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Mechanical Properties of Cross Chiral Honeycomb(CCH) structure for the Soft and Adjustable Wearable Suit using Auxetic Structure

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Abstract

This paper is to present the design consideration of the adjustable flexible auxetic structure which is used in the soft wearable suit with the multi-layer materials. In order to design a macro-auxetic structure with the elastic flexibilities of the soft wearable suit, it is important to make the auxetic unit cell with the elastic adjustability. We make the tension experiments of several specimens, for verifying the mechanical structural characteristics of auxetic unit cell with flexure hinge mechanism. Through this approach, the valid geometric parameters of macro-auxetic structure used in the soft wearable suit can be designated.

Keywords: Cross Chiral Honeycomb(CCH), soft Wearable Suit, adjustable wearable suit, Auxetic structures,

I. INTRODUCTION

This study seeks to develop the soft and adjustable stiffness wearable suit with the novel multi-material and multi-layer pads that are comfortable to wear and effective in protecting and supporting body parts that are subject to blunt impact as shown in Fig. 1. Airbag inflation and deflation mechanism on the adjustable stiffness pads with auxetic foam play the role of the protection of falling-down and body assistance support, whose of configurations are reversible. Periodic cellular structure used in auxetic foam were first considered in the field of lightweight construction due to their high specific stiffness, damping and energy absorbing properties [1]. Usually, the mechanical properties and the deformation behavior can be controlled by appropriate choice of the underlying unit cell [2,3] and by adjusting the relative density [4]. This behavior is described by a negative Poisson's ratio.

The proposed body protection and support pad will address a safety issue prominent in elderly people, industry workers, law enforcement/military personnel, and sport players. Among the population of those people, blunt impact due to various causes such as falls, and blast waves reduce quality of life, increase the possibility of early death, and cause extremely high medical costs to incur. Therefore, it is important to develop new body protectors that best combine each individual's requirements of wearing comfort (flexible, light weight), ease of fitting (customized), ensured protection, and cost-effectiveness. The mechanism for ideal input force distribution or shunting are explained and suggested for designing the adjustable stiffness pads using various combinations of materials and layers to reduce the risk of injury and support the body. The results show that the auxetic-shape structure can be an effective component of optimized body protection and support pads using a combination of various materials and geometrical dimensions.

In this paper, auxetic-shaped structures with various combinations of materials and components are investigated and potential application in body protection and support is discussed in terms of shock energy absorption, adjustable stiffness characteristics and comfort. CAD modeling and some experiments were conducted to evaluate and suggest the performance and effectivenessof the auxetic structures. A possiblitiy of making pad structures thinner and ligher will be examined through an optimization process using the gemetric dimensions, in the future works.

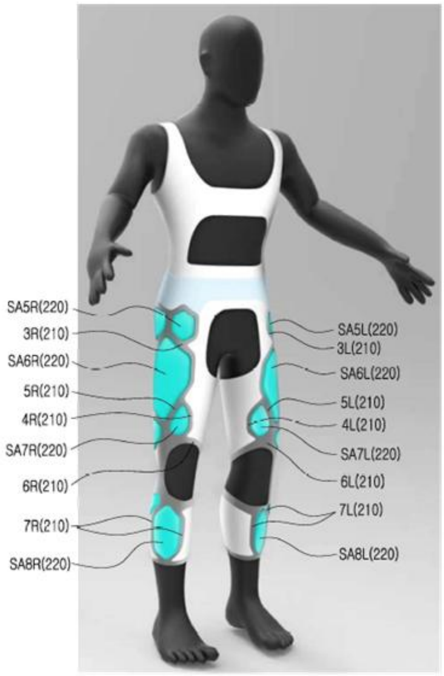


Figure 1. Soft and adjustable wearable suit

Auxetic materials are a class of meta-materials which exhibit negative Poisson's Ratio. They have been known for over a hundred years but have only gained attention in recent decades. They can be single molecules, but more often they consist of an engineered material with a particular structure on the macroscopic level. Auxetics are created by modifying the macrostructure of the material so that it contains hinge-like features which change shape when a force is applied. If a tensile force is applied the hinge-like structures extend, thus causing lateral expansion. If a compressive force is applied the hinge-like structures fold even further causing lateral contraction**.** Thus, man-made auxetic materials may be used to manufacture the adaptive clothes with the adjustable stiffness. The adaptive clothes need the auxetic material garment patches with the adjustable stiffness, which have the mechanically structural rigidities adjustably shown in Fig. 2. They have the auxetic cell shown in Fig. 3. Fig. 4 shows the geometric dimensions of the branch of auxetic cell

3D printer (FORMIGA P110, EOS) was used to make the specimen and printing material called to PEBA2301. We used a universal testing machine (QM100SE, QMSYS) to measure the mechanical properties of 3D structural specimens.

II. DESIGN OF AUXETIC CELL AND EXPERIEMNTS

Various promising designs were generated and investigated based on criteria such as performance, comfort, and manufacturability. One of those designs utilizes auxetic-shaped layer and thin fabric membrane component that is very strong in tension but flexible in tension and compression. Auxetic materials are a class of meta-materials on the cell geometry which exhibit negative Poisson's Ratio. The structural characteristics of auxetic material depends on the cell geometry. The size of auxetic block is 30mm X 30 mm

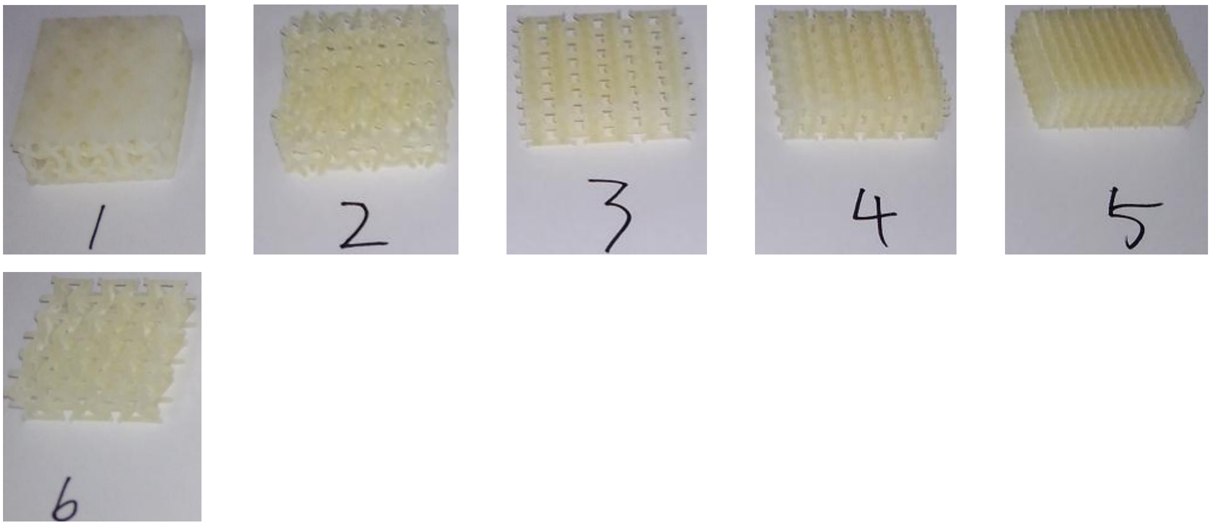


Figure 2. Auxetic structure specimens

Fig. 2 shows various auxetic structure specimens. Sample 1 is CCH(cross chiral honeycomb) structure with the top and bottom plate which is to protect the warping behaviors of auxetic cell. Sample 2 is CCH structure and samples 3,4,5 and 6 are various re-entrant honeycomb structures. Re-entrant honeycomb structure's properties are good theoretically but not experimentally. In this paper, sample 2 is selected as the valid prototype for the soft and adjustable wearable suit[5-8].

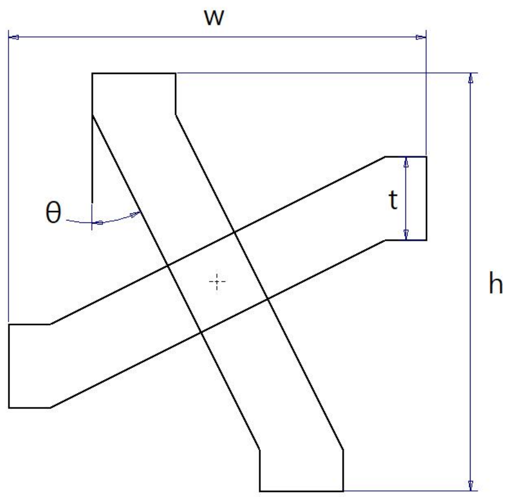
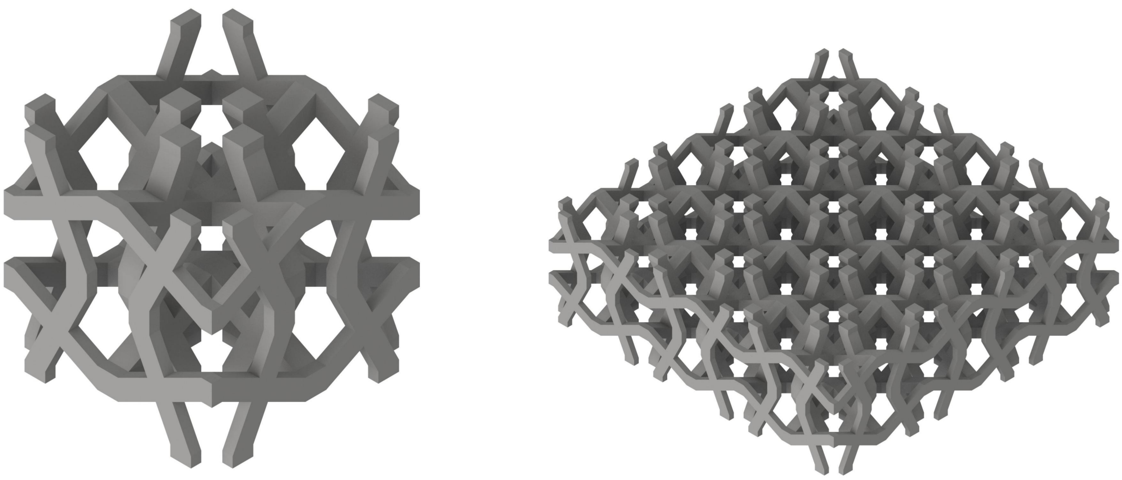


Figure 3. Schematics of the simplified structure



(a) Unit cell of CCH structure (b) 3 by 3 CCH lattice

Figure 4. 3D models of CCH structure

The CCH has a symmetrical geometry and can readily be patterned into 3D structure with rotation in or out of plane. Fig. 3 shows a structural schematic model in the plane views and Fig. 4 is a unit cell and lattice structure.

The CCH structure has four primary geometric parameters: width of unit cell (w), height of unit cell (h), the tilt angle of the strut (θ) and strut's thickness (t), as shown by Fig. 2. Unit cell and struts cross-sectional shape are supposed square. (w = h)

The behaviors of struts are similar to spring motion as shown in Fig. 4. So, the potential energy of structure is related only to strut length and the repulsive force, F can be given by,

$F = K_i\delta_i$ (1)

where F is the applied force, K_i is the force constant and δ_i is displacement.

For this model, force constant, K is given by,

$$K = \gamma \frac{E_s t^2}{l} \quad (l = \frac{h}{\cos\theta}) \quad (2)$$

where l is each strut length, the geometric factor, γ and E_s is the intrinsic Young's modulus.

Target payload is applied to CCH structure in z direction and stress σ_z is shown as yielding point. The payload, F is obtained by

$$F = \sigma_z A = \sigma_z l^2 cos^2\theta \quad (3)$$

when σ_z is constant, F is constant at any locations and strut length, l is constant. Compression load is operated on the flat fixture of unit cell. Thus, the above area, A is assumed to the area of flat fixture.

The structure displacement caused by deformation of strut length can be expressed as

$$\Delta Z = l\cos\theta - l_2\cos\theta_2$$

$$= l\cos\theta - \sqrt{(l - \frac{F}{K})^2 - l^2 sin^2\theta} \quad (4)$$

where$l_2 = l - \delta,\ \sin\theta_2 = \frac{l\sin\theta}{l_2}$, ΔZ is z-direction displacement and δ is changing value of strut length.

Based on eq. (3) and (4), the Young's modulus in z-direction is obtained as,

$$E_z = \frac{\sigma_z}{\varepsilon_z} = \frac{\frac{F}{(l\cos\theta)^2}}{\frac{\Delta Z}{l\cos\theta}}$$

$$= \frac{F}{l\cos\theta\,(l\cos\theta - \sqrt{(l - \frac{F}{K})^2 - l^2 sin^2\theta})} \quad (5)$$

III. RESULTS AND DISCUSSION

Using the auxetic sample of 3x3 CCH(cross chiral honeycomb) structure, stress-strain curve a nd strain coefficient are shown in Fig. 6 and 7 for the compressibility percentages(a. 0%, b. 2 0%, c. 30%, d. 40%). Fig. 5 and 6 are the average values through 5 times experiments for eac h samples, in which the solid line shows the experimental value of UTM and the symbol depic ts the inflection point on the structural change or analogical yielding point (5 kg_f/cm^2). Others except the analogical yielding phenomenon of the specimen with the 0% compressibility have more yielding points in the test range. This analogical yielding point shows the boundary bet ween CCH configuration and compressed bulk and increases on the increasing compressibilit y. The mechanical characteristics of CCH gradually disappear on the compression rate and in the above of 40% and it means a physical property is similar to the solid structure.

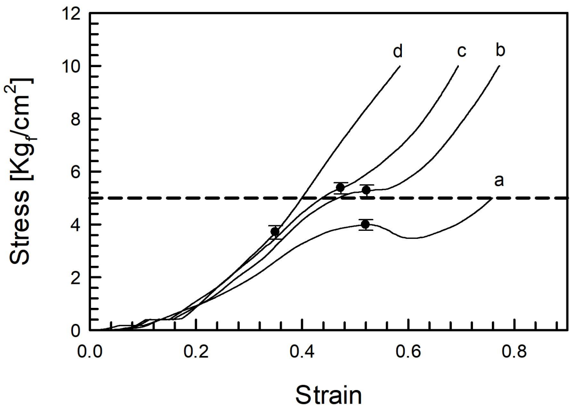


Figure 5. The stress to CCH structure as a function of strain for a:.non-compression, b:20%-compres sion, c:. 30%-compression, d: 40%-compression. UTM results is given by solid lines; symbols denote yield points; the chain line represent our reference value, 5

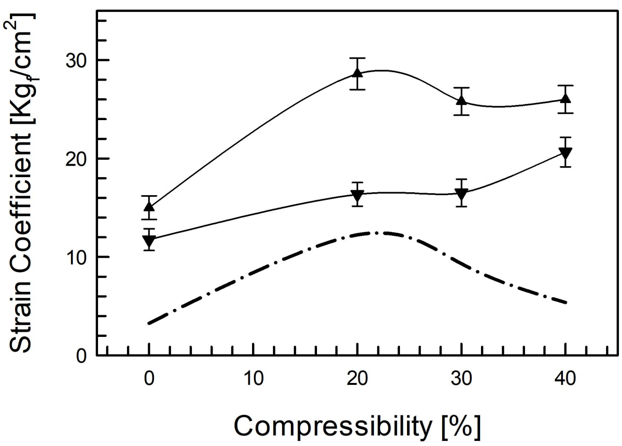


Figure 6. Strain coefficient as a function of compressibility

Fig. 6 shows the strain coefficient on the compressibility, which is the slope of stress-strain cu rve. The strain coefficient means the resistance capacity to the external compression force and material strength. The lower-triangle and upper-triangle respectively shows the slop of the pr e- or post- inflection points and the chain-dot line is the difference of two values. The initial p hysical property of auxetic pad depends on lower-triangle. The more upper-triangle, the more resistance force to the external compression force. This buckling mode of auxetic pad changes in 20% compression rate and depends on the CCH structure. It is estimated that the maximum influence will be 22% compression rate.

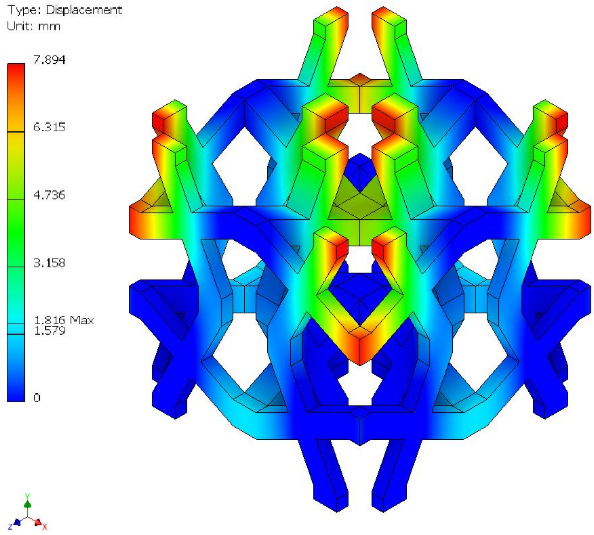


Figure 7. Stress contour of CCH structure model under the payload

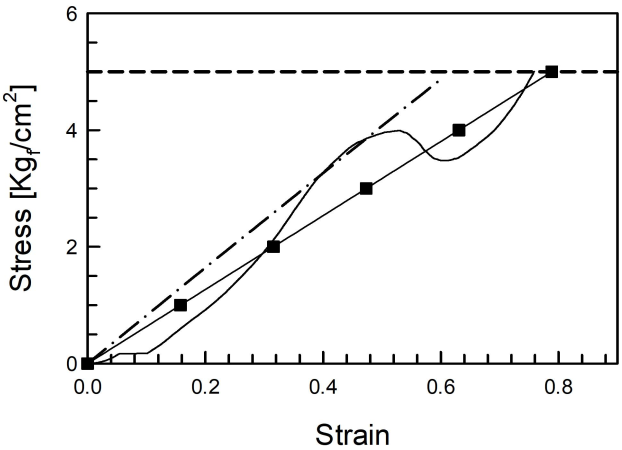


Figure 8. Stress-strain curve of CCH structure; UTM results is given by solid lines; symbols denote computation result; the chain line represent our reference value, 5 and chain dot line is calculated by eq. (5)

Fig. 7, 8 shows the displacement of z direction under the payload. This model's geometric factor γ is 4.25 by experiment result when the tilt of strut angle is 26.57 degree. Stress-strain curve has the bifurcation at the yield point. First part has low slope because of structural influence. But after inflection has high slope by bulk properties.

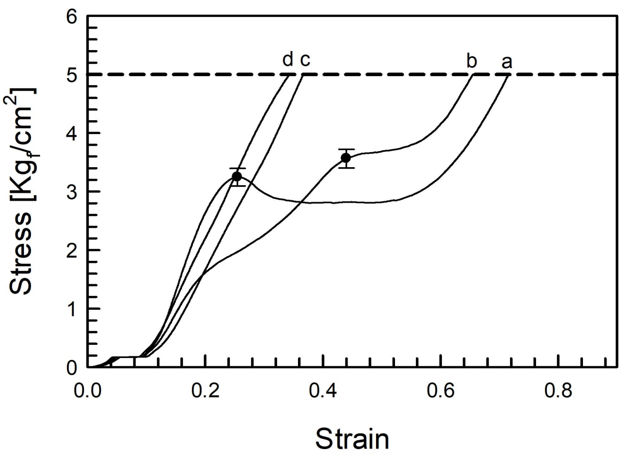


Figure 9. Stress-strain curve of CCH(a: 10 degree, b: 20 degree, c:. 30 degree, d: 40 degree) UTM results is given by solid lines; symbols denote yield points; the chain line represent our reference value, 5

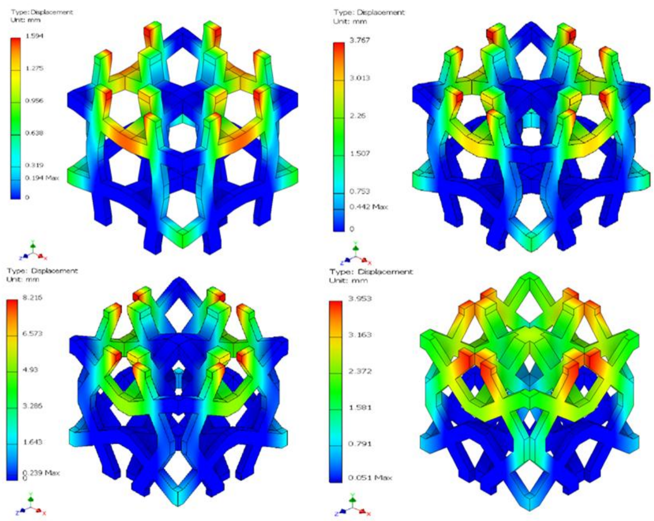


Figure 10. Stress contour of CCH structure on the angle distributions

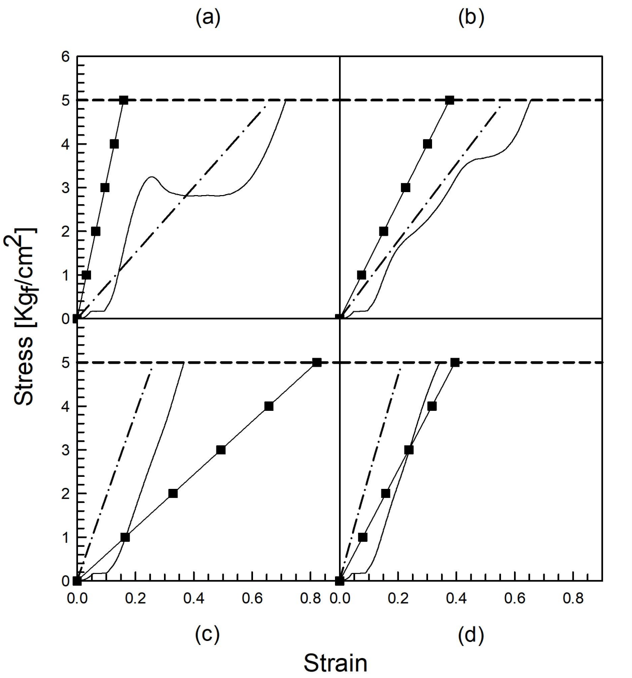


Figure 11. Stress-strain curve of CCH (a: 10 degree, b: 20 degree, c: 30 degree, d: 40 degree). UTM results is given by solid lines; symbols denote computation result; the chain line represent our reference value, 5 and chain dot line is calculated by eq. (5)

Fig. 9, 10, 11 shows the stress-strain curve on the rotation variable(θ) of CCH bridge. The low er rotation angle, the more resistance capacity and the faster inflection. The inflection range d ue to the CCH structural deformation and configuration are clearly collapsed at 20 degrees. U nder 10 degrees, the analogical yielding range and linear range are shown. The more obvious t he inflection range, the more clear are the strength and flexibility changes, and the external for ce absorption is expected to be excellent. Over 30 degrees, It is similar to the bulk from the be ginning of external force and does not show the structural characteristics of CCH.

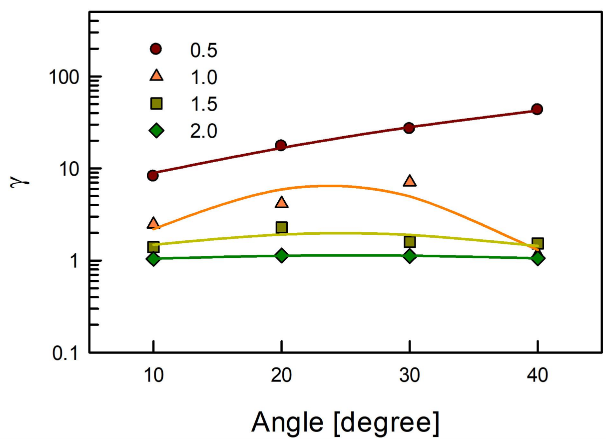


Figure 12. Geometric factor in eq. (2) according to angle distributions

By using logarithmic scale in Fig. 12, we can see the reduced geometric factor γ as a function of angle distributions.

IV. CONCLUSION

We can see that the strut thickness has influence on the adjustable behavior of auxetic cell. In order to have the soft adjustable stiffness in the auxetic cell under the given payload, the resist ance force for changing behavior can maintain under strut angle and thickness.

For using the feasible macro-auxetic cell as the soft adjustable stiffness suit, the geometric fac tor is recommendable in the negative slope, which means that the structural behavior has the h ard foam over the a certain of strut angle and the flexible foam under one. Thus, the valid stru t angle, thickness and length should be taken into account under the given payload which is th e structural target.

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