Available online at www.sciencedirect.com

ScienceDirect

Procedia Structural Integrity 35 (2022) 247–253

Structural Integrity Procedia

www.elsevier.com/locate/procedia

2nd International Workshop on Plasticity, Damage and Fracture of Engineering Materials

Analysis of Stress and Strain in the Tetrachiral Metamaterial with Different Kinds of Unit Cell Connections

L.R. Akhmetshin[a,b]*, I. Yu. Smolin[a,b]

[a]*Institute of Strength Physics and Materials Science of Siberian Branch of Russian Academy of Sciences,*
2/4 Akademicheskii pr., Tomsk, 634055, Russia
[b]*Tomsk State University, 36 Lenin ave., Tomsk, 634050, Russia*

Abstract

Metamaterials are artificially created materials whose unique properties are due to their structure rather than the chemical composition of the base material. The unit cells form the basis of a metamaterial. When creating the metamaterial, one should distinguish the methods of connecting its unit cells. The paper considers two methods of unit cell connection in a three-dimensional metamaterial—joining and overlapping. Connecting the cells in the metamaterial by joining method may lead to a differently directed rotation of the rings, which will have a negative effect on the entire sample of the metamaterial. In the case of the other connection method, there is no differently directed rotation, so it would appear reasonable that creating a sample of a metamaterial by this method would achieve greater values of twist. The asymmetric deformation pattern is investigated in this work. For the two methods considered, also different results were obtained on stress distribution and strain localization in the sample under uniaxial loading. In the system of two cells in the metamaterial obtained by the joining method, an additional center of localization of deformation occurs at the junction of the two edges, which make up the tetrachiral element.

Keywords: Mechanical metamaterial; chirality; joining; overlaping; numerical simulation; twist.

---

* Corresponding author. Tel.: +7-953-923-8013 ; fax: +7-382-249-2576 .
E-mail address: akhmetsin.lr@gmail.com

10.1016/j.prostr.2021.12.071

1. Introduction

Metamaterials are artificially created materials. Their unique properties are determined by their structure rather than the chemical composition of the base material. Metamaterials are subpart into optical, acoustic, mechanical, and others according to their field of application as pointed out by Tan et al. (2019) and Bertoldi et al. (2017). Mechanical metamaterials are characterized by unusual mechanical properties. Yu et al. (2018) indicate that mechanical metamaterials are classified into three main groups according to their elastic constants rather than their composition (metals, ceramics, or polymers). The classification was based on the fundamental mechanics of materials.

Comparing a material and a metamaterial, an analogy can be drawn between them based on the lattice structure. A material is based on a strictly ordered arrangement of atoms, while in a metamaterial the atoms are replaced by unit cells. The building blocks of mechanical metamaterials deform, rotate, bend, fold, and snap in response to mechanical forces, and are designed so that adjacent building blocks can act together to create the desired collective behavior. Among other types of metamaterial, lattice structures achieve the highest efficiency due to their lower specific gravity (Cummer et al., 2016). In recent years, research interest in cellular metamaterial structures has expanded from purely mechanical to general physical, chemical, and biological properties.

Among the types of metamaterial structures, chiral structures are very popular. This structure can be designed as a left or right handed material (Grima et al., 2008). A simple chiral element has a central ring and ligaments extending from it (Prall and Lakes, 1997). The number of ligaments will determine the name of the chiral structure.

For the first time, the sample of a metamaterial consisting of the cellular tetrachiral structures was obtained in the work by Frenzel et al. (2017). The authors showed an unusual effect consisting in the twisting of the rod sample. The obtained result is an analogue of optical activity and is denoted as “mechanical activity”.

If we talk about the damping properties of products made of mechanical metamaterials, their application is promising for various industries, in particular, their use for the conversion of mechanical waves arouses interest. The small-scale metamaterials help concentrating and effectively absorbing energy (Tan et al., 2019). Such metamaterials have been accepted as optimal candidates for use in flexible aircraft structures and as analogues of spokes in non-pneumatic tires. In biomedical engineering, there are many possible applications for the use of metamaterials, such as prostheses, implants, stents, scaffolds, dilators, sutures, ligament/muscle retainers, bandages, and orthopedic linings (Bhullar et al., 2015).

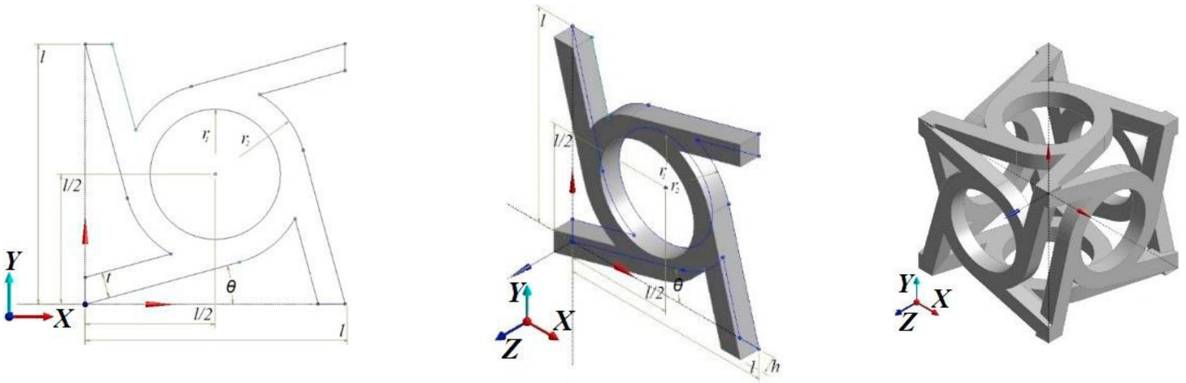
The development of products from mechanical metamaterials is given special relevance by the advances in the development of modern 3D printing technologies. The 3D production technologies are promising and competitive compared to traditional ones due to high productivity and the ability to create parts with complex geometry to achieve previously inaccessible properties (Kweun et al., 2017).

Connecting cells in mechanical metamaterials has not been described in the works known to the authors. Recovering this information is a significant problem. As a consequence, it is not known how cell bonding can affect strain localization and stress distribution in the sample. The purpose of this work is to investigate the knowledge gap on connecting the elementary cells of a metamaterial to create a three-dimensional pattern and the effect of this on the localization of deformations. Mathematical modeling in this case acts as a good tool. Numerical calculations save time in producing samples for full-scale testing, as well as saving the cost of full-scale testing.

2. Base part

In order to create a three-dimensional sample from mechanical metamaterial, it is necessary to create an elementary cell in the form of the cube, which in turn consists of tetrachiral sides (Fig. 1). The geometric model was created in the Design Modeler module of the Ansys Workbench software package.

Chirality is a property of asymmetry. An object or a system is chiral if it is distinguishable from its mirror image. Tetrachirality means that the structure contains the ring and four ligaments connected tangentially to the ring and interacting with other cells. After the unit cell is created, it must be replicated to create the sample. As was found out and will be shown in this paper, the arrangement of the unit cells plays an important role in the deformation behavior of the metamaterial sample.



a b c

Fig. 1. Construction of the metamaterial: (a) sketch of the chiral element, (b) two-dimensional structure, (c) unit cell of the metamaterial.

The two-dimensional chiral element is shown in Fig. 1b. The parameters determining the geometric dimensions of the unit cell are as follows: l is the length of the unit cell, t is the width of the ligament, h is the thickness of the ligament, r_2 is the outer radius of the ring element, r_1 is the inner radius of the ring element, θ is the slope angle of the ligament. The angle θ is plotted between the metamaterial ligament and the horizontal plane and is dependent on the parameters r_2 and l, calculated as:

$$\theta = arccos\left(\frac{2R}{\sqrt{2}*L}\right) - 45°.$$

3. Mathematical statement

The problem of uniaxial loading of the mechanical metamaterial sample was solved in the case of linear elasticity theory. Hooke's law was chosen as the constitutive relation. The elastic constants used in this work are taken as, $E = 2.6$ GPa is Young's modulus, $\nu = 0.4$ is Poisson's ratio. The constants correspond to the material model of ABS plastic.

Numerical modeling was performed using the finite element method in the ANSYS software package. The unit cell is treated as the system of beams which are modeled as a set of three-dimensional solid elements in the finite element calculations.

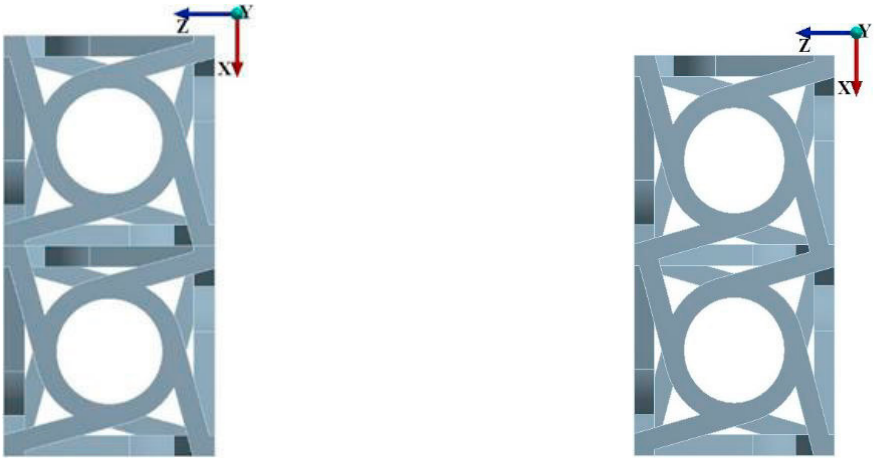
To analyze the behavior of the metamaterial sample under uniaxial loading conditions along the longest dimension of the sample, the boundary conditions were applied as follows:

$$U_x^{bot} = U_z^{bot} = U_z^{bot} = 0,\ U_y^{top} = 3u.$$

These equations mean a fixed constraint of the bottom face of the sample and a predefined displacement of the top face. The displacement is given as a function of the parameter u. The displacement can be specified with a plus or minus sign, which leads to tension or compression, respectively. For the given values of the metamaterial structure parameters, a displacement of 1.5 mm corresponds to the 3 % uniaxial deformation of the metamaterial sample. The deformation appears to be small for the applicability of the elasticity theory and the limitation of displacements that do not lead to contact interaction of the constituents of the unit cell structure.

4. Methods of connection of the unit cells

The unit cells form the basis of a metamaterial. When creating the metamaterial one should distinguish the methods of connecting them (Fig. 2). The simplest method is "joining" one cell to another, as shown in Fig. 2a.



a b

Fig. 2. Methods of connecting cells in the metamaterial, (a) “joining”, (b) “overlapping”.

This method involves connecting one unit cell to second. Another method to connect unit cells is based on overlapping edges of adjacent cells, as presented in Fig. 2b. This type of connection is denoted as “overlapping”. One can see that a side of the first cell is also a side of the other cell. This method is characterized by the merging of sides from neighboring cells at the junction place.

The differences in the methods of connecting the unit cells are noticeable even at the connection of two cells. It can be seen that with the “joining” method, there is a doubling of thickness in the area where the two cells are joined. In the method of “overlapping”, no thickening occurs and this method will likely be more economical, due to the absence of some cell faces.

5. Results and discussion

5.1. Distinction in the methods connecting the two cells

Tetrachirality, based on the ring and four ligaments, allows the spinning of two-dimensional structures along some direction. This suggests that when a uniaxial load is applied (compression/stretching), an additional degree of freedom appears, namely the rotation of the ring (Fu et al., 2017). Due to the rotation of the ring, the distance between other elements of the same plane will be reduced.

Let us conside a system of two unit cells with a chiral structure, which will be twisted (Fig. 3). To analyze the mechanical twisting motion, consider the area of unit cell connection. The arrangement of cells in the metamaterial in the “joining” way may lead to a multidirectional rotation of the rings of elementary cells of the metamaterial, which is shown in Fig. 3 a. Moreover, the differently directed rotation will occur in one plane, which will have a negative effect for the sample of the metamaterial completely. In the case of “overlapping” cell connection, there is no unidirectional rotation, so it would appear natural that creating a metamaterial sample by the “overlapping” method will achieve greater values of twist (Fig. 3b).

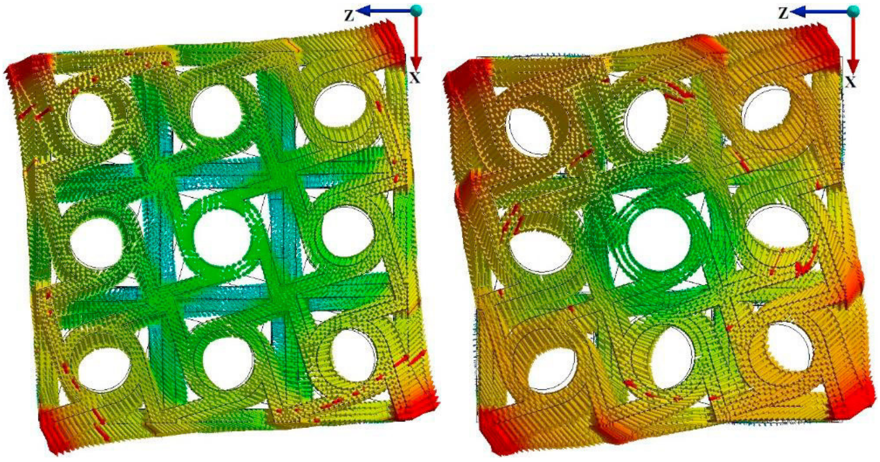
Let us consider the rotation in the system of two elementary cells of the metamaterial obtained by “joining”. The oppositely directed rotation of the intersecting faces in a system of cells joined by the “joining” method, reduces the twisting effect of the structure. In a two-cell system, there is a difference between the “joining” and “overlapping” methods. In a system of two cells joined by “overlapping”, there is no unequal directionality. This plays to our advantage when we need to increase the angle of twist. But this effect also has the disadvantage that one of the cells loses its stability, which is not seen in a system of two cells joined by “joining”. This effect can be clearly seen in Fig. 3 as an asymmetric picture of the mechanical behavior of the lower cell for the “overlapping” method (highlighted in red square).

a b

Fig. 3. Asymmetric deformation behavior in the system of two cells created by (a) “joining” and (b) “overlapping” methods.

5.2. Distinction in the methods connecting the nine cells

After the results on asymmetric mechanical behavior, it was suggested that this effect is related to the fact that there is a lack of a sufficient number of supporting faces. In other words, an odd number of faces under uniaxial loading resists the loss of stability worse, and, as a consequence, the deformation is asymmetric. It was decided to take a system consisting of 9 cells (3×3) because the number of cells in each axis should be the same in three orthogonal axes. By the corresponding displacement vectors of the elementary cells, we can assume that the mechanical behavior must be symmetrical in both methods. The assumption was confirmed, asymmetric deformation disappears at a certain position of the cells, which can be seen in Fig.4.



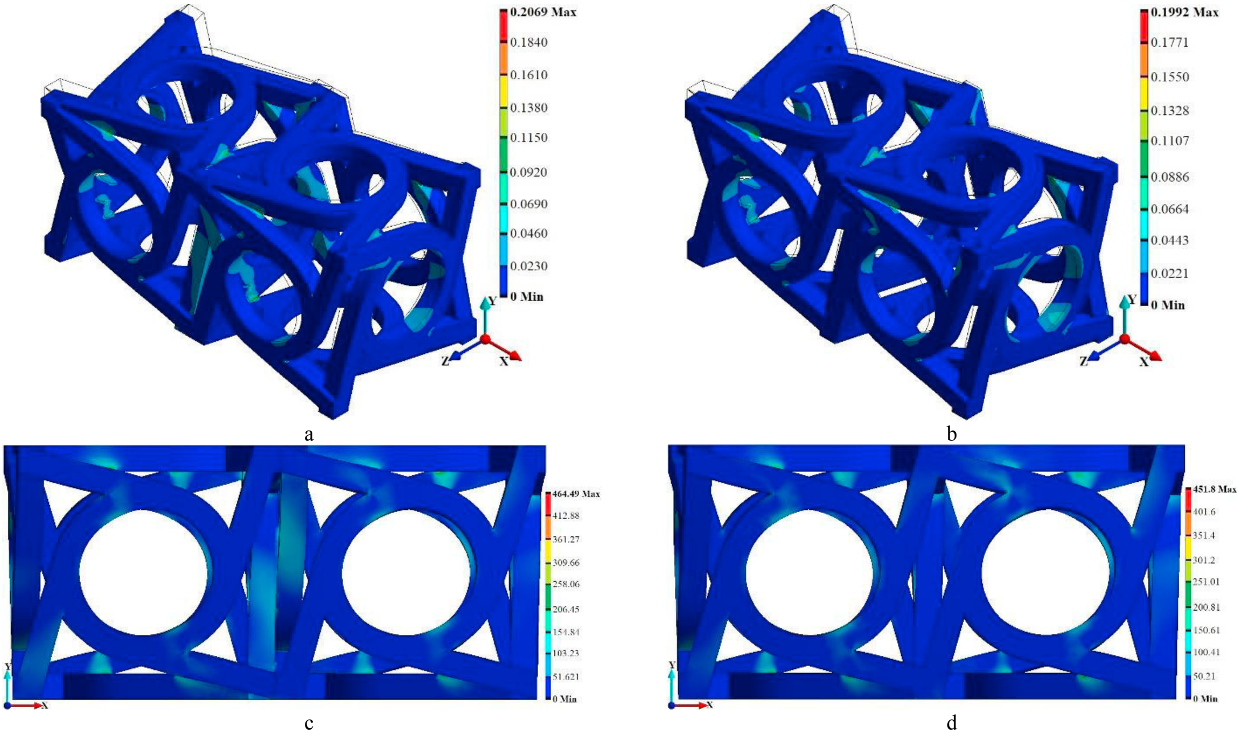
a b

Fig. 4. Symmetric deformation behavior in the system of 3×3 cells created by (a) “joining” and (b) “overlapping” methods

5.3. Strain and stress analysis

It is a well-known fact that the main concentrators of stresses and localization of deformation are the joints of the elements of the structure. In this metamaterial structure, these are the areas where the ligaments and the ring join, as well as where two ligaments touch each other perpendicularly. It is interesting that during uniaxial compression of the system of two elementary cells, the strains and stresses take minimum values in the ligaments. This effect can be attributed to the twisting mechanism of the ring, the strains are evenly distributed along all four ligaments. Due to ring twisting, strains are found in the tetrachiral unit cell in the ring element (Fig. 5a, b) in both joining and overlapping methods. This is due to the fact that at the moment of uniaxial loading, the ring deforms more than the ligaments and these deformations are similar to bending deformations. This effect was also noted by Akhmetshin and Smolin (2020), where a rod of similar structural cells is considered. In addition, in the system of two cells in the metamaterial obtained by the "joining" method, an additional center of localization of deformation occurs at the junction of the two edges, which make up the tetrachiral element (Fig. 5a). The character of the deformations is also similar to the deformations during bending. This can be understood as the effect of one cell on the second cell and vice versa.

ANSYS software package allows one to analyze different parameters of stress state during structural analysis. Equivalent stresses (von Mises stress) are of especial interest due to the importance of shear stress for ductile materials. Considering quantitative values of equivalent stresses, we note that the values of stresses arising in the system of two cells connected by the "overlapping" method are less than in "joining". In the case of the response of a rigidly fixed cell face, the support reaction in different methods of cell connection is also different. In the "joining" method, it is necessary to apply 2 times more forces than in the "overlapping" method for a similar displacement of the upper face. This is due to the inability of the structure to freely deform by twisting the ring.



a b

c d

Fig. 5. Distribution of (a, b) strains and (c, d) equivalent stresses in the system of two cells created by (a, c) "joining" and (b, d) "overlapping" methods.

6. Conclusion

In conclusion, we have considered the static way of loading a system of elementary cells of a metamaterial within the framework of linear Cauchy elasticity theory for the case of three-dimensional homogeneous chiral cell structures, which have become the subject of recently published numerical papers on mechanical metamaterials. We found that the deformations are localized in the ring elements of chiral structures and are not localized in the ligaments. It has been shown that deformations occur when two cells influence each other in the “joining” method. The advantages and disadvantages of each of the joining methods in the two-cell system have been described. In the “overlapping” method, the rotation angle is greater than in the “joining” method, but the cells connected by the “joining” method are more stable.

Mathematical modeling by the finite element method is acceptable for predicting the deformation behavior of a mechanical metamaterial sample. In a general sense, the dream of materials science is to design materials rationally to avoid tedious trial and error experiments.

In this paper, a new type of metamaterial cell connection is developed by eliminating anti-twisting edges and understanding the direction of motion. When the metamaterial is subjected to uniaxial loading directed along the rod, cell deformation will cause the chiral structures to rotate. We believe that this technological advance will make it possible in the future to achieve the required mechanical behavior according to customer requirements.

The main results of this paper concern the analysis of the distributions of stresses and strains in a loaded sample made from a mechanical metamaterial. This is a necessary base for the evaluation of possible damage and fracture in these materials. The main stress concentrators and loci of strain localization are the joints of the structure elements. In this metamaterial structure, these are the areas where the ligaments and the rings join, as well as where two ligaments touch each other perpendicularly. In addition, in the system of two cells in the metamaterial obtained by the “joining” method, an additional center of strain localization occurs at the junction of the two ligaments, which make up the tetrachiral element.

Perhaps this work will be helpful in solving some problems of topological optimization of the metamaterial’s microstructure (Köpfler et al., 2019). It will be interesting to see future in-situ experiments.

Acknowledgement

The work was performed according to the Government research assignment for ISPMS SB RAS, project FWRW-2019-0035.

References

Akhmetshin, L. R., Smolin, I. Yu., 2020. The Localization of Deformations in Mechanical Metamaterial with a Twist. Numerical Investigation. AIP Conference Proceedings 2310, 020008. doi: 10.1063/5.0034083

Bertoldi, K., Vitelli, V., Christensen, J., Hecke, M., 2017. Flexible Mechanical Metamaterials. Nature Reviews Materials 2, 17066. doi:10.1038/natrevmats.2017.66

Bhullar, S.K., Lala, N.L., Ramkrishna, S., 2015. Smart Biomaterials - a Review. Review on Advanced Materials Science 40, 303–14.

Cummer, S. A., Christensen, J. and Alù, A., 2016. Controlling Sound with Acoustic Metamaterials. Nature Reviews Materials 1, 16001.

Frenzel, T., Kadic, M., Wegener, M., 2017 Three-Dimensional Mechanical Metamaterials with a Twist, Science 358(6366), 1072–1074. doi: 10.1126/science.aao4640

Fu, M.-H., Zheng, B.B., Li, W.-H., 2017. A Novel Chiral Three-dimensional Material with Negative Poisson’s Ratio and the Equivalent Elastic Parameters, Composite Structures 176, 442–448. doi: 10.1016/j.compstruct.2017.05.027

Grima, J.N., Gatt, R., Farrugia, P.-S., 2008. On the Properties of Auxetic Meta-Tetrachiral Structures. Physica Status Solidi (B) 245, 511–520. doi: 10.1002/pssb.200777704

Köpfler, J., T. Frenzel, Kadic, M., Schmalian, J., Wegener, M., 2019. Topologically Protected Twist Edge States for a Resonant Mechanical Laser-Beam Scanner. Physical Review Applied 11, 034059. doi: 10.1103/PhysRevApplied.11.034059

Kweun, J. M., Lee, H. J., Oh, J. H., Seung, H. M., Kim, Y.Y., 2017. Transmodal Fabry-Pérot Resonance: Theory and Realization with Elastic Metamaterials. Physical Review Letters 118, 205901-1–205901-6. DOI: 10.1103/PhysRevLett.118.205901

Prall, D., Lakes, R.S., 1997. Properties of a Chiral Honeycomb with a Poisson’s Ratio of −1. International Journal of Mechanical Sciences 39(3), 305–314.

Tan, T., Yan, Zh., Zou, H., Ma, K., Liu, F., Zhao, L., Peng, Zh., Zhang, W., 2019. Renewable Energy Harvesting and Absorbing via Multi-Scale Metamaterial Systems for Internet of Things. Applied Energy 254, 113717

Yu, X., Zhou, J., Liang, H., Jiang, Zh., Wu, L., 2018. Mechanical Metamaterials Associated with Stiffness, Rigidity and Compressibility: A Brief Review. Progress in Materials Science. 94, 114–173. doi: 10.1016/j.pmatsci.2017.12.003