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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

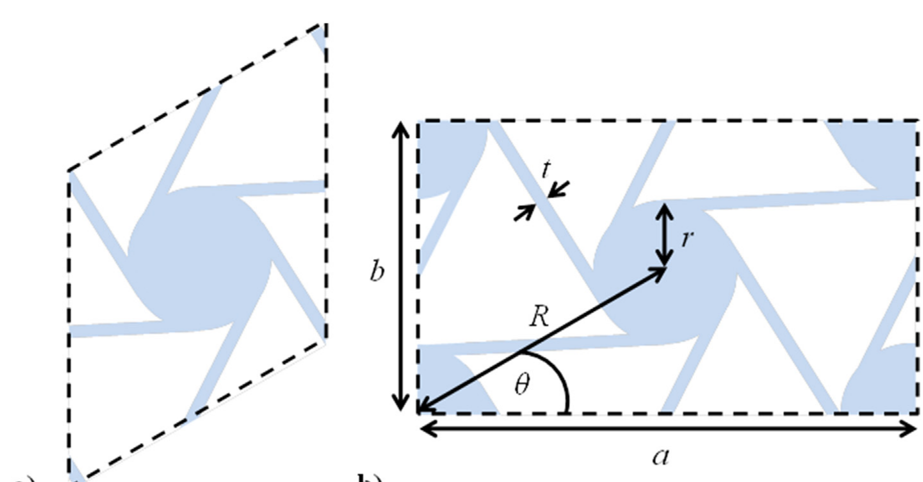

Fig. 1. a) A 1×1 rhomboid hexachiral unit cell. b) A 1×1 rectangular hexachiral unit cell with its parameters.

consistent with analytical models derived by Attard et al. [53], Bacigalupo and Gambarotta [56], Spadoni and Ruzzene [43] and Prall and Lakes [36], meaning that the modelling methodology used is appropriate.

Following validation of the simulation method, the mechanical properties of several disordered hexachiral systems were simulated. As mentioned previously, the disorder considered in this study involved random translational disorder. This entails the displacement of nodes from their 'ideal' position, a situation which in turn, invariably leads to a system whose ligament lengths are distributed over a range of values with limits depending on the degree of disorder applied to the system. This method was chosen in order to simulate systems with comparable densities, providing that the ligaments have a large length to thickness ratio.

Disorder was generated by displacing each chiral node by a random distance through a uniform distribution algorithm (defined by the permitted degree of displacement, d, from its 'proper' position in an ideal system, as shown in Fig. 2.) This parameter was defined as a percentage of the maximum permitted random displacement, d_{max}. This threshold was defined as the maximum amount of displacement that a node could undergo, in any direction, without the risk of overlapping with one of its neighbouring counterparts and thus compromising the topology of the system. This value was defined by:

$$d_{\max} = \frac{R}{2} - r$$

where, R is the distance between each node in a pristine hexachiral honeycomb and r is the radius of each node (see Fig. 2a). In other words, the systems studied here are generated simply by moving the circular nodes upwards or downwards, leftwards or rightwards without changing the radius of the nodes as illustrated in Fig. 2c and the animation in the supplementary information (ANIM01.gif) where a system which is referred to as belonging to the $x\%\ d_{max}$ group, being a system where each chiral node is displaced horizontally by $d\cos(\theta)$ and vertically by $d\sin(\theta)$, where θ is randomly chosen within the range $0^{\circ} < \theta \leq 360^{\circ}$ and d is randomly chosen within the range $0 \leq d \leq x\%\ d_{\max}$.

Note that the method used in this study is not the only possible route which one could use to introduce translational node disorder into hexachiral systems. The method used here however, was chosen on the basis that it produces systems with comparable densities. This is an important factor, since the introduction of displacement disorder creates a large number of variables which discourages comparison between similarly disordered systems. By using this approach, the type of allowed variables is limited mainly to factors which are strictly related to the disorder in question such as dispersion of ligament lengths and displacement of nodes, whilst eliminating factors such as variations in the total number of nodes and ligaments, which could lead to undesirable complications when comparing the mechanical properties of different systems.

Initially, a total of 50 disordered systems were simulated in this study, ten for each of the following five degrees of displacement, d; 10%, 30%, 50%, 70% and 90% of $d_{\max}$. Note that although in theory the maximum displacement that could have been applied is $d_{\max}$, this value is inadmissible since at this degree of disorder it is still possible for two nodes to be displaced in such a manner as to just touch each other, resulting in a 'ligament' with a length of zero between them. Therefore, the highest degree of disorder studied was set to 90% of $d_{\max}$ in order to avoid the possibility of such an occurrence. For each system, the node radius, r, was set to 2.5, the ligament thickness, t, to 0.1 and the 'ideal' distance between each node, R, to 15. This resulted in a $d_{\max}$ value of 5 for each case. All simulations on disordered systems were performed on 4×4 cells

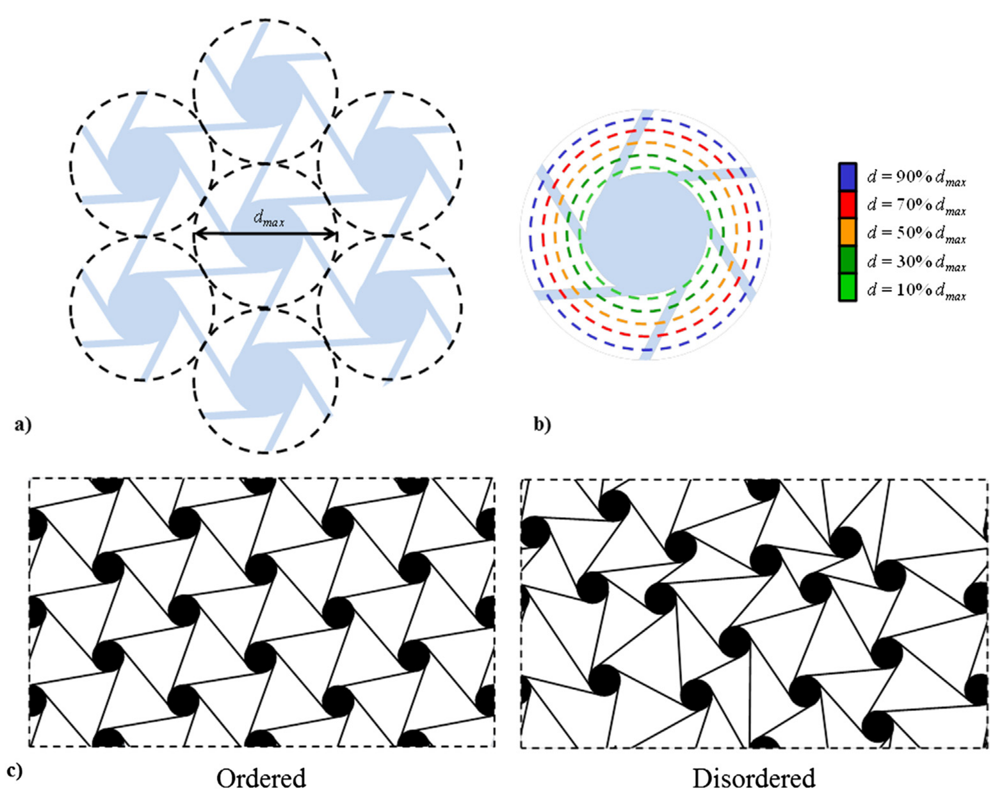

Fig. 2. a) Diagram of an ideal hexachiral with circles signifying the maximum displacement. b) Diagram of one hexachiral node with circle signifying each degree of displacement used. c) Figure of an ordered and disordered hexachiral system.

following convergence tests to determine a suitable representative sample size. This resulted in a cell possessing an a and b value of 26 and 15 respectively giving a unit cell with dimensions of $4a \times 4b = 104 \times 60$. These systems, by method of construction, were such that the minimum ligament length to thickness ratio was always very high, even for the most highly disordered systems considered here. This means that for such systems with slender ligaments the flexing of ligaments is expected to remain as the main deformation mechanism of each system. However, it is possible to have cases where the ligaments (in an equivalent ordered system) already possess a relatively low length to thickness ratio and thus a significant amount of disorder may lead to the occurrence of ligaments with even lower values. This may affect the deformation mechanism of the system since it is well known that very short thick ligaments would not flex easily. In order to investigate this effect, a further set of simulations was conducted on systems with a maximum degree of disorder of 90% d_{max} and ligament thicknesses, t, of: 0.5 and 0.9, i.e. systems which may be considered as having thick ligaments.

3. Results and discussion

Plots displaying the variation in the Poisson's ratios and Young's moduli with increasing degree of disorder for the initial set of structures (i.e. systems with $t = 0.1$) are shown in Fig. 3, where the results indicate that for slender ligaments the average Young's modulus is gradually increasing as the degree of disorder increases while the Poisson's ratio remains close to −1, with no discernible upward or downward trend. This value of −1 corresponds to the one predicted by various analytical models of the non-perturbed systems [36,43,53,56]. Also, the values for the Young's moduli in both directions are tending towards 3.03 MPa on decreasing the amount of disorder, which is consistent with, and falls well within the range of, that estimated by analytical models for this system, i.e. 2.11 MPa [43], 2.89 MPa [56], 2.95 MPa [53] and 3.78 MPa [36].

It is also evident from these plots that the values obtained from various structures with the same degree of disorder show very little deviation. This is indicative that for the systems considered here, the sample size used is large enough to allow one to obtain a good representation of a randomly disordered macroscopic system, although this finding on its own does not give definite evidence that the sample size is appropriate. For example had this conclusion been based solely on the Poisson's ratios, it could have been misleading since the disorder studied here does not result in a discernible variation in the Poisson's ratio. A better indication of convergence is the fact that results obtained by systems having larger unit cells gave similar results to the once reported here.

The finding that the Poisson's ratio remains relatively unchanged is very surprising since previous research on both translational disorder and missing rib defects in auxetic systems, namely re-entrant honeycombs and rotating triangles [47–50,54], have

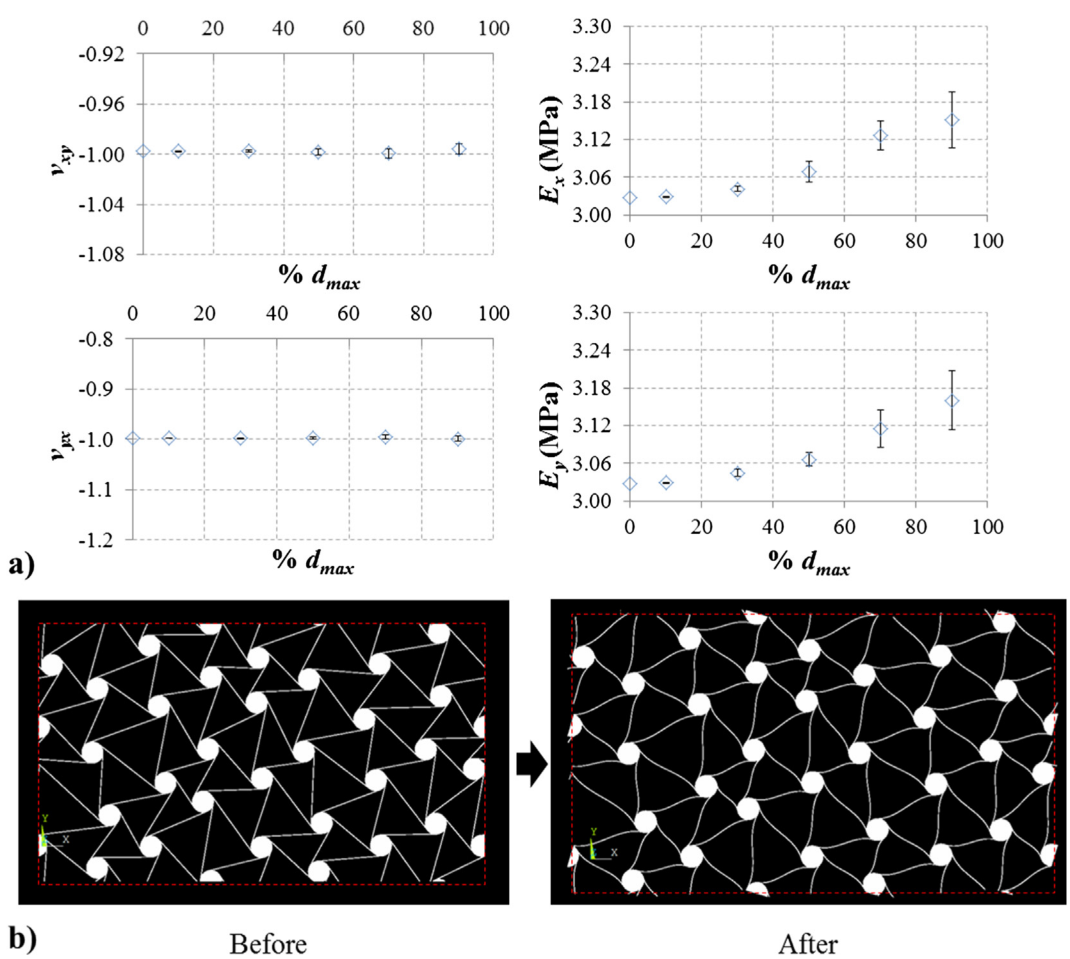

Fig. 3. Results for systems with slender ligaments. a) Plots showing the average Poisson's ratios and Young Moduli of ten chiral honeycombs each with varying degrees of disorder along with the standard deviation in the results obtained. b) A 90% d_{max} system before and after the application of tensile force in the x-direction.

indicated that the Poisson's ratio tends towards zero on increasing the amount of disorder within the system. However in the case of hexachiral honeycombs, it appears that translational disorder has minimal effect on the Poisson's ratio of the system.

As mentioned previously, the system also became stiffer on increasing the degree of disorder (see Fig. 3). In the systems studied here, where one could argue that the extent of distortion introduced is not extensive, this increase in Young's modulus is not particularly drastic, with the maximum value obtained being merely *ca*. 6% greater than the Young's modulus of an ideal hexachiral system. Had the extent of disorder been more extensive, for example a system where each node is indeed transposed by the maximum amount permitted in this study, then the variation in the Young's modulus would have been much more extensive, with the systems potentially becoming far more stiff.

This trend, i.e. that the Young's modulus increases with an increase of disorder, was to be expected since on increasing the amount of random node displacement, one is also increasing the disparity in ligament lengths, which leads to an increase in the number of short ligaments (i.e. ligaments which are shorter than those found in an ideal, non-disordered system). Such short ligaments have a lesser tendency to deform via flexing than longer ligaments. Although one could argue that, by this reasoning, there is also a greater number of longer ligaments and thus the two effects cancel each other out, a claim which is supported by the fact that the average ligament length is more or less the same for each system, it is important to remember that due to the manner in which the system is constructed, any stiffening of which is introduced by the presence of short ligaments is manifested by a stiffening of the whole structure. Furthermore, the relative positions of short and long ligaments are also likely to play a role in determining the Young's moduli of these systems. In a hexachiral system each node is joined to six others by six ligaments and therefore it is extremely unlikely that, in a random environment, a system which contains a uniform distribution of ligament lengths (i.e. equal number of longer and shorter ligaments when compared to the ideal ligament length) and positions (i.e. each short ligament is next to a long ligament) can be obtained. In fact, as illustrated in Fig. 4, systems where three short ligaments connect three nodes in the form of a small triangle are not uncommon. Such configurations could put extra restrictions on the rotation of these nodes and in turn limit the deformation of the other adjoining longer ligaments. This hypothesis is also supported by the fact that all nodes within the system deform in a *quasi*-uniform manner, thus reinforcing the notion that by restricting the rotation of one node, one can hinder the deformation of the overall system.

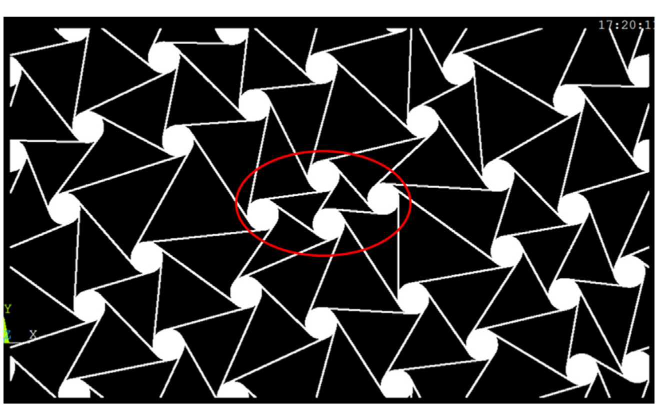

Fig. 4. A 90% d_{max} system with an aggregation of short ligaments. Such systems were found to have higher moduli suggesting that aggregation of short ligaments would stiffen these structures.

Although the results obtained seem to indicate that translational disorder has little effect on the mechanical properties of hexachiral honeycombs, particularly the Poisson's ratio, as one can note from the graphs in Fig. 5a, the effect of disorder on the mechanical properties of these systems becomes more pronounced as t increases. Before examining these results further however, it is important to note that even in their non-disordered state, these systems do not possess a Poisson's ratio of -1, but of -0.916 and -0.694 respectively for the systems of $t = 0.5$ and 0.9, as has also been predicted in other studies [39]. Also the densities of systems with thick ligaments are slightly less comparable to each other as opposed to systems with small ligament thicknesses.

In fact, as shown in Fig. 5a, systems with ligament thicknesses of 0.9 show a significant increase in their Poisson's ratio (i.e. the Poisson's ratio becomes less negative) on introducing translational disorder within the system. The percentage increase in the Young's modulus is also significantly greater when compared with thin ligament chiral systems with an equivalent degree of disorder. This is probably due to the fact that since in this case the ligaments already have a small ligament length to thickness ratio in the equivalent non-disordered system, the introduction of disorder results in the introduction of a greater number of even shorter ligaments which would have more extreme length to thickness aspect ratios. These thick, short ligaments are expected to have a very significant bearing on the overall deformation profile of the system since in thick ligaments the effects of shear deformation become more pronounced than in slender beams, whose behaviour may be predominantly described by bending deformations [57]. However a full in-depth investigation into the exact deformation mechanism of hexachiral systems with thick ligaments is beyond the scope of this discussion since the main aim of this work is to quantify the effect of translational disorder in hexachiral systems.

Before we conclude it is important to note that the study conducted here is limited by considering only a periodic system where through the method of construction used, the unit cell size and shape did not change. In reality, however, one could also have a situation where the overall dimensions and aspect ratios of the sample would change on the introduction of translational disorder. With this in mind, a series of preliminary simulations on two hexachiral structures (both with $t = 0.1$, ordered and disordered with a maximum displacement of 90% d_{max}) with different a/b ratios other than the standard $\sqrt{3}$ for regular hexachiral honeycomb were also run. As one can see from Fig. 6a, these systems no longer possess an angle θ of 30° and sport two sets of ligaments with different lengths as opposed to the uniform ligament size observed throughout a regular system. It is also clear from the plots in Fig. 6b, that these systems no longer possess a Poisson's ratio of -1 in their non-disordered state and are anisotropic, confirming that if through disorder or otherwise, alterations to the a/b ratio of chiral honeycombs are made, the mechanical properties of these system will be significantly changed. Nevertheless, the plots confirm once again that the Poisson's ratio of hexachiral systems is not significantly affected by translational disorder of the nodes within the representative unit cell, providing that the a/b ratio remains constant.

Furthermore, the system studied here, even if designed to model the effect of disorder, is still limited since it does not account for any irregularities apart from translational disorder of the nodes. For example, it is being assumed that the material used to construct the system is defect-free and perfectly uniform, all the nodes have equal size and a perfectly cylindrical shape and all the ligaments have a uniform cross-section. In reality, such

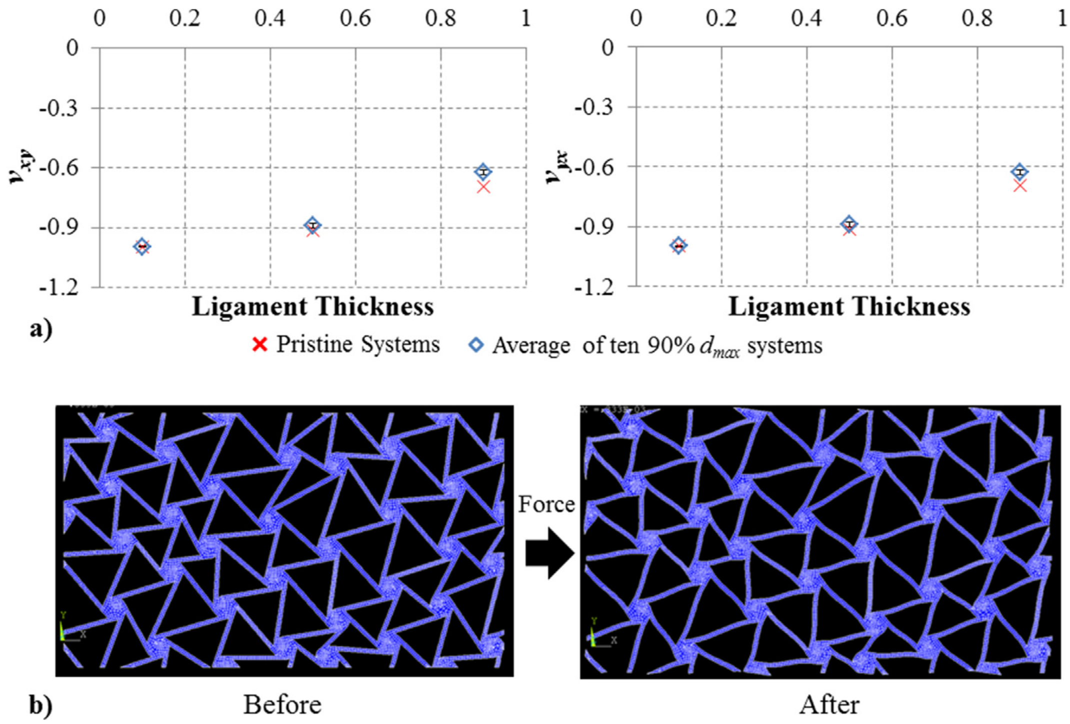

Fig. 5. a) Results for non-slender ligaments: Graphs showing the Poisson's ratios of $t = 0.1$, 0.5 and 0.9 pristine regular hexachiral systems as well as the average and standard deviation of ten systems with disorder of upto 90% d_{max} systems of each type. Note that the standard deviation, indicated on the graphs through the error bars, is extremely small. b) Diagram showing a $t = 0.9$ system before and after deformation induced by a force in the x-direction.

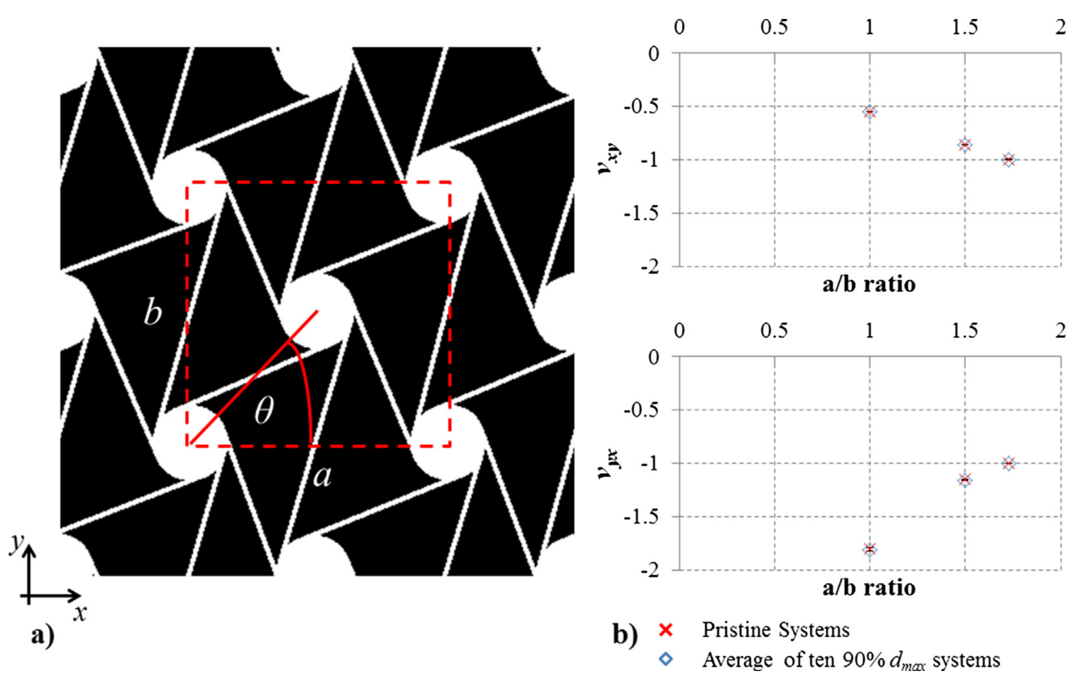

Fig. 6. a) Figure of an irregular hexachiral honeycomb with $a = b$ and a θ angle of 45°. b) Plots showing changes in Poisson's ratios for ordered regular hexachiral and irregular hexachirals along with an average and standard deviation for ten disordered systems of upto 90% d_{max} each.

level of ideality is unlikely to be achieved. For example, even if the manufacture process was such so as to eliminate any possible other form of defect, with time and repeated use, any system of this type is expected to experience some sort of degradation. Such degradation is more than likely to affect the macroscopic mechanical behaviour of the system, and hence, some deviations would be expected from the work reported here. Nevertheless, one expects that the main trends simulated here, which are applicable to small strains, would still be present to some extent in real systems.

It is also worth noting that the simulations conducted here were based on a single material system. However, the main trends observed are also expected to be present in the equivalent hexachiral systems which are built from more advanced and modern materials such as composites. Thus for example, it is envisaged that systems such as the ones considered here built from composites which can sustain under extreme and harsh environments, including ones capable of withstanding extreme mechanical and thermal loads, especially low temperatures or composites built from natural fibres such as the ones studied by Hui et al. [58–60]. Such hexachiral composite systems are likely to benefit from both the advantages afforded as a result of having negative Poisson's ratio as well as those which arise from the intrinsic properties of superior composite material with which the hexachiral is constructed [46]. This is of considerable interest, especially when taking into account the vast number of applications for composites and auxetic systems which include aerospace, military and automotive uses amongst others.

4. Conclusions

In this study, the effect of translational disorder of nodes on the mechanical properties of hexachiral honeycombs was investigated using the Finite Element method. From the results obtained we can conclude that translational disorder has no significant effect on the Poisson's ratio of hexachiral honeycombs, 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. The Young's modulus of the system was also found to increase on increasing the extent of disorder.

These findings indicate that the hexachiral honeycomb system, unlike other auxetic geometries, is extremely tolerant to translational disorder and possesses the outstanding capability of retaining more or less its original Poisson's ratio despite degrees of disorder of up to 90%. This property, for example, can be extremely useful in industry, especially in facilitating the manufacturing process of systems based on hexachiral honeycombs, since high precision does not appear to be an essential requirement for the production of systems with a desired set of mechanical properties. However, while this work highlights an intriguing class of auxetic systems which possess the ability to retain more or less their original mechanical properties at high degrees of disorder, further studies are required in order to discover the full potential of these systems with respect to defects and disorder. We hope that this work will stimulate further research on the effect of translational disorder on other chiral systems as well as the effect of other types of imperfections, such as missing ligament or node defects, on the mechanical properties of this class of systems. We also hope that this work will provide additional impetus to industrialists aiming to develop products involving auxetics of this type, for example composite sandwich panels with a hexachiral core.

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.compositesb.2015.04.057.

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