Study on a Novel Dual-Layer Graded Honeycomb Metamaterial for Bridge Anti-Collision Structures

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ABSTRACT

With the rapid expansion of bridge infrastructure and the increasing frequency of ship-bridge collision accidents, traditional anti-collision measures have exhibited limitations in dispersing and absorbing impact energy. This study proposes a novel dual-layer composite gradient mechanical metamaterial for impact mitigation based on the honeycomb configuration within a bridge anti-collision structure. The structure comprises two functional units. The upper layer is a high-porosity energy-absorbing layer, which achieves efficient and gradual release of the initial impact energy through a gradient distribution of porosity and wall thickness. And the lower layer is a high-stiffness support layer that provides the necessary structural support and impact resistance, ensuring stability of the whole structure under extreme loads. By the well-designed composite gradient honeycomb configuration of the proposed mechanical metamaterial, the anti-collision structure acquires exceptional mechanical properties such as lightweight, high energy absorbing efficiency, and enhanced impact cushioning performance. This research investigates a feasible design of the dual-layer graded honeycomb metamaterial through theoretical modeling and numerical simulations. By conducting dynamic compression and drop hammer impact simulations, the dynamic impact response and energy-related performance are comprehensively studied. Results indicate that the proposed dual-layer composite gradient mechanical metamaterial can significantly reduce the impact load, enhancing both the energy absorption efficiency and safety, therefore advancing the construction of the bridge anti-collision structure.

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INTRODUCTION

Ship-bridge collisions in recent decades have exposed critical vulnerabilities in conventional civil infrastructure [1-4], driving an urgent demand for next-generation anti-collision systems that integrate energy dissipation, structural resilience, and adaptive functionalities. Traditional protective systems often exhibit inadequate energy absorption efficiency and face challenges under extreme impact scenarios due to mechanical property limitations inherent in natural materials [5]. This limitation shows the imperative to develop metamaterial-inspired solutions, where engineered architectures enable the superior energy absorption (EA) performance and effective impact-mitigation ability.

Mechanical metamaterials [6, 7], characterized by exceptional behaviors, address the limitations of conventional materials and offer transformative potential for engineering applications [8]. Among these, honeycomb-based architectures have emerged as a promising candidate due to their tunable cellular geometries and scalable manufacturability. Recent advanced honeycomb designs for improving mechanical properties have been widely investigated [9]. Gradient honeycombs with spatially varying parameters, such as cell-wall thickness [10], angle [11], configurations [12], and hierarchical filling [13], effectively enhance EA performance compared to uniform construction, and can be well applied in lightweight and impact-resistant structural designs in aerospace, transportation, and marine engineering [14-16]. While gradient honeycombs excel in EA, their porous architectures often compromise structural rigidity, limiting applicability to scenarios requiring simultaneously high load-bearing capacity and impact resistance of bridge piers subjected to ship collisions.

Therefore, this study proposes a novel dual-layer graded honeycomb (DLGH) structural topology tailored for bridge anti-collision systems. For the proposed graded design, the upper and lower layers employ hexagonal cells with varying porosities to simultaneously fulfill impact mitigation and structural support requirements. The structural design of the DLGH is conducted, and its EA capacity along with structural bearing performance are evaluated through numerical simulations. The proposed cell size-induced graded honeycomb topology design represents a promising approach for superior EA performance and advanced structural resilience, offering enhanced safety and reliability for critical infrastructure applications.

METHODS

Structural design

Considering the cell size variation and graded design strategy, a dual-layer graded honeycomb (DLGH) metamaterial is constructed, and the specific structural configuration is illustrated in Figure 1. The DLGH structure consists of two layers with different porosities. The upper layer contains large sizes of hexagonal cells for EA ability, while the lower layer incorporates relatively small cells and enables structural support due to its denser configuration.

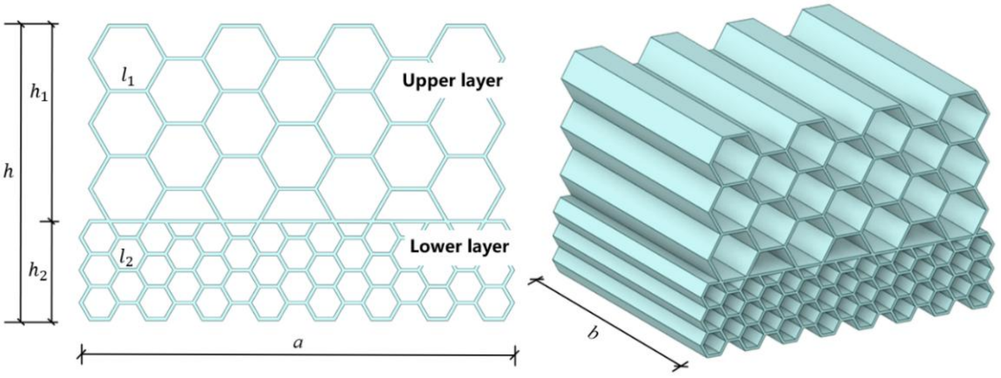

Figure 1. Design of the DLGH metamaterial.

For the proposed DLGH configuration, functionally differentiated geometric parameters are employed to realize the gradient porosity architecture. The upper layer utilizes amplified cell dimensions to maximize effective absorption and dissipation of impact energy. And the lower layer is engineered with a compressed cellular geometry to achieve diminished porosity, thereby ensuring mechanical integrity through enhanced strength, stiffness, and buckling resistance. Strategic maintenance of uniform wall thickness across both layers ensures interfacial stress homogenization, effectively mitigating localized stress concentrations while maintaining the system's functional gradient architecture.

Geometric parameters

The relationship between the structural density and configuration parameters in the traditional hexagonal honeycomb [17] is:

$$\rho = \rho_{\mathrm{r}} \frac{2t}{\sqrt{3}l} \tag{1}$$

in which t and l are the wall thickness and side length of a unit cell respectively. And then, the effective density of EA layer and structural support layer ρ_1 and ρ_2 can be obtained accordingly. Assuming that heights of layers are h_1 and h_2, then the density ρ_{c} of the DLGH structure can be derived from:

$$\rho_{\mathrm{c}} = \frac{h_1\rho_1 + h_2\rho_2}{h_1 + h_2} \tag{2}$$

And there exists a certain geometric relationship between the edge lengths of the upper and lower substructures to ensure the continuity of the upper and lower levels. For n-order configuration, the relationship is expressed as $l_1 = (1/2)^n l_2$. Figure 1 shows the 1st order design.

Numerical simulation

The finite element method (FEM) is employed to investigate the mechanical behaviors of the DLGH metamaterial. Considering the primary objective of investigating the dynamic and impact response of the DLGH metamaterial, simulations of dynamic compression and drop hammer impact are conducted in Abaqus/Explicit. As depicted in Figure 2, two models, including a simplified one with fewer subunits and a more complex one with more subunits, are established. Due to the computational intensity and computational efficiency, the simplified model is first adopted to illustrate the deformation mode of the proposed DLGH structure under dynamic compression. Subsequently, to further investigate the structural response under high strain-rate loading conditions and for practical applications, the complex DLGH model is applied to the dynamic compression and the drop hammer impact simulation.

The side lengths of subunits are: l_1=10 mm, l_2=5 mm, t=0.5 mm. The modal size of the simple model with less units is specified as: h_1=34.64mm, h_2=25.98 mm, while the corresponding values for the complicate model are 51.96 mm and 25.98 mm. And the length of the DLGH along the in-plane direction is set to 50 mm and 100 mm respectively. In the drop hammer simulation, the hammer head is hemispherical of 32 mm diameter with the mass of 10 kg. The matrix material parameters are uniformly defined for both quasi-static and dynamic simulations. An aluminum alloy is adopted for the DLGH structure with a density of 2700 kg/m^3, a Poisson's ratio of 0.3, and a Young's modulus of 69 GPa. Plasticity is governed by the Johnson-Cook constitutive model, where the initial yield stress is 280 MPa, the hardening coefficient is 100 MPa, paired with a 0.2 hardening exponent. To capture the strain rate effect in dynamic loading scenarios, a strain rate sensitivity coefficient 0.02 is introduced. Temperature-related effects are not considered in this study.

For mesh types, the DLGH core adopts S4R shell element with 2.5 mm grid size, while plates are rigid solids of 5 mm C3D8R. The hammer component is C3D10M. And the general contact is employed. The tangential behavior is defined by a friction coefficient of 0.2, while the normal interaction adopts a hard contact constraint. The lower base plate is fixed, and the upper compression plate applies to the prescribed compressive load. For dynamic simulation, the moving plate moves with 6 m/s velocity. And in drop hammer simulation, the impact velocity of the hammer head is 8 m/s.

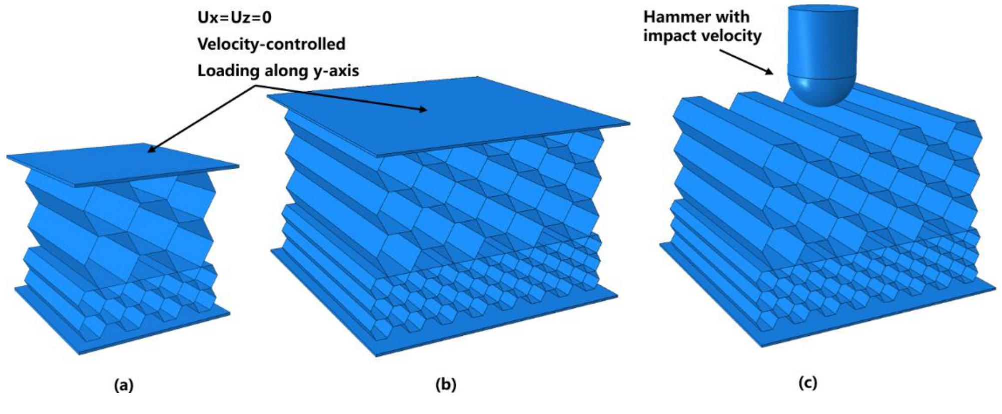

Figure 2. FEM simulation settings: (a) simple model for dynamic compression; (b) complex model for dynamic compression; (c) drop hammer impact.

PERFORMANCE ANALYSIS

This section systematically examines the mechanical characteristics and EA efficiency of the DLGH metamaterial under various simulation scenarios.

Analysis metrics

To quantify and evaluate the EA performance of the proposed DLGH structure, several metrics are employed. With $\sigma(\varepsilon)$ and ε representing the stress and strain respectively, the absorbed energy E is calculated from the stress-strain curve:

$$E = \int_0^{\varepsilon} \sigma(\varepsilon) d\varepsilon \tag{3}$$

Accordingly, EA efficiency η is defined as:

$$\eta = \frac{\int_0^{\varepsilon} \sigma(\varepsilon) d\varepsilon}{\sigma} \tag{4}$$

The specific energy absorption (*SEA*), a critical indicator for evaluating structural energy performance, is obtained from:

$$SEA = \frac{\int_0^{\varepsilon} \sigma(\varepsilon) d\varepsilon}{\rho_c} \tag{5}$$

Additionally, the plateau stress, obtained by averaging the stress over the plateau region, is also significant for evaluating the EA performance. These metrics collectively serve as benchmarks for evaluating the EA-related ability of the DLGH metamaterial collectively.

Results and analysis

The dynamic deformation process of the simple DLGH with less subunits is presented in Figure 3 (a). And Figure 3 (b) depicts the obtained stress-strain curve and the cumulative absorbed energy. During the elastic phase, the stress increases linearly with strain, reaching an initial peak of about 0.80 MPa. Following this, a plateau phase is observed, with a calculated plateau stress of 0.61 MPa. In this stage, the internal units undergo gradual inward rotational deformation. From approximately 3 ms, the rotational deformation of the upper layer approaches completion, transitioning into a densification process which results in a continuous increase in stress beyond a strain of 0.42. And throughout this period, the lower layer remains nearly undeformed, after which it exhibits similar rotational deformation modes as the upper layer. This leads to global densification under sustained compression. Fluctuations in stress are observed throughout the dynamic process, characteristic of the collapse mechanisms within the graded structure.

Then, the complicated model of the DLGH is investigated. The deformation process is depicted in Figure 4 (a), and the associated stress-strain and EA efficiency curves are illustrated in Figure 4 (b). The structure exhibits a plateau stress of approximately 0.63

MPa. During the elastic deformation phase, when the strain is below 0.015, the EA efficiency remains relatively low. As the structure transitions into the plateau stage, the efficiency progressively increases, reaching a peak of 32.5% at a strain of 0.289, corresponding to the progressive collapse mechanism during the stress plateau. Beyond a strain of 0.42, the efficiency sharply declines to 12.8% at 0.61 strain, indicating the process of densification in the upper layer. Subsequently, a partial recovery of efficiency is observed, reaching 30.4% at a strain of 0.71, attributed to the delayed collapse and gradual compaction of the lower layer. As full densification proceeds, the efficiency eventually declines again.

Through calculation, the normalized density of DLGH relative to the matrix material is 0.077. *SEA* values are 8.92 J/g and 7.93 J/g for the simple and complex models, respectively. Although both models exhibit similar plateau stresses due to identical unit cell geometry and deformation mechanisms, the complex model shows a slightly lower SEA, which is mainly caused by increased non-synchronous collapse between different regions, weakened boundary constraints, and enhanced dynamic instability within the larger structure. Overall, the dynamic compression simulations demonstrate that the DLGH structure achieves reasonable deformation modes and effective EA, maintaining structural integrity while achieving a lightweight design.

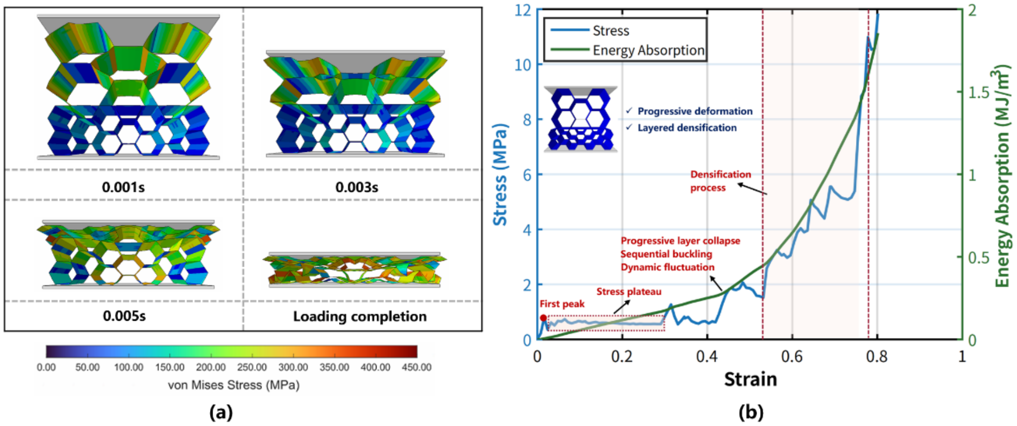

Figure 3. Results of the dynamic compression simulation on the simple DLGH: (a) deformation process; (b) the stress/EA-strain curve.

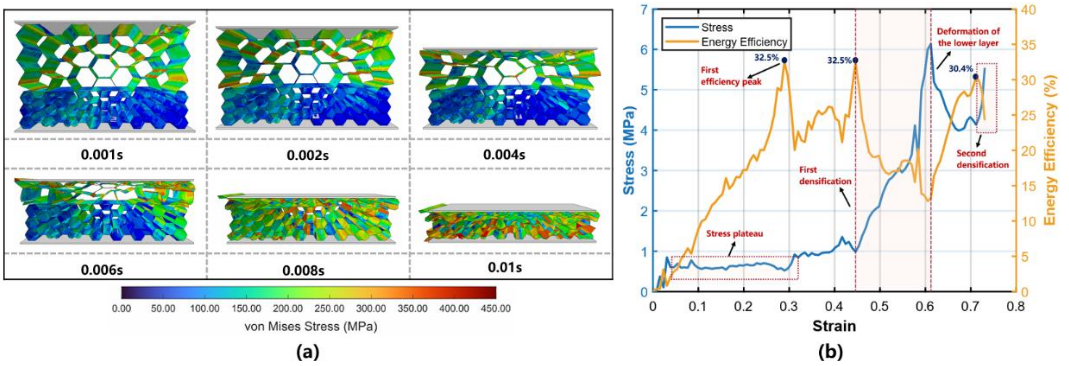

Figure 4. Results of the dynamic compression simulation on the complex DLGH: (a) deformation process; (b) the stress/energy efficiency-strain curve.

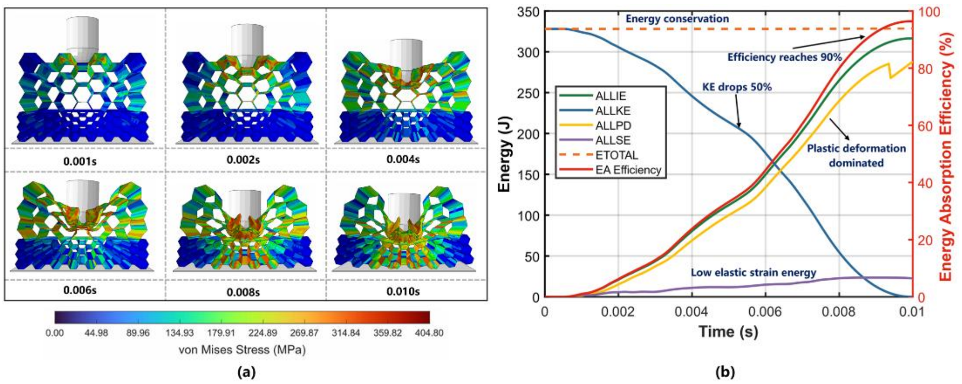

Figure 5. Results of the drop hammer simulation: (a) deformation process; (b) energy-time history curve.

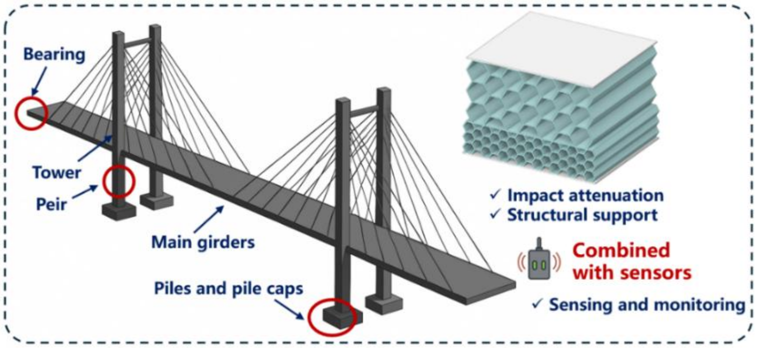

Figure 6. DLGH-based critical components employed in operational bridges.

The Drop-hammer simulation further implicates the impact response. The energy evolution curves and EA efficiency curve are shown in Figure 5. ALLIE, ALLPD, ALLSE, and ETOTAL represent the internal energy, plastic dissipation energy, elastic strain energy, and total energy of the DLGH model, respectively, while ALLKE denotes the kinetic energy of the hammer. It can be observed that, the kinetic energy of the impact hammer is progressively absorbed and converted into internal energy within the DLGH. During the initial stage, the structure experiences elastic deformation, followed by the plastic-dominated dissipation mechanism. Ultimately, the impact energy is efficiently absorbed by the DLGH structure, achieving an EA efficiency of approximately 96%.

Through numerical simulations, the mechanical responses and EA performances of the DLGH are comprehensively investigated. Due to its lightweight and high-efficiency EA characteristics, the proposed DLGH metamaterial shows great potential for application in critical components of in-service bridges, providing effective collision resistance and impact protection while maintaining sufficient load-bearing capacity, as demonstrated in Figure 6.

CONCLUSION

A novel dual-layer graded honeycomb (DLGH) metamaterial is proposed and investigated in this paper. Through structural design and numerical simulations, the

DLGH structure not only exhibits relatively high EA capacity but also maintains structural strength, achieving a synergistic balance between impact resistance and structural integrity. The porosity-gradient configuration of DLGH enables dual functions of EA and load bearing, thereby serving as an effective anti-collision structure for critical components in bridge engineering.

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