Mass production of re-entrant cubic auxetic structure

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Abstract. The unique characteristics of auxetic materials has attracted significant attention in the research domain. Its distinguishing negative Poisson’s ratio has found its way to targeted applications where normal materials fail to deliver the expected results. The manufacturing of macro sized auxetic structures has always been a challenge. This paper proposes the possibility for mass production of auxetic structures. Materials available in standard shapes are utilized to manufacture the auxetic structure. A new re-entrant cubic auxetic structure is developed, analysed and fabricated. This auxetic structure provides a better scope for mass production.

Keywords: Auxetic structure, Negative Poisson’s ratio, Impact absorption, Re-entrant unit cell, Repeating units.

1. Introduction

Auxetic materials have shown significant advantages over conventional materials in certain applications. Even though there is a substantial demand for auxetic materials[1,2] the limitations in manufacturing them has been a bottle neck. The trend has slowly shifted from manufacturing, auxetic materials [3–8] to auxetic structures[9–16]. A wide range of auxetic structures have been identified and studied[8,17]. Due to the negative Poisson’s ratio of the auxetic structure they thicken laterally when stretched axially and become thinner in the lateral direction when compressed axially. This peculiar nature makes it suitable for blast resistant structures with better force distribution[18]. Numerous attempts have been made to produce auxetic structures using non-conventional techniques. Auxetic structures are produced using additive manufacturing techniques [9,10,12,19–23] while few attempts were made to fabricate it as composite structures [11,24–26]. The adoption of direct laser writing [20,22,27,28] and metal deposition techniques [19,29] proved to provide better surface finish compared to the traditional manufacturing process. Selective laser melting is found to have better control over the geometry of the structure[16,21].

Auxetic structures are better suited for low velocity impact applications[7] and double arrowhead structures showed to follow the same characteristics[30]. Under such loads the deformation sequence of the structure is uncertain. This can be overcome by selectively strengthening the parts of the structure[31]. Though few materials were tested to exhibit auxetic properties, Magalhaes et al [32] found that the geometry of the auxetic structure has more influence than its material properties. With maximum energy absorption as the prime motive, optimal cell geometries were developed [13,15] but,
they still lack the feasibility of mass production. Non-conventional manufacturing techniques require specialised equipment and a controlled environment. Designing an auxetic structure that has a simple geometry with a unit cell that provides room to be easily scaled without compromising its auxetic nature is a challenging task. This paper has addressed this my modifying the idealised unit cell derived from an auxetic foam [5] to make it more suitable for mass production.

2. Selection Criteria
The auxetic structure is selected and modified based on four key factors. The structure should have less repeating units, better scalability, use standardised raw materials and mainly the feasibility for mass production. A new re-entrant cubic auxetic structure Figure 1 is developed based on these key factors. A repeating unit shown in Figure 2 is a sub unit that constitute a unit cell (Figure 3). This unit cell exhibits auxetic properties. The lesser the repeating units the easier would be the assembly of the unit cell. These unit cells must have the provision to link with other such unit cells so it can be scaled with minimal effort. The materials used to fabricate the auxetic structure must be available in standard dimensions. This eliminates the additional step of in house fabrication. Finally the shape of the structure must be simple and cost effective to be assembled.

3. Optimizing the re-entrant cubic cell geometry
The cubic unit cell (Figure 1) that resembles a systematically collapsed cube is re-entrant in nature. This cell can be divided into repeating units that can be further subdivided into standard geometric shapes. Based on the availability of standard sized raw materials aluminium cubes (6.1 mm) and steel links (Ø 1.3 mm) are selected. These are fixed parameters in the unit cell. The repeating unit (Figure 2) consists of 5 steel links assembled in a particular formation to facilitate assembly with other repeating units. The re-entrant cubic unit is an assembly of 6 repeating units (Figure 4). The dimensions of the unit cell assembly can be controlled with two parameters, length of the steel link (l) and angle (θ) between the steel links (Figure 2).

| Table 1. Factors and levels |
|-----------------------------|
| Factors                  | Levels |
| Link length, l (mm)       | 1  | 2  | 3  |
| Link angle, θ (deg)       | 65 | 70 | 75 |
Figure 4. Assembled re-entrant cubic unit cell. a) Front view, b) Isometric view.

Figure 5. Boundary conditions for analysis.

Table 2. Orthogonal array

| Test case | Factor 1 | Factor 2 | Stress (MPa) | Poisson’s ratio |
|-----------|----------|----------|--------------|-----------------|
| 1         | 1        | 1        | a            | a               |
| 2         | 1        | 2        | a            | a               |
| 3         | 1        | 3        | 186          | -0.483          |
| 4         | 2        | 1        | a            | a               |
| 5         | 2        | 2        | 228.99       | -0.576          |
| 6         | 2        | 3        | 260.86       | -0.388          |
| 7         | 3        | 1        | a            | a               |
| 8         | 3        | 2        | 301.89       | -0.539          |
| 9         | 3        | 3        | 335.08       | -0.404          |

*a Infeasible assembly

These parameters are assigned 3 levels to determine the optimum combination (Table 1). The desired functionality of the unit cell is to provide the maximum negative Poisson’s ratio with minimal induced stress, while subjected to an external force. L9 orthogonal array is used to analyse feasible test cases (Table 2). A compressive load of 25 N is applied in the axial direction of the cubic unit cell with its bottom link fixed (Figure 5). Tests are conducted with the combinations shown in the orthogonal array to identify the combination that provides the desired output.

4. Results and discussions
The optimal combination of the factors and levels were determined through analysis. Not all test cases could be analysed, as test cases 1, 2, 4 and 7 rendered an infeasible assembly for the combination of link length and link angle. A link length of 25mm and a link angle of 70° provides the favorable output with a Poisson ratio of -0.576 and an induced stress of 228.99 MPa. Based on the findings the first prototype is fabricated (Figure 6). The proposed model has good scope to be scaled. This is possible by connecting just one link in the direction to be scaled as shown in Figure 6.
5. Conclusion
Designing an auxetic structure that provides the maximum negative Poisson’s ratio is always desired. But, fabricating such a complex geometry may at times be infeasible. Both, auxetic nature with manufacturing feasibility needs to be considered while designing the auxetic geometry. This article has proposed a new re-entrant cubic unit cell that has potential for mass production using conventional machines. The newly designed auxetic structure is analysed to determine the optimal geometry while retaining its auxetic nature. The repeating units in this auxetic structure is designed to be easily fabricated using standard raw materials. This new re-entrant cubic auxetic structure can also be scaled without compromising its functionality.

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