Axial Compression Behavior and Design of Conical Energy Absorption Boxes Filled with Graded Aluminum Foam Postprint

Authors: Xiwei Wu

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Abstract

To satisfy the demands of structural lightweighting and energy absorption, superior energy-absorbing box structures were designed and investigated. Simulation and lightweight design of the quasi-static axial compression behavior of gradient aluminum foam-filled tapered energy-absorbing boxes were performed using ABAQUS finite element software. The validity of the finite element computational model was verified through comparison with experimental results from literature. Subsequently, the influence of factors including the tapered base angle of square cross-section energy-absorbing boxes, the number of trigger grooves, the height and depth of trigger grooves, and gradient material parameters on the energy absorption characteristics of gradient aluminum foam-filled tapered energy-absorbing box structures under axial compression was investigated. Thereafter, optimization design was conducted on the gradient aluminum foam-filled tapered energy-absorbing box structure with the optimization objectives of achieving lower peak load and superior energy absorption for structures of equal mass. The results indicate that these factors exhibit favorable effects on enhancing the energy absorption characteristics of the energy-absorbing box. The optimized gradient aluminum foam-filled tapered energy-absorbing box structure demonstrated a 20% reduction in maximum peak force and a 3.6% improvement in specific energy absorption, along with a smoother crash force-displacement curve that is more beneficial for energy absorption by the energy-absorbing box.

Full Text

Quasi-static Axial Compressive Behavior and Design of Conical Energy-Absorbing Box Filled with Gradient Foam Aluminum

WU Xiwei[1],[2], **ZHANG Jianxun**[1] [1]. State Key Laboratory for Strength and Vibration of Mechanical Structures, School of Aerospace, Xi' an Jiaotong University, Xi' an 710049, China [2]. College of Mechatronic Engineering, North University of China, Taiyuan 030051, China

Abstract

To meet the dual demands of structural lightweighting and energy absorption, this study investigates the design and performance of advanced energy-absorbing box structures through finite element simulation using ABAQUS. The quasi-static axial compression behavior and lightweight design of conical energy-absorbing boxes filled with gradient aluminum foam were systematically analyzed. The validity of the finite element model was first verified by comparison with experimental results from the literature. Subsequently, parametric studies were conducted to examine the influence of conical bottom angle, number of induction grooves, groove height and depth, and gradient material parameters on the energy absorption characteristics of the filled conical structures under axial compression. Optimization was then performed with the objectives of minimizing peak load while maintaining excellent energy absorption for structures of equal mass. The results demonstrate that these factors effectively enhance the energy absorption performance. The optimized gradient foam-filled conical energy-absorbing box achieved a 20% reduction in maximum peak force and a 3.6% increase in specific energy absorption, while exhibiting a smoother collision force-displacement curve that is more conducive to energy absorption.

Keywords: conical energy-absorbing box structure; gradient foam aluminum; quasi-static compression; finite element simulation; lightweight design

1. Performance Evaluation Indicators and Design Principles

1.1 Performance Evaluation Indicators Based on design requirements for energy-absorbing box structures, this study adopts three key performance indicators to evaluate the energy absorption characteristics of aluminum foam-filled boxes under quasi-static compression: maximum peak force ($F_{\max}$), total energy absorption (E_{abs}), and specific energy absorption (r_{SEA}).

The maximum peak force $F_{\max}$ represents the maximum collision force generated during the crushing process. Higher values cause more severe damage to the structure, so lower peak forces indicate better cushioning characteristics.

Total energy absorption E_{abs} refers to the total energy absorbed through plastic deformation throughout the crushing process. It is related to crushing force and displacement, expressed as:

$$E_{abs} = \int_0^{\delta_{\max}} F(s)ds$$

where $\delta_{\max}$ is the crushing displacement and $F(s)$ is the crushing force.

Specific energy absorption r_{SEA} is the ratio of absorbed energy to total mass, reflecting the energy absorption capacity per unit mass and providing important guidance for lightweight design:

$$r_{SEA} = \frac{E_{abs}}{m}$$

where E_{abs} is the total absorbed energy and m is the mass of the energy-absorbing box.

1.2 Design Principles The following principles must be adhered to in the design and material selection of energy-absorbing boxes [**?**]:

1) Energy absorption should preferably be converted into irreversible plastic deformation.
2) Deformation modes must be as stable and repeatable as possible to improve structural reliability.
3) Maximum collision force during compression should be as low as possible.
4) The load-displacement curve should be stable and smooth under compressive loading.
5) Energy absorption per unit mass should be maximized.

2. Finite Element Calculation Model

2.1 Comparison with Experimental Results To validate the accuracy of the finite element model, simulation results were compared with static compression experimental data from the literature [**?**]. The dimensions and materials were kept consistent with the experiments, with specific parameters shown in and . [Figure 1: see original paper] presents the load-displacement curves from both simulation and experiment, showing good agreement and thus validating the finite element model.

2.2 Finite Element Model The finite element model consists of three components: an upper rigid plate, filled aluminum foam, and a conical aluminum tube. To match actual energy-absorbing box geometry, the aluminum tube and foam filler were split at the end, with the terminal square block receiving coupled fixed constraints on all six degrees of freedom. The upper rigid plate was constrained in all degrees of freedom except translation along the z-axis, where a smooth displacement loading was applied.

The aluminum tube was modeled using 4-node reduced-integration shell elements (S4R), the rigid plate using 4-node 3D bilinear rigid quadrilateral elements (R3D4), and the foam filler using 8-node linear brick elements with reduced integration (C3D8R). General contact was defined with a 0.1 mm gap and a penalty friction coefficient of 0.2. The tube wall thickness was 3 mm.

For the density-graded aluminum foam, density changes were assumed to proportionally affect only the elastic modulus and plastic yield strength, with other parameters remaining constant. The aluminum tube followed an elastic-plastic model with yield stress $\sigma_f = 210$ MPa and linear hardening modulus $E_{tf} = 1$ GPa. The aluminum foam had an elastic modulus of 1 GPa, yield stress and plateau stress of $\sigma_c = 8$ MPa, densification strain of $\varepsilon_d = 0.75$, and post-densification linear hardening modulus of $E_{tc} = 56$ GPa, as shown in [Figure 2: see original paper]. Component dimensions and material properties are listed in and .

2.3 Mesh Convergence Verification Mesh size significantly affects both computational accuracy and cost. A proper size selection ensures precision while conserving resources. A mesh convergence study was performed on the model from Section 2.2, as shown in [Figure 3: see original paper]. When the total mesh count reached 17,750, the results differed negligibly from those at 26,412 elements. Therefore, to ensure accuracy while saving computation time, the model with 17,750 elements was adopted for subsequent simulations.

2.4 Quasi-Static Validation For quasi-static problems, kinetic energy (ALLKE) must remain below 1% of internal energy (ALLIE), and hourglass energy (ALLAE) must not exceed 5% of internal energy (ALLIE). When these conditions are satisfied, the simulation is considered quasi-static and reasonable. The model from Section 2.2 was used for this validation, as shown in [Figure 4: see original paper]. The energy composition during compression was reasonable, meeting quasi-static analysis requirements. Hourglass energy was controlled within a small positive range, never exceeding 5% of internal energy. The ratio of kinetic to internal energy was maintained within 1% and remained near 0% throughout the compression process.

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3. Influence of Energy-Absorbing Box Parameters on Energy Absorption Characteristics

This section presents numerical simulations of quasi-static axial compression for various conical angles, induction groove parameters, and gradient material configurations to analyze their effects on cushioning capacity and energy absorption performance.

3.1 Conical Bottom Angle The bottom angle is defined as the angle between the side lines formed by the diagonal lines of the bottom and top surfaces [**?**], as illustrated in [Figure 5: see original paper]. Two arrangement modes were considered: forward arrangement (larger cross-section away from the upper pressure plate) and reverse arrangement (opposite orientation), designated as F-80 and R-80 for the 80° case, respectively.

[Figure 7: see original paper] shows the load-displacement and energy-displacement curves for different arrangements and bottom angles. summarizes the maximum peak force, total energy absorption, mass, and specific energy absorption. As the conical bottom angle decreases, the maximum peak force continuously decreases while specific energy absorption increases. For a given angle, forward and reverse arrangements show similar total energy absorption and specific energy absorption, but reverse arrangement significantly reduces peak force and produces smoother curves, demonstrating superior energy absorption characteristics.

Comparison reveals that the reverse-arranged 80° conical box reduces maximum peak force by 37 kN (20% reduction) and increases specific energy absorption by 4.18 J/g (18.5% improvement) compared to the 90° straight box. Therefore, the reverse-arranged 80° conical box was selected for further study.

3.2 Induction Groove Structure Parameters While induction grooves slightly reduce energy absorption, they substantially decrease initial peak force and enable steady load-displacement curve growth for stable energy absorption. This subsection investigates the effects of groove number, height, and depth.

3.2.1 Number of Induction Grooves

Cases with 4, 3, 2, and 1 grooves were studied. Reference planes were created at 35, 70, 105, and 140 mm from the top, with grooves of depth $d = 4$ mm and height $h = 5$ mm, as shown in [Figure 8: see original paper].

[Figure 9: see original paper] illustrates the final deformation patterns. Grooves initiate folds at specific locations, making deformation more idealized. The 4-groove configuration appears most suitable as an ideal energy absorber.

[Figure 10: see original paper] presents load-displacement and energy-displacement curves for different groove numbers, with evaluation metrics in . Increasing groove number slightly reduces total energy absorption but significantly decreases initial peak force and guides structural deformation, resulting in a more stable crushing force-displacement curve that better protects equipment.

3.2.2 Induction Groove Height

With depth fixed at $d = 4$ mm, groove heights of $h = 4, 5, 6$ mm were analyzed. [Figure 11: see original paper] shows the corresponding curves, with metrics in . All three cases exhibit similar initial crushing forces. Total energy absorption first increases then decreases as height increases from 4 mm to 6 mm. The $h = 5$ mm case shows 13.8% higher specific energy absorption than $h = 4$ mm (with 13.4% higher peak force) and 18.6% higher specific energy absorption than $h = 6$ mm (with 15.6% higher peak force). Considering the need for adequate energy absorption and lightweight design significance, $h = 5$ mm was selected for further study.

3.2.3 Induction Groove Depth

With height fixed at $h = 5$ mm, depths of $d = 3, 4, 5$ mm were analyzed. [Figure 12: see original paper] shows the curves, with metrics in . As depth increases from 3 mm to 5 mm, initial peak force continuously decreases, making the collision force curve rise more smoothly. Final maximum peak forces are similar, and depth changes do not affect total energy absorption. Therefore, $d = 5$ mm was selected for subsequent studies.

3.3 Aluminum Foam Gradient Gradient materials exhibit varying properties along the gradient direction, offering superior mechanical performance. This subsection investigates the effects of foam gradient on static compression energy absorption.

3.3.1 Aluminum Foam Density Gradient

Positive density gradient (density increasing from top to bottom) and negative gradient were defined, with foam densities of 180, 225, 270, 315, and 360 kg/m^3 in five layers, as shown in [Figure 13: see original paper]. Density changes were assumed to proportionally affect only elastic modulus and plastic yield strength.

[Figure 14: see original paper] presents load-displacement and energy-displacement curves for different density gradients, with metrics in . Foam gradient does not affect initial peak force, which remains similar across all cases. Positive density gradient significantly reduces maximum peak force, while negative gradient increases it. The effect on energy absorption characteristics is minimal. Positive gradient reduces maximum peak force by 5% compared to uniform density, with only 0.34% reduction in specific energy absorption. Therefore, positive density gradient was selected for further study.

3.3.2 Layer Division of Density Gradient

This section examines finer density gradations. Using the same top (180 kg/m^3) and bottom (360 kg/m^3) densities, the foam filler was divided into 10 and 17 uniform layers with positive gradient to investigate layer number effects.

[Figure 15: see original paper] shows curves for different layer divisions, with metrics in . Layer division has minimal effect on load-displacement and energy-displacement curves but can reduce maximum peak force during crushing. Total energy absorption and specific energy absorption are essentially unaffected. Considering all factors, 17-layer positive density gradient was selected as the final improved model.

3.4 Comparison Before and After Optimization This subsection compares the final optimized structure with a straight-walled square-section foam-filled box without inclination, grooves, or density gradient. [Figure 16: see original paper] shows the load-displacement and energy-displacement curves, with metrics in . The optimized structure exhibits a smoother load-displacement curve with significantly reduced initial and maximum peak forces. While total energy absorption decreases slightly, specific energy absorption improves markedly.

The optimized structure achieves a maximum peak force of 147.87 kN, representing a 20% reduction from the original 184.87 kN. Specific energy absorption increases from 22.64 J/g to 23.45 J/g (3.6% improvement), with a smoother collision force curve more suitable for energy absorption applications.

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4. Conclusions

This study employed ABAQUS finite element analysis to simulate the quasi-static axial compression characteristics of gradient foam-filled conical energy-absorbing box structures, providing a reference for energy-absorbing box design. Optimization was performed with objectives of low peak load and excellent energy absorption for equal-mass structures. The results demonstrate that the considered factors effectively improve energy absorption performance. The main conclusions are:

1) Parameters including conical bottom angle, number of induction grooves, groove height and depth, and gradient material parameters significantly affect the energy absorption characteristics of gradient foam-filled conical energy-absorbing boxes under axial compression.
2) The conical bottom angle can substantially increase specific energy absorption while reducing initial peak force, and moderately decrease crushing force during collision.
3) Induction grooves enable deformation to approach the ideal symmetric folding mode, reducing initial peak force while guiding deformation. Groove height and depth play important roles in reducing peak force and improving specific energy absorption.
4) Aluminum foam density gradient and layer division number significantly reduce collision force and contribute to lightweight design and specific energy absorption improvement.

5) Compared with straight-walled boxes, the optimized gradient foam-filled conical structure reduces maximum peak force by 20% and increases specific energy absorption by 3.6%. The designed structure demonstrates superior performance with a smoother collision force-displacement curve that is more conducive to energy absorption.

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Note: Figure translations are in progress. See original paper for figures.