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Influence of translational disorder on the mechanical properties of hexachiral honeycomb systems

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ABSTRACT

Chiral honeycombs are one of the most important and oft studied classes of auxetic systems due to their vast number of potential applications which range from stent geometries to composites, sensors and satellite components. Despite numerous works on these systems, however, relatively few studies have investigated the effect of structural disorder on these structures. In view of this, in this study, the effect of translational disorder on hexachiral honeycombs were investigated through a Finite Element approach. It was found that this type of disorder has minimal effect on the Poisson's ratios of these systems provided that the ligament length to thickness ratio remains sufficiently large and the overall length to width ratio of the disordered system does not differ considerably from that of its ordered counterpart. This makes it ideal for use in various applications and products such as sandwich composites with an auxetic core.

1. Introduction

Auxeticity [1] is a term attributed to materials which exhibit the anomalous behaviour of expanding laterally on application of a uniaxial tensile strain, i.e. possess a negative Poisson's ratio [2]. These materials exhibit some highly remarkable properties and may be used in a number of practical applications. For example, it has been postulated that auxetic materials can form doubly curved synclastic curvature making them ideal for applications in automotive, aerospace and nautical industries. Sometimes they are also incorporated into composites [3–10] to form systems with superior properties such as sandwich panels with an auxetic core [11,12].

Many researchers have studied this remarkable property, which is derived primarily from the geometry and deformation mechanism of the system [13]. This geometric dependency has given rise to the assertion that auxeticity is scale independent [13], a claim which is supported by numerous reports of macro-, micro- and nano-level systems showing auxetic behaviour [14–22]. There are several known geometries which impart a negative Poisson's ratio, with chiral systems being one of the most important classes of auxetic systems. These systems were initially studied by Wojciechowski [23,24], were later simplified by Lakes [25] and implemented by Sigmund and co-workers [26]. These systems where then generalized by Grima [27], who also proposed a nomenclature system based on the geometry of the representative units and the chirality of these units within the system. They have been the subject of numerous detailed studies due to their vast array of potential applications which include amongst others, stent geometries [28–30], satellite antenna designs [31–33], sensors and composite sandwich panel structures [11,12] and morphing wings [34,35].

The mechanical properties of chiral systems have been studied thoroughly in the past from both an analytical and a modelling perspective [36–45]. However, the majority of these works have focused mainly on ideal systems, which although useful in elucidating the manner in which typical chiral systems are expected to behave mechanically, do not give a complete picture of the true behaviour of real systems that are subject to deviations from an ideal perfect state. A typical case in point is the presence of defects that may be introduced during the manufacturing process, which

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could have a significant impact on the mechanical properties of these systems. Also, even in case where these structures are manufactured though some advanced manufacturing technique such as closed mould processing which limits or avoid at all the presence of similar defects [46], one could have geometric imperfections induced by shrinkage effects, or, by local deformation of the core as a result of concentrated loads.

The significant effect that defects can have on the mechanical properties of otherwise perfect systems has been demonstrated in a number of studies, with hexagonal honeycombs being the most prominent example in the field of auxetics [47–50]. However studies by Pozniak and Wojciechowski on anti-tetrachiral systems with dispersion in node size have also indicated that, in some cases, disorder may not play a significant role in determining the mechanical properties of a system [51]. This highlights how crucial it is to assess the extent to which the mechanical properties of structures may change with the introduction of defects, in order to ensure that the presence of defects does not compromise the mechanical characteristics of the structure.

In view of this, in this work, we shall be studying the effect of dimensional (shape) imperfections in the form of displacement of nodes on the mechanical properties of hexachiral honeycombs, a class of chiral structures which in their ideal (non-disordered) state possess an isotropic Poisson's ratio of -1. Such perturbations of the geometry of the lattice, which could be considered as a form of translational disorder can be induced by manufacturing process, shrinkage induced phenomena and uneven loading of the core.

2. Method

In this study, the mechanical properties of disordered hexachiral honeycombs were computed using the Finite Element software ANSYS13 provided by Ansys Inc [52]. In order to simplify the simulation method and evaluation of results, a rectangular unit cell was used to model these systems instead of the standard rhomboid unit cell [36,53], as shown in Fig. 1b. For a regular and ordered hexachiral system, such a (periodic) rectangular unit cell (henceforth referred to as 1×1 unit cell) comprises a total of two nodes and six ligaments and would have dimensions of $a \times b$, the width and length of the rectangular unit cell respectively. These parameters, as evident in Fig. 1b, are in turn determined by the distance between the chiral node centres, R, as well as the angle between them, θ. Since in a six-fold rotational symmetry hexachiral system, θ is 30°, the a/b ratio must be fixed at $\sqrt{3}$ in order to maintain regularity. The other parameters required to build the unit cell are the ligament thickness, t and the chiral node radius, r. Here one should note that although such a small system, a sample consisted of a single unit cell, may be suitable to model the mechanical properties of an idealised hexachiral system, provided that the correct periodic boundary conditions are used, it is clearly not suitable to represent a system with any disorder. This will therefore necessitate the use of larger representative samples. In this work the representative samples will have a form of periodic rectangular cells having the size of $x_r a \times y_r b$, where x_r and y_r are the numbers of 1×1 (disordered) unit cells along the x- and y-directions respectively, in analogy with other studies on disordered systems [51].

As in a previous study on chiral systems [44], the PLANE183 element type was used to simulate all systems modelled here. This element is a higher order 2D 6-noded element with two degrees of freedom at each node and quadratic displacement behaviour. Following convergence tests, the meshsize was set to $t/2$ (i.e. half the thickness of the ribs). This step is extremely important since the choice of element size plays an important role in determining the reliability of the results obtained while at the same time minimising the computational costs involved in the simulation method [54]. The Young's modulus and Poisson's ratio used to describe the material properties of the system were isotropic and were set at 200 GPa and 0.3 respectively. In order to eliminate influence of edge effects, periodic boundary conditions were employed. By operating under the assumption that if an object is periodic in both the x- and y-directions, it must follow that the deformation on the edge of the unit cell is identical to that on the opposing edge. This behaviour is described by the displacement relationships derived by Suquet [55] which were used to describe the constraints equations. These conditions imply that, at all times during deformation, lines on opposing edges have the same slope and length.

In this work, the effect of uniaxial on-axis tensile loading was simulated, where loading in the x-direction was simulated through the application of a uniaxial tensile force on the FEA nodes which lie on the right and left edges of the periodic cell, whilst for loading in the y-direction, a force was applied on the top and bottom edges of cell. In both cases, the simulations were solved linearly.

In order to validate that the system is adequately constructed, constrained and the appropriate periodic boundary conditions are being used, systems with a negligible amount of disorder, which may be considered as 'non-perturbated' hexachiral systems, were simulated. As discussed in below, the Poisson's ratio of such systems was found to be *ca.* -1, while the Young's modulus was also

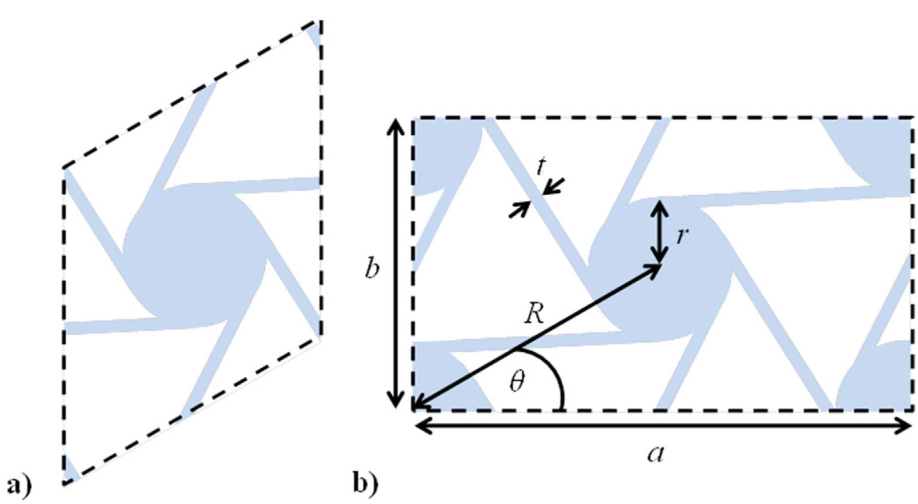

Fig. 1. a) A 1×1 rhomboid hexachiral unit cell. b) A 1×1 rectangular hexachiral unit cell with its parameters.