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Axial Compression Performance of Square Tube Filled with Foam Aluminum

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ABSTRACT

As a typical buffer energy absorbing structure, thin-walled tube filled with foam aluminum has good mechanical properties and energy absorption characteristics. Therefore, the axial compression performance of square tube and foam aluminum filled square tube was experimentally studied by quasi-static mechanical loading method. On the basis of the existing experimental research and theoretical analysis, the strain rate is introduced into the dynamic compression theory, and the mathematical model of the average crushing force of foam aluminum filled square tube under the axial quasi-static and impact loads is obtained. By comparing the theoretical results with the simulation results, the error of quasi-static and impact state is 2.8 and 8%, respectively. The feasibility of the theoretical analysis is verified. This paper not only proves that foam aluminum filling can significantly improve the bearing capacity and energy absorption performance of square tube structure in the axial compression process, but also provides a more specific theoretical basis for the axial compression energy absorption design of square tube filled with foam aluminum.

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NOMENCLATURE

ρ	Density ($\mathrm{kg \cdot m^{-3}}$)
σ_s	Yield strength (MPa)
P_m	Average load of single collapse of thin-walled square tube (MPa)
σ_f	Platform stress of foam aluminum core bearing alone (MPa)
σ_0	Yield stress of thin-walled square tube materials (MPa)
b	The width of the square tube (mm)
t	The thickness of square tube's wall (mm)
C	Interaction coefficient between foam aluminum and tube wall
Φ	The volume fraction of solids contained in the edges of foam aluminum cells
ε_f	The maximum strain value during the deformation of foam aluminum

P_1	Loads borne by the interaction between foam aluminum and metal thin-walled square tubes (MPa)
P_mf	Average crushing load of square tube filled with foam aluminum under quasi-static axial load (MPa)
P_m^d	Average crushing load of square tube under axial impact load (MPa)
$\dot{\varepsilon}_\mathrm{f}$	The strain rate of foam aluminum under quasi-static axial load
$\dot{\varepsilon}_\mathrm{f}^\mathrm{d}$	The strain rate of foam aluminum under dynamic impact load
P_mf^d	Average crushing load of square tube filled with foam aluminum (MPa)
m	Strain rate sensitivity coefficient
L	Height of foam aluminum specimen(mm)

Subscript

d	Dynamic

1. INTRODUCTION

Foam aluminum is a new type of structural and functional porous material developed rapidly in recent years. It has low density, high porosity, closed holes or open holes structure characteristics. However, due to the large number of holes in the structure of foam aluminum, foam aluminum is not suitable for use as structural material alone. It is usually used as a composite member with traditional dense metal, so as to achieve the best mechanical properties under certain loads, such as compression and bending properties. At the same time, foam material hided in closed and dense components can play a certain role of corrosion protection. At present, it

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has been widely used in mechanical, construction, aerospace, especially in automobiles [1-3].

The sandwich structure consisting of foam aluminum core and metal panel generally has the advantages of light weight, high specific strength, high specific stiffness and good shock absorption. In recent years, domestic and foreign scholars have carried out a lot of experiments and numerical simulation research on foam aluminum filling structure. To overcome the 3D modelling problem of closed-cell foams structure, Akhavan et al. [4] present the method based on CT-scan and digital optic microscope imaging combination. The quasi-static axial compression performance of foam aluminum sandwich double tube structure was studied by Yu et al. [5] It was found that the energy absorption efficiency of the new structure was much higher than that of the conventional foam aluminum sandwich tube. Zhang [6] carried out the crashworthiness optimization model of aluminum alloy cone tubes filled with functional density gradient foam aluminum under low velocity impact. The research shows that the peak load of the strong bonded foam aluminum filled cone tube in collision is lower, the load change is more stable, and the energy absorption is greater than the energy absorption. The torsion test of the galvanized steel tube filled with foam aluminum under high temperature was carried out by Wang et al. [7], and the test results showed that the torsion bearing capacity of the galvanized steel filled with foam aluminum decreased with the increase of porosity, and increased with the increase of steel content and slenderness ratio. The conducted quasi-static compression energy absorption experiments on foam aluminum filled corrugated plate structures by Yan [8,9] et al, and found that the compression stress of foam aluminum filled corrugated plate was much higher than the sum of the compression stress of foam aluminum filled corrugated plate and hollow corrugated plate alone, showing an obvious coupling enhancement effect. In addition, the compression test and numerical simulation of the composite structure formed in the void and corrugated core of the closed cell foam aluminum filled sandwich plate were carried out under low-speed impact. The results show that the filling of foam aluminum reduces the buckling wavelength, and the plastic energy dissipation of the foam-filled core is much higher than that of the hollow core. The axial-compressive experiment of circular tube filled with foam aluminum core was studied by Gilchrist et al. [10], the results showed that the tube with the smallest inner diameter and the largest foam thickness is more suitable for energy absorbing parts. Duarte et al. [11] had studied the deformation mode of pipe the filled with foam aluminum. During the deformation process, the foam aluminum filler restrained the tube wall to buckle inward and made the energy absorption process more stable. Kader et al. [12] demonstrated the deformation mechanism of foam aluminum by using topology optimization for the first time, and relate the deformation to the mechanical response in the impact process.

At present many literature has the mechanical properties of the foam aluminum is carried on the detailed elaboration, but the study of structure of foam aluminum filler is relatively small, and most only involves numerical simulation research, the foam aluminum filled square tube under quasi-static and impact load is the average crushing load and energy absorption properties of the mathematical model of research are still lacking .This paper aims to studied the axial compression performance of square tube filled with foam aluminum by using experiment and simulation method. Through the experiments, the difference of deformation mode, bearing capacity and energy absorption efficiency between square tube and foam aluminum filled tube are analyzed. And the mathematical model of average crushing load of foam aluminum filled square tube under static and dynamic compression is obtained. In order to verify the theoretical analysis results, the theoretical calculation results and simulation results are compared with the experimental results. The results are to further explain the deformation mechanism of the foam aluminum filled structure, and it also provides a theoretical basis for the design of axial compression energy absorption the of square tube filling structure.

2. EXPERIMENTAL STUDY

2. 1. Sample Preparation The hollow square tube used in this experiment is Q235 low carbon steel cold drawn thin-walled square tube, the size is 30×30×80 mm, and the wall thickness is 1.2 mm. For the uniaxial compression test of square tube specimen, taking into account the processing technology level of the laboratory and the particularity of the foam aluminum filled square tube structure, the cuboid shape of 27×27×80 mm is determined by the wire cutting method as a sandwich body for filling the empty square pipe. The closed cell foam aluminum used for filling thin wall square core is produced by melt foaming method from Shenyang Dongda advanced material development limited company. Its matrix material is ZL102 aluminum alloy, with an average pore size of 3 mm~4 mm and a relative density of 0.22. The data of material parameters and mechanical properties are provided by the manufacturing company, as shown in Table 1. The stress-strain curve of the closed cell foam aluminum under unaxial quasi-static compression is shown in Figure 1.

The tube wall and the foam aluminum core are bonded by epoxy resin. After the epoxy resin has been completely cured, a thin-walled square tube filled with foam aluminum is prepared, as shown in Figure 2.

TABLE 1. Material parameters of closed-cell foam aluminum

Parameter	Value
Density ρ/kg·m^{-3}	540
Elastic modulus E/MPa	254
Poisson's ratio μ	0.33
Yield strength σ_s /MPa	8.1

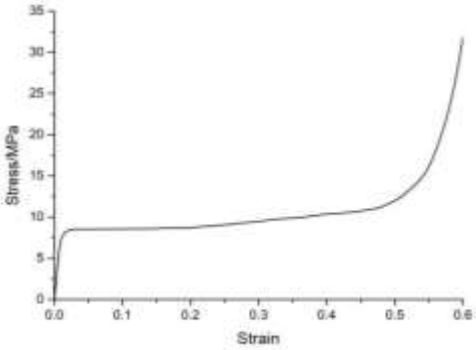

Figure 1. Compression stress-strain of foam aluminum

Figure 2. Specimen of compression experiment

2. 2. Experimental Equipment and Methods SANS-CMT5205 microcomputer controlled electronic universal testing machine is used in the experiment. The whole experiment process is controlled by microcomputer. The load value, displacement value, experimental loading speed and experimental curve are displayed dynamically in real time. The loading displacement curve is recorded automatically.

During the experiment, there is no special fixture (such as clamp), the specimen is placed in the middle of the rigid platform, and the pressure plate of the testing machine directly loads the end face of the square tube specimen. The loading rate is 0.1 mm/s (the strain rate is 10^{-2}). The loading stops, when the displacement of the plate is 55 mm (the total strain is 0.7) or the specimen collapse. In order to compare the experimental results, the quasi-static compression experiments of hollow square tubes and square tubes filled with foam aluminum are carried out, the process of text as shown in Figures 4 and 5. Three repetitions are tested in each case, and the average value is taken as the experimental result.

2. 3. Experimental Results and Analysis The axial compression load displacement curves of foam aluminum, hollow tube, foam aluminum filled tube and foam aluminum + hollow square tube (calculated value) is placed in the same coordinate system, as shown in Figure 7.

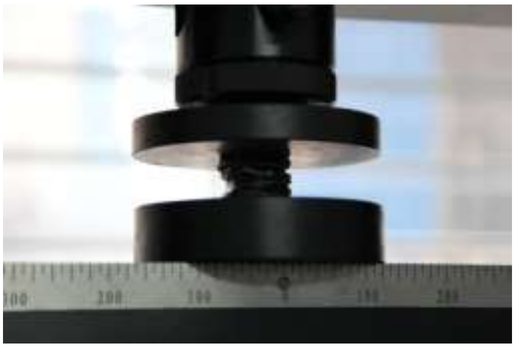

Figure 3. Quasi-static compression result of thin-walled square tube with foam aluminum filler

Figure 4. Quasi-static compression result of hollow square tube

Figure 5. Comparison of compression test results between square and square tubes filled with foam aluminum

Combined with Figures 5 and 7, it can be seen that when the square tube is compressed, the loading force first reaches an initial peak value, then decreases sharply, and then fluctuates periodically into a stable bearing area. Each load fluctuation on the load displacement curve corresponds to the formation and complete flattening of a fold. The formation of each fold includes the inner and outer folds of the pipe wall, corresponding to the two peaks of each fluctuation. After being completely flattened, the folds are regularly distributed on both sides of the undeformed tube wall. Similarly, we can also find out from the analysis of Figures 4 and 7. The fluctuation on the load displacement curve of the square tube filled with foam aluminum is related to the number and location of the fold in the crushing process. Before the upper and lower pipe walls which formed the fold contacted with each other but were not compacted, the load was reduced to the minimum, and it was shown as a trough on the load displacement curve. At the same time, the peak load of the foam aluminum filled square tube is not obvious when it collapsing. When the compressible part of the square tube is fully compacted, the bearing capacity of the structure increases rapidly.

By comparing the load-displacement curves of foam aluminum filled square tubes and empty square tubes, it is known that the equivalent yield strength of square tubes filled with foam aluminum increases, and the crest, trough and corresponding load and average load increase on the compression load displacement curve. In the whole crushing process, the compression load is much higher than that of the corresponding empty square tube under the same compression displacement. From Figure 7, the mean load of the empty square tube is only 17.26KN, while the mean load of the square tube filled with foam aluminum is 33.04KN, which is 1.91 times the mean load of the empty square tube. At the same time, the compression process can also be found that due to the filling of foam aluminum, the compression distance of the structure is reduced, as shown in Figure 6.

Due to the filling of the foam aluminum core, the trend of the bending of the square tube is restrained. It makes the folds of thin-walled tube shorter and the number increased. At the same time, when the tube wall folds into the foam aluminum core, the multi-directional extrusion of the foam aluminum material increases the plastic deformation of the foam aluminum. As a result, the bearing capacity and energy absorption capacity of the foam aluminum filled tube structure are greatly improved. Because the yield stress of the metal tube wall is much larger than the yield stress of the foam aluminum, the deformation of the aluminum foam core is restricted by the wall of the tube, which results in the same deformation mode of the aluminum foam core as the fold of the tube. This is the contribution of interaction to the crushing load, which makes the average crushing load of aluminum foam-filled structure increase by 30%, which is higher than the sum of the crushing load of thin-walled empty square tube structure and foam aluminum filled structure.

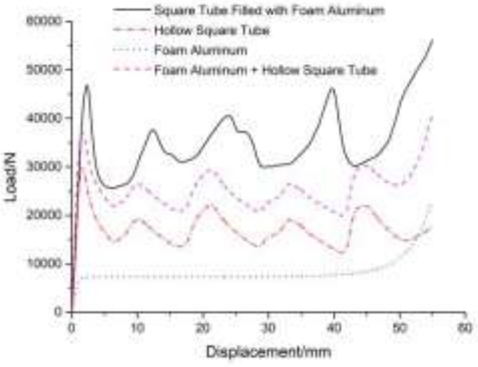

Figure 6. Interaction between foam aluminum and tube wall

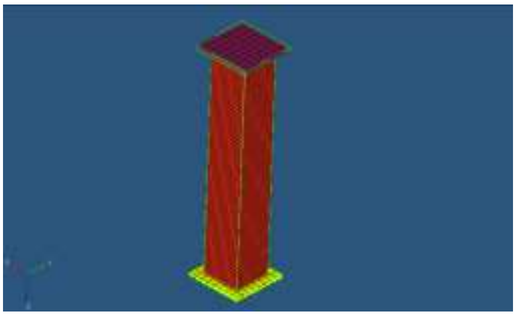

Figure 7. Finite element model of compression

3. QUASI STATIC COMPRESSION PERFORMANCE ANALYSIS OF SQUARE TUBE FILLED WITH FOAM ALUMINUM

The axial compression load of thin-walled square tubes filled with foam aluminum can be divided into three parts: the load bearing capacity of the foam aluminum alone, the load carrying capacity of the thin-walled hollow tube separately, and the load acting on the interaction between the foam aluminum and the thin-walled hollow pipe.

Hanssen et al. [13] through the experimental study of the thin-walled square tube filled with foam aluminum under axial impact condition, the average load formula of the filled structure under quasi-static axial load is obtained.

$$P_{\mathrm{mf}} = P_{\mathrm{m}} + b^2\sigma_{\mathrm{f}} + Cbt\sqrt{\sigma_{\mathrm{f}}\sigma_0} \tag{1}$$

3. 1. Average Crushing Load of Square Tube Under Quasi-Static Load Wierzbicki and Abramowicz [14] have studied the collapse process of thin-walled square tubes by experiments, and have given the typical fold of symmetrical deformation mode. The average load formula of single crushing of thin-walled square tubes stated as follows:

$$P_{\mathrm{m}} = 13.06\sigma_0 t^{\frac{5}{3}} b^{\frac{1}{3}} \tag{2}$$

$$\sigma_0 = \frac{\sigma_{\mathrm{u}} + \sigma_{\mathrm{y}}}{2} \tag{3}$$

For the foam aluminum filled square tubes studied in this paper, the material is Q235 low carbon steel square tube, its yield strength is 235 MPa, tensile yield strength is 380 MPa, and the above values are calculated by substitution formula P_m=16.909KN.

3. 2. Average Crushing Load of Foam Aluminum under Quasi-static Loading

The ratio of plateau stress σ_{f} of closed cell foam aluminum to the yield stress σ_{s} of foam aluminum matrix is:

$$\frac{\sigma_{\mathrm{f}}}{\sigma_{\mathrm{s}}} \approx 0.3\left(\phi\frac{\rho_{\mathrm{f}}}{\rho_{\mathrm{s}}}\right)^{3/2} + 0.4(1-\phi)\left(\frac{\rho_{\mathrm{f}}}{\rho_{\mathrm{s}}}\right) \tag{4}$$

By fitting the stress-strain curve of foam aluminum, the constitutive relation expression of foam aluminum material is obtained:

$$\sigma(\varepsilon) = \begin{cases} \sigma_{\mathrm{f}} & \varepsilon \le \varepsilon_{\mathrm{c}} \\ \left(1 + a_0 \mathrm{e}^{\varepsilon/b_0}\right)\sigma_{\mathrm{f}} & \varepsilon_{\mathrm{c}} < \varepsilon \le \varepsilon_{\mathrm{f}} \end{cases} \tag{5}$$

The coefficients of a_0 and b_0 can be obtained by fitting the stress-strain curves. $a_0 = 2.3\times10^5$ and b_0 =0.06411. By integrating Equation (5), the average stress of foam aluminum material in the process of 0~ ε_{f} strain is:

$$\sigma(\varepsilon_{\mathrm{f}}) = \frac{1}{\varepsilon_{\mathrm{f}}}\int_0^{\varepsilon_{\mathrm{f}}} \sigma(\varepsilon)\mathrm{d}\varepsilon = \sigma_{\mathrm{f}} + \frac{1}{\varepsilon_{\mathrm{f}}} a_0 b_0 \sigma_{\mathrm{f}}\left(\mathrm{e}^{\varepsilon_{\mathrm{f}}/b_0} - \mathrm{e}^{\varepsilon_{\mathrm{c}}/b_0}\right) \tag{6}$$

The base material of foam aluminum used in this paper is ZL102 aluminum alloy, and its yield strength is σ_{s} =240MPa. The substitution stress (4) can obtain the theoretical value of the platform stress of σ_{f} =7.340MPa.

According to the stress-strain curve in Figure 1, ε_{c} and ε_{f} are taken as 0.7 and 0.5, respectively. By substituting the parameters into Equation (6), $\sigma(\varepsilon_{\mathrm{f}})$ =8.393MPa can be obtained. The theoretical results agree well with the platform stress values of 8.1MPa for foam aluminum specimens.

3. 3. Interaction between Foam Aluminum Core and Tube Wall

Due to the filling of foam aluminum, the foam aluminum core provides constraints when the tube wall buckled inward. The effective length of each plastic fold decreases. The proportion of the tube wall bending inward also decreased. This results in a higher average load. The contribution of the interaction between the foam aluminum core and the metal thin-walled square tube to the average load is expressed as follows:

$$P_1 = C \times \sigma_{\mathrm{f}}^{\alpha_1} \times \sigma_0^{\alpha_2} \times r^{\alpha_3} \times t^{\alpha_4} \tag{7}$$

According to the experiment of Hassen and Abramowicz [13, 14], when α1=α2=0.5, α3=α4=1, C is a dimensionless constant, and the value of C is 5. Therefore, Equation (7) can be simplified as: follows:

$$P_1 = 5bt\sqrt{\sigma_{\mathrm{f}}\sigma_0} \tag{8}$$

The interaction between the foam aluminum core and the tube wall can contribute to the average crushing load by introducing the relevant data into the formula (8). The contribution of the interaction between the foam aluminum core and the tube wall is P_1 =7.853KN.

By subbing into Equation (1) the average crushing load of the thin-walled square tube under the quasi-static axial load obtained through theoretical analysis, the platform stress of the foam aluminum material under the single load, and the interaction between the foam aluminum core and the tube wall, the average crushing load of the thin-walled square tube under the quasi-static axial load can be obtained:

$$P_{\mathrm{mf}} = P_{\mathrm{m}} + b^2\sigma_{\mathrm{f}} + Cbt\sqrt{\sigma_{\mathrm{f}}\sigma_0} =$$

$$16.909 + 0.03^2 \times 8.39\times10^6 + 7.853 = 32.3157\ \mathrm{KN}$$

The experimental data are taken into the formula of quasi-static compression average crushing load of foam aluminum filled square tubes deduced by Hanssen et al. [13] The results are compared with the theoretical and experimental results. It can be seen that the error between the theoretical results and the experimental results is smaller and more accurate. The comparison results are shown in Table 2.

4. DYNAMIC COMPRESSION PERFORMANCE ANALYSIS OF SQUARE TUBE FILLED WITH FOAM ALUMINUM

Different from the deformation behavior under quasi-static load, the member is subjected to large impact load in a short time, and the whole deformation process is a complex nonlinear dynamic response process. It has very obvious dynamic characteristics, and the plastic flow usually occurs in the collision area of the component. The plastic flow deformation of many materials will be affected by the strain rate.

4. 1. Collapse Load of Square Tube Under Impact Load

Due to the obvious strain rate effect of low carbon steel, Cowper-Symonds model is used to consider the effect of strain rate on the mechanical properties of

TABLE 2. The theoretical calculation results of the average crushing load of square tubes filled with foam aluminum are compared with the experimental results

Experimental result	Theoretical calculation results		Compare the calculation results	
	P_m /KN	Relative error /%	P_m /KN	Relative error /%
33.04	32.3157	2.2	32.1998	2.6

pipe wall materials. Combined with the dynamic yield stress formula described by the model and the experimental and theoretical analysis results of Abramowicz and Jones [15], the average crushing load of thin-walled square tube under axial impact load is obtained as follows:

$$P_{\mathrm{m}}^{\mathrm{d}}=13.06\sigma_0 b^{\frac{1}{3}}t^{\frac{5}{3}}\left[1+\left(0.33\frac{V_0}{bD}\right)^{\frac{1}{q}}\right] \tag{9}$$

In the above equation D, q are constants, D= 6844s-1, q=3.91. Put relevant parameters into Equation (9) to calculate the load response of empty square pipe impact is 22.068KN.

4. 2. Crushing Load of Foam Aluminum Under Impact Loading

For foam aluminum, the yield stress under dynamic loading is:

$$\sigma_{\mathrm{f}}^{\mathrm{d}}=\sigma_{\mathrm{f}}\left(\frac{\dot{\varepsilon}_{\mathrm{f}}^{\mathrm{d}}}{\dot{\varepsilon}_{\mathrm{f}}}\right)^m \tag{10}$$

In the formula, σ_{f} is the yield stress of foam aluminum under quasi-static axial load; $\dot{\varepsilon}_{\mathrm{f}}$ is the strain rate of foam aluminum under quasi-static axial load; $\dot{\varepsilon}_{\mathrm{f}}^{\mathrm{d}}$ is the strain rate of foam aluminum under dynamic impact load, V_0 is strain rate sensitivity coefficient, and the value is 0.039.

When the impact velocity is V_0 the strain rate of foam aluminum under dynamic impact load is:

$$\dot{\varepsilon}_{\mathrm{f}}^{\mathrm{d}}=\frac{\varepsilon_{\mathrm{f}}}{T}=\frac{\varepsilon_{\mathrm{f}}}{\varepsilon_{\mathrm{f}}L/V_0}=\frac{V_0}{L} \tag{11}$$

Substituting Equation (12) into Equation (11).

$$\sigma_{\mathrm{f}}^{\mathrm{d}}=\sigma_{\mathrm{f}}\left(\frac{V_0}{\dot{\varepsilon}_{\mathrm{f}}L}\right)^m \tag{12}$$

4. 3. Energy Absorption Characteristics of Square Tubes Filled with Foam Aluminum under Impact Loading

Under the dynamic impact axial compression load, the interaction between the foam aluminum core and the tube wall has a smaller impact on the average load than that of the thin-walled hollow tube and the foam aluminum core. Therefore, the effect of strain rate on the average load of foam aluminum core and tube wall is not considered. Substitute Equations (9) and (12) into Equation (1), and the average crushing load of foam aluminum filled square tube under dynamic impact axial compression load is:

$$\begin{aligned}P_{\mathrm{mf}}^{\mathrm{d}}&=P_{\mathrm{m}}^{\mathrm{f}}+b^2\sigma_{\mathrm{f}}^{\mathrm{d}}+Cbt\sqrt{\sigma_{\mathrm{f}}\sigma_0}\\&=13.06\sigma_0 b^{\frac{1}{3}}t^{\frac{5}{3}}\left[1+\left(0.33\frac{V_0}{bD}\right)^{\frac{1}{q}}\right]\\&+b^2\sigma_{\mathrm{f}}\left(\frac{V_0}{\dot{\varepsilon}_{\mathrm{f}}l}\right)^m+Cbt\sqrt{\sigma_{\mathrm{f}}\sigma_0}\end{aligned} \tag{13}$$

By putting relevant parameters into Equation (13), the average crushing load of foam aluminum filled square tube under impact can be calculated as 39.1KN.

5. SIMULATION

In order to further study, the accuracy of theoretical analysis, HyperMesh and LS-DYNA finite element analysis software were used to simulate the axial compression deformation of the structure under impact.

5. 1. Modeling and Meshing

Figure 8 shows the finite element model of axial compression. The tube wall and foam aluminum are all divided into 2 mm mesh sizes. The shell of the thin-walled square tube is made of two dimensional Shell163 thin shell element. The thickness of the element is 1.2 mm and the shape of the cell is quadrilateral. The foam aluminum core is divided into three dimensional Solid164 elements, and the cell shape is hexahedron. The compression model is divided into 11760 individual elements, 3360 thin shell elements and 128 rigid elements. The rate of deformation is an important factor in the impact process. It is necessary to consider the strain rate effect in the impact simulation analysis. So, the Cowper-Symonds model is used as the material model for the impact simulation of aluminum foam filled square tube structure [16,17].

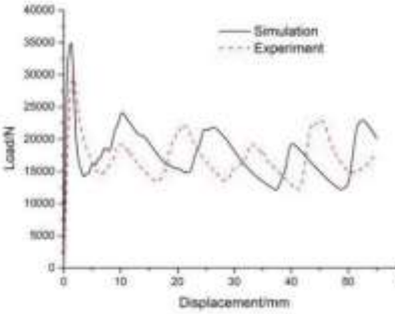

Figure 8. Quasi-static compression load-displacement of empty square tube

5. 2. Analysis of Compression Simulation Results

The compression deformation behaviors of empty square tube and foam aluminum filled square tube samples under quasi-static and impact loads were numerically simulated. The results obtained were compared with the experimental results and analyzed as follows.

(1) Compression simulation results and analysis of square tube

Figures 9 and 10 are the numerical analysis results of load displacement curve and the simulation results of quasi-static compression of hollow square tube.

The relative error of the three methods is shown in Table 3. The results of numerical simulation and theoretical calculation are very close to the experimental results, which shows that the process and conclusion of theoretical analysis of low carbon steel square tube structure are consistent.

(2) Compression simulation results and analysis of square tube filled with foam aluminum

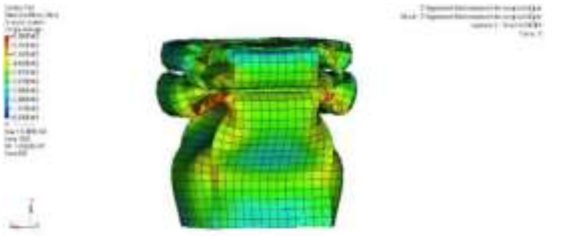

Figure 9. Quasi-static compression simulation results of square empty tube

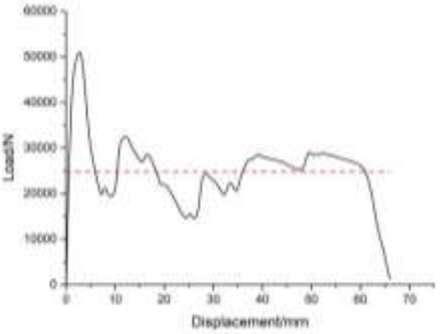

Figure 10. Dynamic compression load-displacement curve of square empty tube

TABLE 3. Average crushing load of square empty tube by theoretical calculation, numerical simulation and experimental

Experimental result	Theoretical calculation results		Numerical simulation results	
	P_m /KN	Relative error /%	P_m /KN	Relative error /%
17.26	16.909	2.1	17.931	3.9

Figures 11 and 12 are the comparison of the load displacement curves obtained from the quasi-static compression simulation analysis of the foam aluminum filled square tube with the experimental data and the quasi-static compression simulation results of the foam aluminum filled square tube.

By comparing the two curves, it can be seen that the initial peak load, average crushing load and the overall trend of load displacement curve obtained by simulation analysis are close to the experimental data. The average crushing load obtained by simulation analysis is 33.27KN, which is slightly larger than the average crushing load obtained by experiment 33.04KN, and the error is only 0.7%. It shows that the process and conclusion of theoretical analysis of the quasi-static compression load of square tube filled with foam aluminum are effective.

The compression load displacement curve of the foam aluminum filled square tube under dynamic load is shown in Figure 13.

It can be seen from Figure 13 that the average crushing load of the square tube filled with foam aluminum under impact loading is 36.22KN, and the error between theoretical analysis value 39.1KN and the average crushing load theoretical value of foam aluminum filled square pipe under impact is 8%. It is proved that the theoretical analysis results of the average crushing load of foam aluminum filled square tubes are

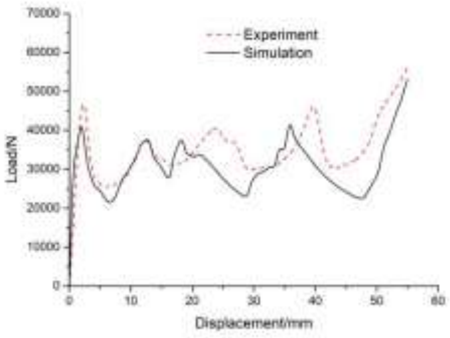

Figure 11. Quasi-static compression load-displacement of square tube with foam aluminum filler

Figure 12. Quasi-static simulation results of square tube with foam aluminum filler

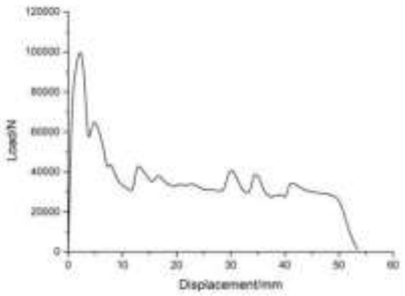

Figure 13. Dynamic compression load-displacement curve of square tube filled with foam aluminum

available when the dynamic impact axial compression load is proved.

6. CONCLUSION

(1) The research results show that the filling of foam aluminum improves the bearing capacity and energy absorption performance of the square tube structure during axial crushing process. Not only is the foam aluminum core bearing some load, but the interaction between the foam aluminum core and the tube wall also contributes to the improvement of the load capacity and energy absorption.

(2) The initial peak load and average crushing load of the specimen obtained from the simulation analysis are close to the experimental data. The simulation results show that the average crushing load is 33.27 KN, and the experimental results show that the average crushing load is 33.04 KN, and the error between them is only 0.7%. The calculated average load of quasi-static collapse failure is 32.32KN, which is very close to the simulation and experimental results. It shows that the process and conclusion of theoretical analysis of the quasi-static compression load of square tube filled with foam aluminum are effective.

(3) The effect of strain rate on the average crushing load of filled square tube is introduced into the theoretical analysis of dynamic compression, and the theoretical analysis value of dynamic compression is 39.1KN. Compared with the average crushing load of 36.22KN, the error is 8%. The error between the two is small. It can be seen that the formula for calculating the average load of axial compression failure of foam aluminum filled square tube structure under impact load is correct and reliable.

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Persian Abstract

چکیده

به عنوان یک ساختار معمولی جذب کننده انرژی بافر ، لوله دیواره نازک پر از آلومینیوم فوم دارای خواص مکانیکی خوب و ویژگی های جذب انرژی است. بنابراین ، عملکرد فشرده سازی محوری لوله مربع و لوله مربع پر از آلومینیوم فوم به طور آزمایشی با استفاده از روش بارگذاری مکانیکی شبه استاتیک مورد مطالعه قرار گرفت. بر اساس تحقیقات تجربی و تجزیه و تحلیل نظری موجود ، نرخ کرنش به تئوری فشرده سازی دینامیکی وارد می شود و مدل ریاضی متوسط نیروی خردایش لوله مربع پر از آلومینیوم فوم تحت بارهای شبه استاتیکی و ضربه محوری به دست می آید. با مقایسه نتایج نظری با نتایج شبیه سازی ، خطای شبه استاتیک و حالت ضربه به ترتیب ۲.۸ و ۸٪ است. امکان تجزیه و تحلیل نظری تأیید شده است. این مقاله نه تنها اثبات می کند که پر کردن آلومینیوم فوم می تواند به طور قابل توجهی ظرفیت تحمل و عملکرد جذب انرژی ساختار لوله مربع را در فرآیند فشرده سازی محوری بهبود بخشد ، بلکه مبانی نظری خاص تری را برای طراحی جذب انرژی فشرده سازی محوری لوله مربع پر از کف آلومینیوم فراهم می کند