube.

Overall, the predicted results have shown that the employment of origami pattern on the square tube has reduced the initial peak force (IPF) and increased the crush force efficiency (CFE). The specific energy absorption (SEA) of the origami tubes under static loading is improved while for impact loading, the SEA showed a slight reduction. Based on this study, it can be observed that the geometry and dimension of the origami pattern influence the crush response of the tube. Further detail parametric study needs to be carried out to optimize the crush response of the tube in terms of IPF, CFE and SEA under static and dynamic loadings. The study has shown that the origami pattern can be employed on various tubular structures to improve their crush performance for a wide range of application.

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