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Auxetic Perforated Mechanical Metamaterials with Randomly Oriented Cuts

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Auxetic perforated systems constitute one of the most important classes of mechanical metamaterials due to the relative ease and simplicity through which these systems may be produced. In recent years, this concept has risen to prominence with numerous researchers proposing a plethora of perforation patterns, ranging from circular holes to ellipses or slits, which may convert conventional materials to auxetics. However, all of these works considered highly symmetric, perfect and defect-free designs, an approach which may have its limitations and not provide a complete picture of the mechanical behavior of these systems when implemented in actual real-life situations. In view of this, this work will look at the possibility of achieving a negative Poisson's ratio through the use of slits and perforations which are cut in an increasingly randomly oriented manner. In particular, this work will propose a novel class of perforated systems containing quasi-random cuts based on the rotating squares motif and looks at how the Poisson's ratios and stiffness in such systems are affected by "randomness" or "disorder" in slit orientations. It was found, through simulations and experiments, that despite the disorder and randomness in orientation, the systems studied still retain auxetic characteristics. This suggests that a high degree of symmetry is not necessarily required for the system to exhibit auxetic behavior, thus confirming the viability and practicality of perforated mechanical metamaterials for real-life applications.

The effect of perforations on the mechanical properties of sheets has long been of interest to scientists in the field of material science. In fact, in the 1960s, plates with circular holes attracted considerable attention in connection with the analysis and design of tube sheets for boilers and pressure vessels for nuclear reactors.[1–4] Recently, however, perforated systems have been studied with respect to their potential to exhibit auxetic behavior. Since the pilot studies on auxetic metamaterials created through circular and diamond shape perforations by Bertoldi et al.[5] and Grima and Gatt,[6] respectively, numerous studies have attempted to create other similar systems, both 2D and 3D, with the aim of exploring the full potential of these systems. These perforated systems include metamaterials which mimic the behavior of rotating unit modes such as rotating squares, rectangles, parallelograms, triangles, cubes, and hierarchical and mixed shape units,[5–15] chiral honeycombs,[13,15,16] and re-entrant mechanisms.[15] Recently, there has also been additional emphasis on the use of slits/cuts which besides converting a previously nonauxetic sheet of material into an auxetic one also have the added advantage of significantly reducing material waste.[11,13–15] It must be said that the concept of creating auxetics through cuts and perforations is particularly appealing since this method is likely to offer a cost-effective route to manufacture auxetics at a large scale, with all the associated benefits,[17] which include the ability to form dome-shaped structures[18] and improved indentation resistance.[19]

Despite the considerable literature on the subject, all of these works consider primarily highly symmetric ideal systems without any randomness in their design or imperfections. However, it is well-known that although highly symmetric and almost perfect systems do indeed exist, even in nature (for example, in single crystals), it is very common to have systems which are less ordered in their microstructure, such as man-made fiber reinforced composites where the fibers are randomly oriented within the matrix. Also an approach which only considers highly symmetric and perfect systems, although not unrealistic, may not provide a complete picture of the mechanical behavior of systems in real-life situations where absolute perfection may be difficult to achieve and, in any case, even the most perfect systems is eventually expected to become imperfect with time through effects like "wear and tear." This makes it imperative to study less symmetric or imperfect systems, especially since previous studies on disordered auxetic systems have yielded a mixed response with respect to their mechanical behavior. For instance, while hexagonal honeycomb-based systems have been shown to be distinctly affected by disorder,[20–22] chiral honeycombs have been shown to be less influenced by disordered perturbations in their geometry,[23,24] with their Poisson's ratio remaining more or less constant.

In view of this, this work will explore the mechanical behavior of slit perforated systems where the highly ordered pattern of slits in traditional auxetic perforated systems is replaced by an arrangement where each slit is oriented in a quasi-random manner so as to produce perforated systems which do not contain elements of symmetry.

The systems studied here were investigated through a Finite Element approach using the ANSYS13 software provided by Ansys Inc.[25] In view of the novel nature of this work, one of the simplest perforated systems was studied; namely, a system which in its nondisordered shape has perpendicularly aligned alternating slit perforations which

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DOI: 10.1002/adma.201503653

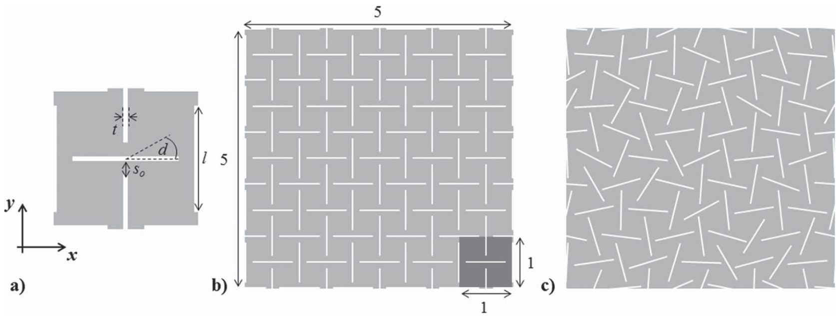

Figure 1. a) The representative unit cell of an auxetic perforated system made up of perpendicularly arranged alternating slits which mimics the behavior of a rotating squares system. b) An ordered perforated system made up of 5 × 5 representative unit cells. c) A disordered perforated system with $d_{max} = 30°$.

mimic the deformation behavior of the auxetic rotating square system[26] (see **Figure 1**b). As shown in Figure 1a, these systems may be characterized by the following parameters: *l*, the length of the slit perforation, *t*, the thickness of the slit perforation, and s_o, the separation between the slits in the ordered system.

Disorder was induced in these systems in the form of geometric perturbations brought about by a random change in the angular orientation or tilt of the slit perforations such that each slit is rotated by a random angle *d* where $-d_{max} < d < d_{max}$ with d_{max} being the maximum magnitude of rotation for a particular system. Thus, a system where $d_{max} = 0$ corresponds to an ordered system (see Figure 1b) since all the slits have $d = 0°$ meaning that they remain in their original orientation. In this study, the maximum degree of permitted random perturbations, d_{max}, was set to 0°, ±5°, ±10°, ±15°, ±25°, and ±30° where, as illustrated in **Figure 2**b,c, systems having d_{max} of ±5° and ±30° are those disordered systems with the lowest and highest degree of randomness, respectively.

The parameters *l* and *t* were left unaltered, with *l* being set to a constant value of 1 and *t* to a value of 0.01. The parameter so, which defines the separation between the slits in the ordered equivalent was also left unaltered at $s_o = 0.1$ but the actual separation between the slits in a disordered system will necessarily vary as a consequence of the geometrical perturbations present in these systems. In setting these parameter, care was taken to ensure that, for the initial set of systems presented here, the actual separation between slits in the disordered systems was always greater than 0, i.e., none of the slits intersected each other. It should be noted that the range of d_{max} considered corresponds to systems where the original "ordered" parent system is easily identifiable (see Figure 2b, $d_{max} = 5°$), to ones where the slits are so randomly oriented that the overall system, to the untrained eye, looks like a system with random slits where the original "ordered" parent system is almost untraceable (see Figure 2c, $d_{max} = 30°$).

In an attempt to obtain an average representation of the expected behavior of these disordered systems, 20 structures were constructed for each level of rotational disorder. Following unit cell size convergence tests (see the Supporting Information), each system was modeled as a 5 × 5 representative unit cell which corresponds to a system made up of 10 × 10 rotating units as shown in Figure 1b,c. Periodic boundary conditions were employed at the edges of the unit cell in order to eliminate edge effects and deformation was induced through

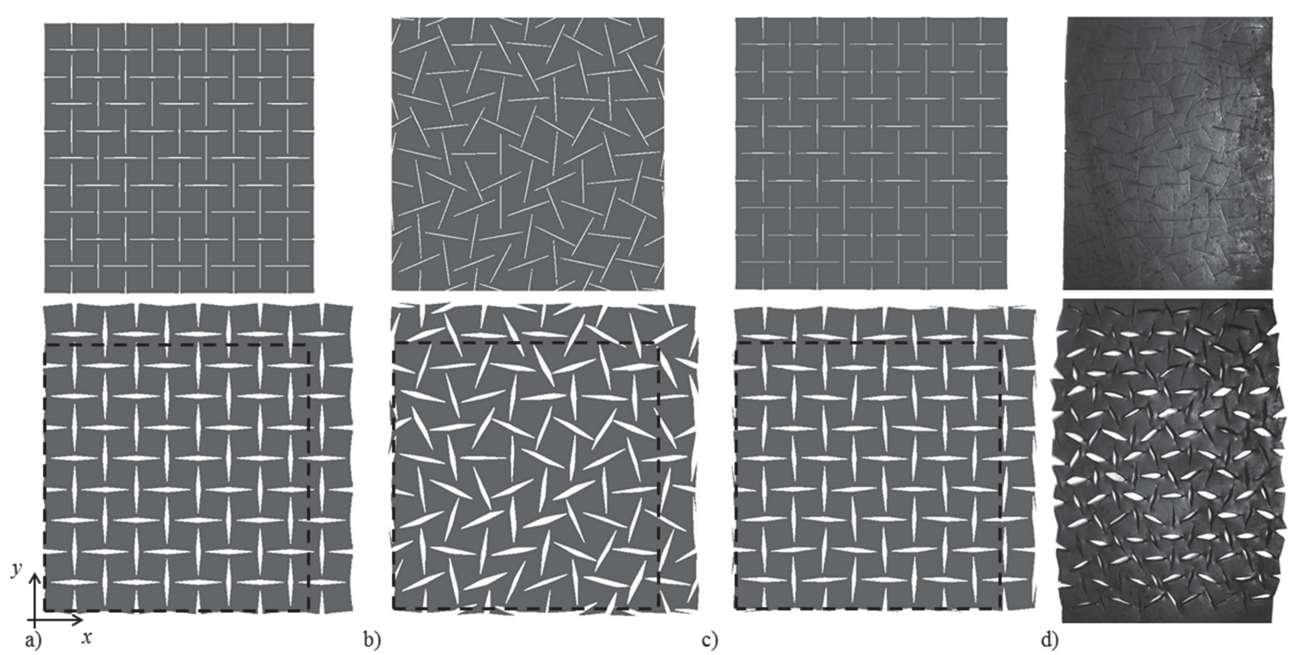

Figure 2. a–c) Simulated and d) experimental stretching of a) $d_{max} = 0°$, b) $d_{max} = ±5°$ and c,d) $d_{max} = ±30°$ systems in the *y*-direction. Note that while systems a) and b) deform in a manner which is extremely similar to the rotating rigid units mechanism, systems c) and d) resemble more closely an irregular quadrilateral rotating system.

the application of a force in the x- and y-directions separately. Each system was studied using the linear material properties of rubber and solved linearly. Further details on the simulation methodology used are provided in the Supporting Information.

In addition to the simulations, actual samples corresponding to the ordered system and the one with $d_{max} = 30°$ disorder were also manufactured out of rubber sheets. These systems were created by perforating a rubber sheet manually; in an ordered manner in the case of the ordered system in a quasi-ordered pattern of alternating slits perpendicular to each other and in the case of the disordered system, by randomly orienting the cuts while ensure that none of them overlapped each other. In order to achieve the desired level of disorder, a computer generated blueprint was first created and the slits were then cut accordingly. Each system corresponded to one made of 6 × 8 unit cells. These samples were tested in tension with measurements of dimensions and strains being made in the centermost region of the sample where the response is known to be more uniform and boundary effects are minimal.[14] The dimensions from which the strains and Poisson's ratio were derived, were measured using videoextensiometry by a Messphysik system while the samples were stretched using a Testometric tensile testing machine at a very slow strain rate. Further details are given in the Supporting Information.

As one can observe from Figure 2 (images of the deformed and undeformed systems) and the plots shown in **Figure 3**, even for the systems with the highest extent of randomness studied here, i.e., where the slits can orient themselves at up to ±30° to the original direction, the Poisson's ratio is highly negative and pronounced. On the other hand, there is a significant increase in the Young's moduli, which is predicted to approximately double with the increase in disorder. Also of interest is the fact that there are only small variations between the properties for stretching in the vertical and horizontal directions.

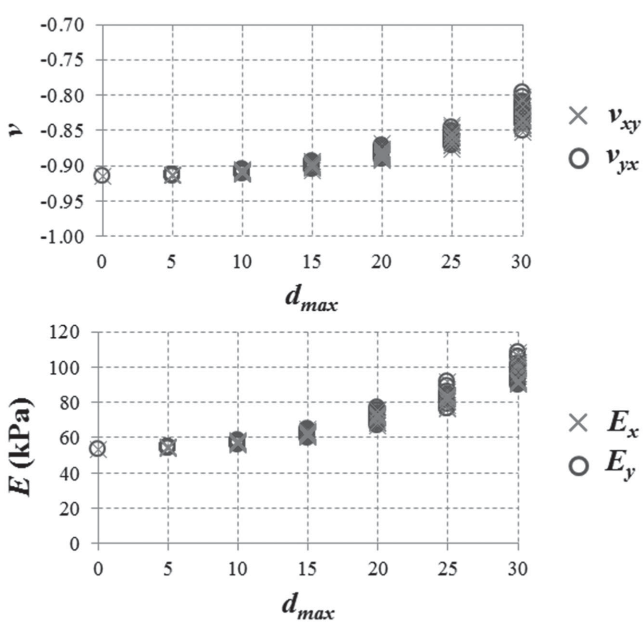

Figure 3. Plots showing how the mechanical properties $ν$ and E change with increasing randomness of slit orientation, d_{max}. Note that all systems roughly retain their isotropic behavior despite the increase in disorder.

These results can be attributed to the fact that as shown in Figure 2c and Video S1 (Supporting Information), the system no longer resembles a uniformly shaped rotating square system upon deformation but rather a system of irregular quadrilaterals rotating in unison, which, as discussed elsewhere,[27] are known to be capable of exhibiting in auxetic behavior. It is important to note that the results of the simulations are reconfirming the robustness of the rotating unit mechanism for generating a negative Poisson's ratio. In fact, the simulations suggest that even the systems with the highest degree of randomness in the angular distribution of the slits (see Figure 3) should exhibit highly auxetic characteristics with the Poisson's ratios being predicted as typically less than −0.8. These values compare well to the ordered equivalent which was simulated to have Poisson's ratios of −0.9, i.e., only ≈0.1 more negative than their more disordered counterparts. Also interesting is the fact that in the case of the real samples, once again the Poisson's ratio of the ordered sample was only more negative by ≈0.1 than its disordered counterpart.

It is beyond the scope of this work to fully account for the discrepancies in these Poisson's ratio measurements, but the results obtained are considered realistic. In fact, earlier work on idealized rotating units had suggested that the Poisson's ratio would change from the value of −1 typical of rotating squares if the shape of the rigid units changes. Thus, the changes in the Poisson's ratio could also be explained, at least in part, by such geometric explanations. Here it must also be noted that although the actual shape of each "rotating unit" differs from a square, the average shape of all units together is still a square, this being an artifact of the method of construction. This may explain, at least in part, why the Poisson's ratios remain so close to those of the ordered counterpart. Another possible explanation for deviation in the Poisson's ratio between the disordered and their ordered counterparts is of a mechanistic origin since in the disordered systems, as discussed below, the auxeticity-inducing "rotating mechanism" becomes less effective. In the case of deviations between the results of the simulation and those from the experimental work, it should be noted that in the latter case, there are noninsignificant edge effect as well as the possibility for the system to deform out of plane.

The increase in Young's moduli is also expected since, unlike in the ordered system, the magnitude of the separation between slits is no longer fixed at a value of s_o, but rather fluctuates between higher and lower values. Since all the "units" within the system are rotating concurrently, "joints" (i.e., region between the end of one slit and another) with a higher separation effectively clamp the rotational deformation resulting in a lower extent of overall deformation. A similar effect was observed in a previous study on translationally disordered hexachiral honeycombs.[24] Another form of clamping that may be hindering rotational deformation is of a geometric origin and arises due to the fact that constructs made from noncongruent irregular perfectly rigid quadrilaterals without any symmetry considerations may become jammed (i.e., units unable to rotate) unless the units themselves are permitted to change their shape. Obviously, jamming is not expected to be fully operational in the systems proposed here as more than one deformational mechanism is taking place. Also, due to the presence of multiple modes of deformation, any form of clamping of the rotational deformation mechanism is also expected to have some effect on the Poisson's ratio. For example, in this case rotation of the units is accompanied by deformations of the material itself. If rotations are clamped, such modes of deformations which would probably result in positive Poisson's ratios, are expected to become more pronounced, meaning that the overall extent of auxeticity is expected to decrease.

The main significance of this work goes beyond the results reported here. The fact that disorder does not appear to have a very significant effect on the Poisson's ratio of these perforated systems indicates that a high degree of symmetry and perfection is not necessarily required to produce perforated mechanical metamaterials exhibiting auxetic behavior. This may have implications in the biomedical industry, particularly in skin grafts which are used to cover burnt or damaged regions of the skin. Normally, in a skin grafting procedure, a piece of skin is cut from a healthy region, perforated, stretched, and placed onto the target area, which is usually much larger than the graft. Previous studies by the same authors have already advocated the merits of using perforation patterns which results in auxetic behavior for this purpose,[12,15] since auxetic skin grafts are expected to cover a much larger surface area in comparison to designs which result in positive Poisson's ratio response. This study, however, takes this application for these auxetic metamaterials one step further. Perforation of the graft, even though conducted through the use of a mesher, is rarely completely precise and accurate due to wrinkling of the skin as well as others mitigating circumstances. Through this study, we have shown that the auxetic behavior of the system may still be retained despite imperfections caused as a result of these factors, thus reiterating their suitability for this application. In addition, should the need arise, these systems may also be created by hand using a scalpel, since a high degree of perfection is not essentially required for the system to retain their auxetic behavior. In fact, the tested sample containing quasi-random perforations shown in Figure 2d was handmade and still achieved auxetic properties (see the Supporting Information for further information on the preparation of these perforated systems).

Furthermore, this work could also provide a blueprint for the design and manufacture of smart textiles which exhibit auxetic characteristics. Such textiles containing a quasi-random arrangement of slits as described here are expected to be breathable, aesthetically pleasing and functional at the same time. Auxeticity is a highly desirable feature in textiles as they could provide a better fit around the natural curved surface of the human body, an essential characteristic for slim fit garments which are designed in a manner that adhere closer to the body frame. Such textiles with enhanced drapability are highly desirable for the manufacture of compression garments, which are most commonly used for sports and medical applications due to their enhanced ability to prevent muscle injury, strain, and fatigue, and at the same time be able to wick sweat away from the body to aid controlled cooling and prevent chafing and rashes. In these textile based applications, a quasi-random perforated system could be more useful than an ordered one especially if the tailoring necessitates sewing along a line of perforations that would inevitably be present in materials with ordered cuts or perforations.

Additional potential products and applications which could combine all these benefits include bandages and personal protection gear, which would exhibit properties characteristic of auxetics such as the ability to form synclastic curvatures and at the same time are not too complex to manufacture.

Before concluding, it is important to note that none of the systems investigated in this study contained slits which overlapped with each other. This is extremely significant since despite the varying degrees of disorder, the geometry of each system may still be roughly classified as an array of quadrilaterals connected together from their corners. However, should the slits overlap each other, as would happen in cases of higher allowed values of disorder, than this quadrilateral motif is lost and the system is expected to experience more drastic changes to its mechanical properties than observed for systems with no overlapping slits (see the Supporting Information). Thus, when producing these systems, care must be taken to avoid overlapping slits when introducing randomness into perforated systems such as those studied here.

Furthermore, although this work has proved that quasi-random slits cut into conventional sheets of material can generate auxetic behavior, there is still scope for additional work, both theoretical and experimental, so as to perfect this concept. For example, one should look at other patterns of perforations, different materials, and possibly even study whether the work proposed here could be transposed in three dimensions through the use of cuts or slits, which as this work has shown need not be in a perfectly ordered manner.

To conclude, this study has shown for the first time that one may convert a regular conventional sheet of rubber-like material to a more value-added auxetic metamaterial with high negative Poisson's ratios through the introduction of nonsymmetric quasi-random cuts. More importantly, this work also highlights the fact that deviations from the ordered symmetric nature of the perforated system do not result in drastic changes to the Poisson's ratio of the system, meaning that a high degree of perfection is not necessarily required to produce these systems. This makes them extremely practical and ideal for use in various applications ranging from biomedical (such as skin grafting) to smart textiles.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

Acknowledgements

This work was funded by the Malta Council for Science and Technology through the R&I-2012-061 Project (SMESH).

Received: July 28, 2015
Revised: September 10, 2015
Published online: November 17, 2015

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