

Study on Engine Hood with Negative Poisson's Ratio Architected Composites Based on Pedestrian Protection

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ABSTRACT

The conventional hood with single material and stiffener structural form conceals some limitations on pedestrian protection and lightweight, not satisfying the requirements of structural strength, pedestrian protection and lightweight contradictory with each other at the same time. In this paper, a novel type hood is proposed to develop sandwich structure using architected cellular material with negative Poisson's ratio (NPR) configuration based on the decoupling thought of structural strength and energy absorption. Core-layer aluminum alloy material with NPR is used to meet the requirement of impact energy absorption, inner and outer skin using carbon fiber is selected to achieve high structural stiffness needed. This paper starts from the relations between geometric parameters of core-layer architected cellular material and mechanical properties, on this basis, the optimal geometric parameters can be expected using the multiobjective optimization method. Eventually, the optimal novel hood can be obtained using three layer thicknesses as optimization variables, minimum HIC value and minimum mass as objectives. It should be noted that global stiffness of the novel hood is not less than that of conventional hood, and entire thickness of the novel hood is not larger than conventional hood and impact intrusion of novel hood is less than safe distance between hood and engine. Based on limitations above, optimal layer thicknesses of architected cellular structure can be achieved. Then, the novel hood is compared with the conventional hood. The results show that the average HIC value of corresponding collision points in the novel hood decreases by 45%. In addition, bending stiffness of the novel hood achieved increases by 33%, and torsional stiffness increases by 67%. While the weight is reduced, 18.95% exactly. Thus, the novel hood proposed in this paper demonstrates outstanding performance in terms of pedestrian protection, structural stiffness enhancement and weight reduction.

Keywords: Architected Composites, Negative Poisson's Ratio, Pedestrian Protection, HIC

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INTRODUCTION

With the development of automotive safety, pedestrian protection has attached more and more attention. It is generally known that at least half of the deceased were due to head injuries. Therefore, improving mechanical properties of engine hood is meaningful by

protecting the head in moderate to severe head-hood collisions. Moreover, the main driver for this is the reduced weight, leading to reduced fuel costs and emissions.

To date, many efforts have been done to reduce collision injuries of head by means of replacing steel into aluminum. However, the satisfying effects are limited to material properties and structures.

also been made on architected cellular material to extend the foam material to honeycomb material for better pedestrian protection. Still, their efforts cannot breakthrough the limitations that fabrication of foam sandwich structure is linked to temperature [1] and need further study. Besides, Xinchun Zhang [2] developed architected cellular material with positive Poisson's ratio, however, this type of material usually has unstable platform stress and higher peak stress which limits its applications on impact protection.

As a result from the previous studies, the further development should more focus on a novel sandwich-type hood, which could equip core-layer material with collision energy absorption properties and skin materials with stiffness properties. The novel concept in this work is to optimize collision performance of hood, using negative Poisson's ratio (NPR) material as core-layer material, aluminum alloy to be specific.

NPR materials are also called auxetic, anti-rubber materials. Since NPR configuration equips architected composites with increased shear modulus, indentation resistance and energy absorption ability[3]. NPR materials have drawn more and more attention due to unique behaviors [4]. Unlike conventional materials, NPR materials may expand when stretching (or shrink when compressing) along a perpendicular direction[5-6]. The unique and desired properties can be utilized to improve energy absorption due to uniform deformation and stable platform stress. With material concentration and higher stiffness, second collision can be prevented effectively. Thus, this paper uses NPR material as core-layer material to improve the collision performance of hood.

This work initially presents the relations between geometric parameters of core-layer architected cellular material and mechanical properties including relative density, stress-strain relationship and unit energy absorption. To verify the accuracy of mechanical model obtained, simulation analysis in ABAQUS software and theoretical results are compared. Then, the optimal geometric parameters can be expected using the multiobjective optimization method in terms of maximum energy absorption, minimum relative density and minimum HIC value. The novel hood is performed the multi-objective optimization design with the optimization parameters of each layer thickness and targets for minimum mass and minimum HIC value. The limitations are that global stiffness of the novel hood is not less than that of conventional hood, and entire thickness of the novel hood is not larger than conventional hood and impact intrusion of novel hood is less than safe distance between hood and engine. Eventually, the novel hood is compared with the conventional hood regarding to HIC value and mass to verify effects of the novel hood on pedestrian protection and lightweight. Meanwhile, the stiffness of the novel hood can also be verified.

MATHEMATICAL DESCRIPTION OF ARCHITECTED CELLULAR STRUCTURE WITH NPR CONFIGURATION

The manner in which materials change shape and size when they are subjected to uniaxial stress or pressure is described and quantified by their elastic constants. These elastic constants include the Poisson's

ratio, which characterizes the resultant strain in the y-direction for a material under longitudinal deformation in the x-direction[7]. Mathematically, this property is defined by:

$$\gamma = -\frac{\varepsilon_1}{\varepsilon_2} \quad (1)$$

Where, ε_1 is the strain perpendicular to the direction of compression or stretching and ε_2 is the strain parallel to the direction of compression or stretching. Because most materials get thinner (negative ε_1) when stretched (positive ε_2), the Poisson's ratio is typically a positive property with values. However, the Poisson's ratio need not to be a positive quantity, and materials having a NPR, commonly known as auxetic material, do exist.

Architected cellular structure with NPR configuration has the characteristics of compression-shrinkage deformation characteristics and the effective Poisson's ratio is negative. The compression-shrinkage deformation of NPR structure under in-plane compression is shown in Figure 1[8-9].

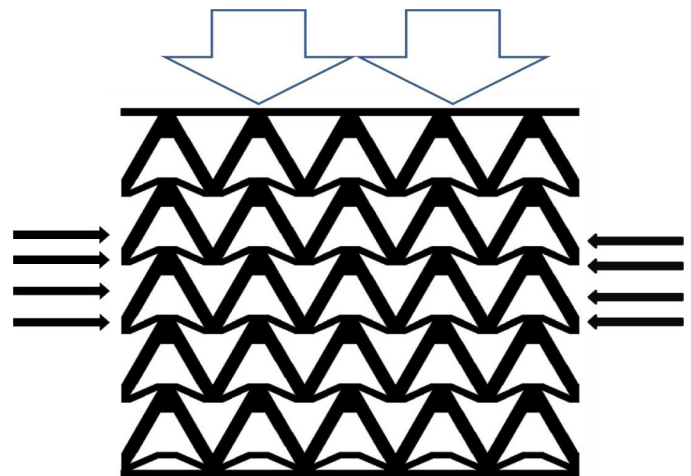


Figure 1. Compression-Shrinkage Deformation of NPR Structure.

A single unit is mostly utilized to obtain equivalent performance of cellular structure, then equivalent model of unit cell is developed. Two 2D cells composed of double V-shaped single-element are cross-linked with each other with a result of constructing a 3D NPR cell. The cells repeat in three directions of core structure. By variable quantities of cells in every direction, the structure can present different mechanical properties to achieve an anisotropic NPR in every direction to satisfy complex requirements of loading, and the NPR effects could be obtained along its symmetry axes[10].

Relations between Relative Density and Geometric Parameters

Relative density of architected cellular structures characterizes resultant equivalent density of architected cellular materials versus the overall material[11]. The relative density is therefore calculated as follows:

$$\rho_{RD} = \frac{\rho_c}{\rho_s} \quad (2)$$

Where, ρ_c stands for equivalent density of architected cellular structure and ρ_s is the density of material used to construct the cells. If geometry model of 2D cellular plane is stretched, the equivalent density can be calculated considering the following equations:

$$\rho_c = \frac{S_1 b \rho_s}{S_2 b} \quad (3)$$

Where b stands for cell thickness. In this case, Eq. (2) can be transformed into:

$$\rho_{RD,2D} = \frac{S_1}{S_2} \quad (4)$$

The relative density $\rho_{RD,2D}$ depends in this case by factors S_1 and S_2 , where S_1 and S_2 are the areas of the internal cell walls and 2D cell unit respectively.

Based on geometric model of 2D cell, total area of cell structure can be calculated considering the following summation.

$$S_1 = S_L + S_M \quad (5)$$

Taking into account thickness coefficient α and length coefficient β , $\alpha = \frac{T_L}{L}$, $\alpha = \frac{T_M}{M}$, $\beta = \frac{N}{L}$, then the total area can be calculated as:

$$S_L = T_L (L + N) = \alpha L^2 + \alpha \beta L^2 \quad (6)$$

$$S_M = T_M (M + N) = \alpha M^2 + \alpha \beta M L \quad (7)$$

$$S_1 = S_L + S_M = \alpha L^2 + \alpha \beta L^2 + \alpha M^2 + \alpha \beta M L \quad (8)$$

While, the area of 2D cell can be described as:

$$S_2 = (H + T_M + T_L) \cdot (L \sin \varphi + N) = (H + \alpha L + \alpha M) \cdot L (\sin \varphi + \beta) \quad (9)$$

Thus, relative density of 2D cell can be obtained as follows:

$$\rho_{RD,2D} = \frac{S_1}{S_2} = \frac{\alpha L^2 + \alpha \beta L^2 + \alpha M^2 + \alpha \beta M L}{(H + \alpha L + \alpha M) \cdot L (\sin \varphi + \beta)} \quad (10)$$

Parameter K is scaling factor of length, which can be written as:

$$K = \frac{M}{L} \quad (11)$$

The relations between parameters L , M , H and K is the following:

$$L \sin \varphi = M \sin \theta \quad (12)$$

$$H = L \cos \varphi - M \cos \theta \quad (13)$$

$$H = L \left(\cos \varphi - \sqrt{K^2 - \sin^2 \varphi} \right) \quad (14)$$

Finally, relative density of 2D cell can be transformed into:

$$\rho_{RD,2D} = \frac{\alpha + \alpha \beta + \alpha K^2 + \alpha \beta K}{\left(\cos \varphi - \sqrt{K^2 - \sin^2 \varphi} + \alpha + \alpha K \right) (\sin \varphi + \beta)} \quad (15)$$

Geometric model and relative density of 2D NPR cell are shown in Figure 2 and Figure 3.

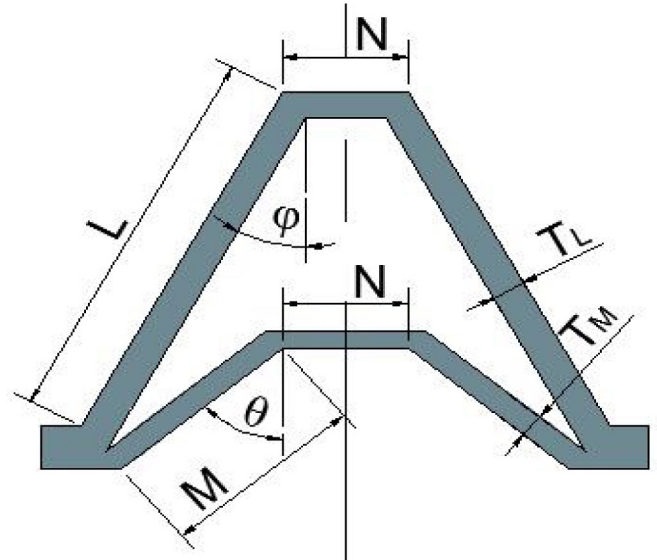


Figure 2. Geometric Model of 2D NPR Cell

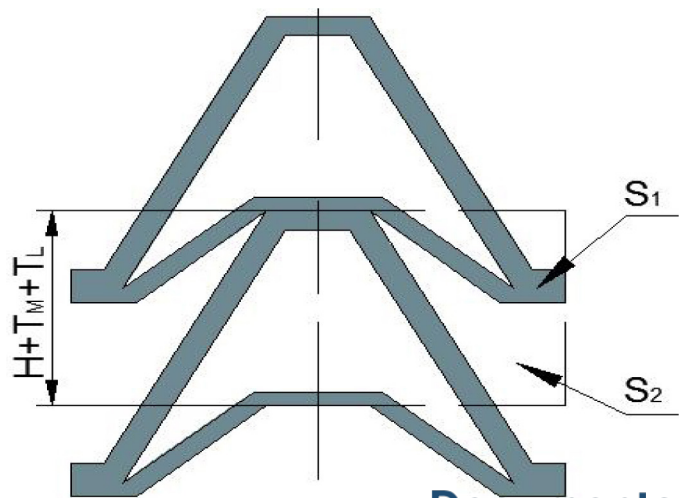


Figure 3. Relative Density of 2D NPR Cell

Relative density of 3D cell is calculated as follows:

$$\rho_{RD,3D} = \frac{V_1}{V_2} \quad (16)$$

Where, V_1 and V_2 are volumes of architected cellular structure and volume of cell unit, respectively:

$$V_1 = S_1 b - \left(\frac{b}{2}\right)^2 (T_L + T_M) \quad (17)$$

$$V_2 = S_2 (L \sin \varphi + \beta L) \quad (18)$$

In this case, relative density of 3D cell can be obtained as follows:

$$\rho_{RD3D} = \frac{\alpha^2 \left(1 + \beta + K^2 + \beta K - \frac{\alpha}{4} - \frac{\alpha K}{4} \right)}{\left(\cos \varphi - \sqrt{K^2 - \sin^2 \varphi} + \alpha + \alpha K \right) (\sin \varphi + \beta)^2} \quad (19)$$

Figure 4 illustrates relative density of 3D NPR cells. For processing and space rationality availability, stuffing beam should not be too longer than height of cell unit. As too longer, architected cellular structure shows lower working ability. Besides, the space between architected cellular material and skins becoming too large could reduce abilities of space utilization. As shown in Figure 5.

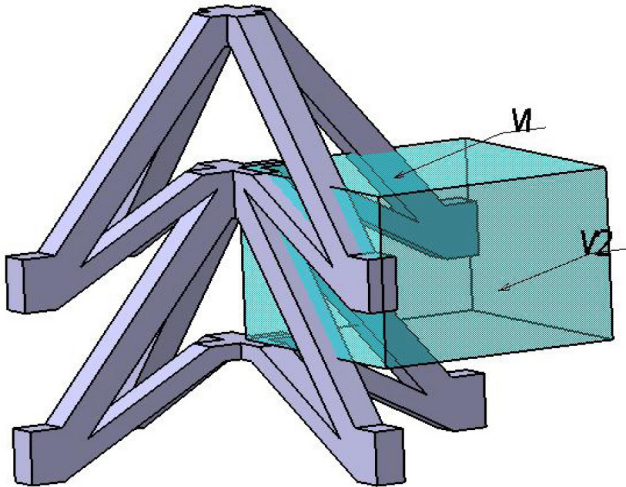


Figure 4. Relative Density of 3D NPR Cells

Thus, length of beams being twice the height of cells is defined as boundary condition, $L < \frac{2H}{\cos \varphi}$. Then results can be obtained as follows, $\varphi_{\min} > \arccos \frac{2H}{L}$, $\cos \varphi_{\min} > \frac{1}{2K}$. If $K \leq 0.5$, angle between cells is $\arccos \frac{1}{2K} < \varphi < \arcsin K$. If $K > 0.5$, the angle is $\arccos \frac{1}{2K} < \varphi < \arcsin K$.

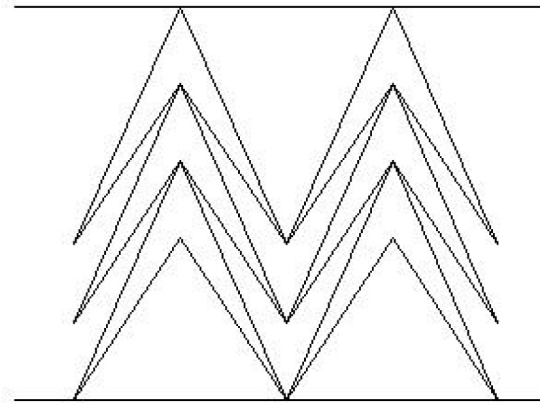


Figure 5. Improper Layout of Architected Cellular Structure

Figure 6 illustrates the relations between range of cellular angle φ and length scaling factor K . To be specific, it can be seen how minimum cellular angle $\varphi_{\min}$ and maximum cellular angle $\varphi_{\max}$ vary with respect to the change when length scaling factor K is varied from 0 to 1. It also can be seen that the blank area between red solid line and blue solid line represents the range of cellular angle. If $K = 0.5$, the cellular angle owns largest value.

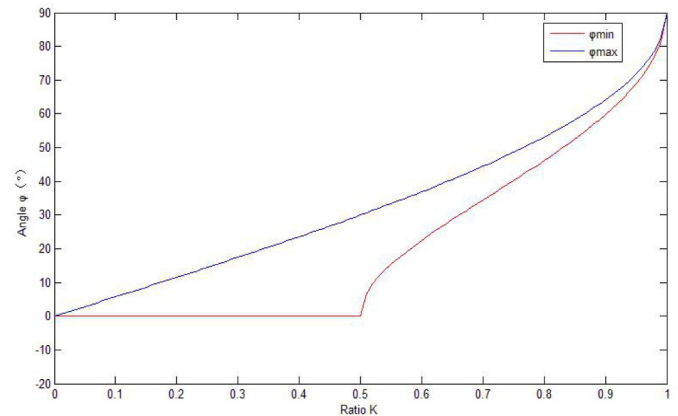


Figure 6. The Relations Between the Range of Cellular Angle φ and the Scaling Factor of Length K

Note that relative density ranges from 0 to 1. When cellular porosity is infinite, the relative density is close to 0, otherwise 1. No matter for 2D cell or 3D cell, relative density is related with cellular angle, thickness coefficient, length scaling factor and proportion coefficient of cell wall. Relative density of cells vary in a large range as the four parameters change.

Stress-Strain Relations

Stress-strain curve of NPR cellular structure under axial compression can be described as:

$$\sigma(\varepsilon) = \begin{cases} \left(\frac{E_{R,ini} + E_{R,max}}{2} \right) \varepsilon & (0 < \varepsilon < \varepsilon_0) \\ \frac{K^2 \sigma_{ys} \alpha^3}{(\beta + \sin \varphi)^2 \sin \varphi} (\varepsilon_0 < \varepsilon < 0.8 \varepsilon_D) \\ \left(\frac{0.2 \varepsilon_D}{0.2 \varepsilon_D - (1 + \varepsilon_0 \nu_R)^2 (\varepsilon - 0.8 \varepsilon_D)} \right)^{3/2} \frac{K^2 \sigma_{ys} \alpha^3}{(\beta + \sin \varphi)^2 \sin \varphi} & (0.8 \varepsilon_D < \varepsilon < \varepsilon_D) \end{cases} \quad (20)$$

The relation between compacted strain and relative density is the following:

$$\varepsilon_D = 1 - A \rho_{RD} = 1 - 2.19 \rho_{RD} \quad (21)$$

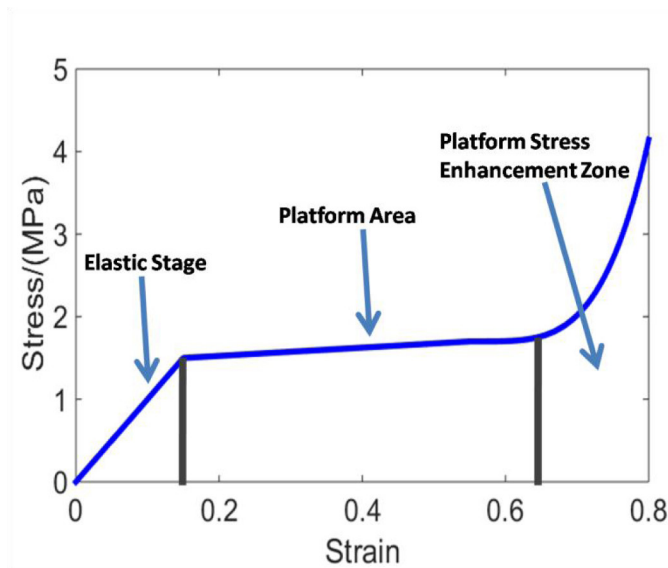


Figure 7. Modeled Stress-strain Curves

As shown in Figure 7, modeled stress-strain curve can be divided into three zones, elastic zone, platform zone and platform stress enhancement zone, respectively. Note that elastic zone indicates initial and maximum equivalent elastic modulus. Platform zone can be described by equivalent platform stress and platform stress-enhanced strain. In addition, platform stress enhancement zone can be described by equivalent Poisson's ratio, equivalent platform stress and compacted strain.

Characterization of Energy Absorption Properties

Under loading condition, energy absorption can be described as surrounding area of collision force-displacement curve and displacement axis. Collision force-displacement curve is related to

overall size of architected cellular structure. To demonstrate energy absorption of varied architected cellular structures, stress-strain curve is utilized in place of collision force-displacement curve.

When stress lies in elastic zone, energy absorption can be described as follows:

$$W_1 = \frac{\sigma^2}{E_{R,ini} + E_{R,max}} \quad (22)$$

Where, $E_{R,ini}$ and $E_{R,max}$ represent initial and maximum equivalent elastic modulus, respectively.

When stress reaches platform zone, energy absorption of elastic zone reaches the highest:

$$W_1 = \frac{\sigma_R^2 \sin^2 \varphi (\beta + \sin \varphi)^2 \left(1 + \frac{1}{K^2} \right)}{2 E \alpha^4 (\cos \varphi - \sqrt{K^2 - \sin^2 \varphi})} \quad (23)$$

Platform zone is divided into two parts: constant platform area and platform stress enhancement area. The maximum energy absorption at the constant platform stress is the following:

$$W_2 = \frac{K^2 \sigma_{ys} \alpha^3}{(\beta + \sin \varphi)^2 \sin \varphi} (\varepsilon - \varepsilon_0) \quad (24)$$

Energy absorption during platform stress-enhanced can be written as:

$$W_3 = \int_{0.8 \varepsilon_D}^{\varepsilon} \left(\frac{0.2 \varepsilon_D}{0.2 \varepsilon_D - (1 + \varepsilon_0 \nu_R)^2 (\varepsilon - 0.8 \varepsilon_D)} \right)^{3/2} \frac{K^2 \sigma_{ys} \alpha^3}{(\beta + \sin \varphi)^2 \sin \varphi} d\varepsilon \quad (25)$$

As mentioned in Figure 7, energy absorption performance is mainly determined by platform zone. Higher platform stress and smaller relative density could enhance energy absorption of platform zone in a more effective way. Moreover, the higher absolute value of equivalent Poisson's ratio is, increased stress and more energy absorption are expected.

Verification of Theoretical Mechanical Model

To verify the relations between structural parameters and mechanical properties modeled presented in this paper. Finite element model of NPR material is constructed in ABAQUS software, as shown in Figure 8. The bottom of the model is fixed with all the degrees of freedom constrained, and the top is free. Displacement Constraints are applied on the plate.