Computational simulation of fracture behaviour in auxetic cellular structure by multiaxial loading

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Abstract. A computational simulation of fracture behaviour in auxetic cellular structure, subjected to multiaxial loading is presented in this paper. A fracture behaviour of the 3D (three-dimensional) chiral auxetic structure under multiaxial loading conditions was studied. The computational models were used to study the geometry effect of the unit cell on the Poisson's ratio and fracture behaviour of the analysed chiral auxetic structure. A 3D computational model was built using FEM-code LS DYNA. The discrete computational model of chiral auxetic structure was built using beam finite elements. The lattice model of the analysed auxetic structure was positioned between rigid plates and assembled in a way to simulate a hydro-compression loading conditions. Between the contacting surfaces interactions in normal (contact) and tangential direction (friction) with the node-to-surface approach were simulated. A developed computational model offers insight in the fracture behaviour of considered auxetic cellular structure and helps to better understanding their crushing behaviour under impact multiaxial loading.

1 Introduction

Cellular structures are a relatively new class of materials in modern engineering practice. These materials represent a unique opportunity for adoption in lightweight structures, which are useful in advanced structural applications. Cellular structures offer additional advantages, such as sound insulation and damping, mechanical energy absorption, durability, etc. [1]. In modern engineering practice cellular structures are mainly used as core of a composite sandwich structures and, consequently, offer very good energy absorption to weight ratio [2], [3]. The new type of cellular structures are auxetic cellular structures, which are new type of meta-materials which exhibit negative Poisson's ratio. The negative Poisson's ratio is a consequence of kinematic moving of the parts of geometry of the structure when an external load is applied [4]. The negative Poisson's ratio offers that the auxetic material flows in the direction of the impact zone [5] and does not flow away from the impact zone compared to the conventional cellular materials. The flow in the direction of the impact zone is one of the most important advantageous characteristics of the auxetic materials in impact engineering and blast protection. Based on this, the auxetic cellular structures have huge potential applications in aerospace engineering, the automobile industry, construction, etc. [6]–[10].

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In the last few decades, a numerous studies in the field of auxetic cellular materials were done. Bückmann et al. [11] investigate quasi-static elastic behaviour of 3D crystalline mechanical metamaterials with negative Poisson's ratio at very small strains. Novak et al. [12] investigated the effect of the porosity, loading direction and strain rate on the mechanical properties of auxetic cellular structures built from inverted tetrapods. The same author in the article [13] experimentally and computationally investigated the effect of the porosity on the crushing behaviour of graded auxetic structures built from inverted tetrapods. Kramberger et al. [14] experimentally and numerical investigated the effect of the shape and distribution of unit cells on the fracture behaviour of 2D (two-dimensional) auxetic cellular structures, under quasi-static loading conditions. Experimental and numerical results have shown that the shape and distribution of unit cells play a significant role in the direction of crack propagation in auxetic cellular structures.

This study is based on the previous research work presented in [2] where a computational model of chiral auxetic structure was built and validated. In this study, the validated computational model was used as a basis for the computational investigation of a fracture behaviour of the 3D chiral auxetic structure under multiaxial loading conditions.

2 Computational analysis

In this section, a computational model of chiral auxetic structure is presented. The computational study is performed using FEM-code LS DYNA. The computational model of chiral auxetic structure is validated based on the uniaxial compression experimental tests which were previously presented in the article [2]. To introduce the multiaxial loading conditions, four rigid plates are considered in treated computational model (see section 2.2).

2.1 Geometries of chiral auxetic structures

In the computational analyses seven different geometries of chiral auxetic structures are considered. The difference between them is the amplitude of the unit cell A which affect on the Poisson's ratio of the structure. The geometry of the unit cell is shown in Fig. 1a, where the struts take the sinusoidal shape, whose turning points meet in the nodal points [2]. The geometric parameters of the unit cell are the following: a nodal distance in horizontal (L_{hor}) and vertical (L_{ver}) directions, amplitude (A_i) and strut thickness (d). In this study, seven different amplitudes of unit cell were selected (from 0 mm to 1.5 mm with a step of 0.25 mm). For each analysed case, the thickness of strut and nodal distance in horizontal and vertical direction was the same for each case (dimensions $L_{\mathrm{ver}} = L_{\mathrm{hor}} = 5$ mm, $d = 0.5$ mm and A = different for each case). Fig. 1 shows seven geometric shapes of chiral auxetic structures which were analysed in this parametric study.

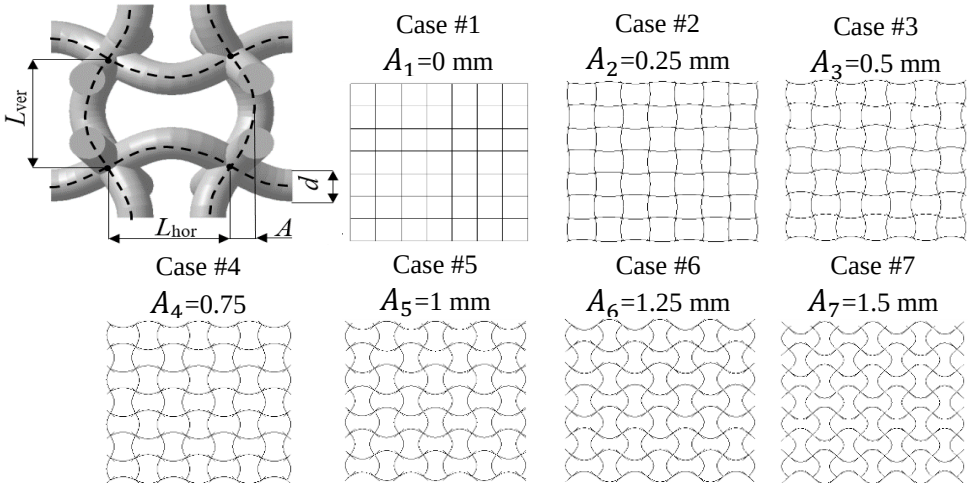


Fig. 1: The geometry of chiral auxetic specimens

2.2 Material model and boundary conditions

2.2.1 Material model

In the computational analysis, the material model (MAT_024) was used to describe the constitutive behaviour of the base material of analysed chiral auxetic structures [15]. This material model is a combination of damage and failure model (MAT_ADD_EROSION). The material parameters which were used in the material model for chiral auxetic structure are presented in Table 1. The parameters are as follows: density ρ, Young's modulus E, Poisson's ratio ν, initial yield stress σ_{yield}, the definition of linear hardening with second point in the stress-strain diagram (σ_2, $\varepsilon_{pl,2}$), and the critical strain ε_{crit}, which defines the start of material damage.

Table 1: Material parameters for auxetic chiral structure

ρ [kg/m^3]	E [MPa]	ν [-]	σ_{yield} [MPa]	σ_2[MPa]	$\varepsilon_{pl,2}$ [-]	ε_{crit} [-]
4430	120000	0.3	1300	1800	0.8	0.15

All six compression plates (top/bottom, back/front and left/right) were modelled using a linear-elastic material model (MAT_ELASTIC). The material parameters which were used in the material model for plates are presented in Table 2.

Table 2: Material parameters for plates

ρ [kg/m^3]	E [MPa]	ν [-]
7850	210000	0.3

2.2.2 Boundary conditions and the finite element mesh

The geometry of chiral auxetic structure was discretised with beam finite elements with cross-section integration. The mesh sensitivity analysis was performed on three different finite element mesh densities [2]. The global size of beam finite elements 0.5 mm was assumed. The total number of beam finite elements representing the chiral auxetic structure was around 11,000. The compression plates were discretised with shell finite elements, with 2 through shell thickness integration points and the thickness of 1 mm. The number of shell finite elements for each plate was 100.

The boundary conditions were prescribed on the compression plates. The constant velocity of 100 mm/s was prescribed in normal direction at the upper, left and back plate to perform

the compression loading, while the other three plates (bottom, right and front) were constrained in all degrees of freedom. In previous work [2] authors used parametric analysis to determine the acceptable increase in the velocity comparison to the experimental quasi-static testing. The acceptable increase in the velocity has been determined by comparing mechanical response (reaction forces) on the bottom and top plates at different loading velocities. The computational model is presented on Fig. 2.

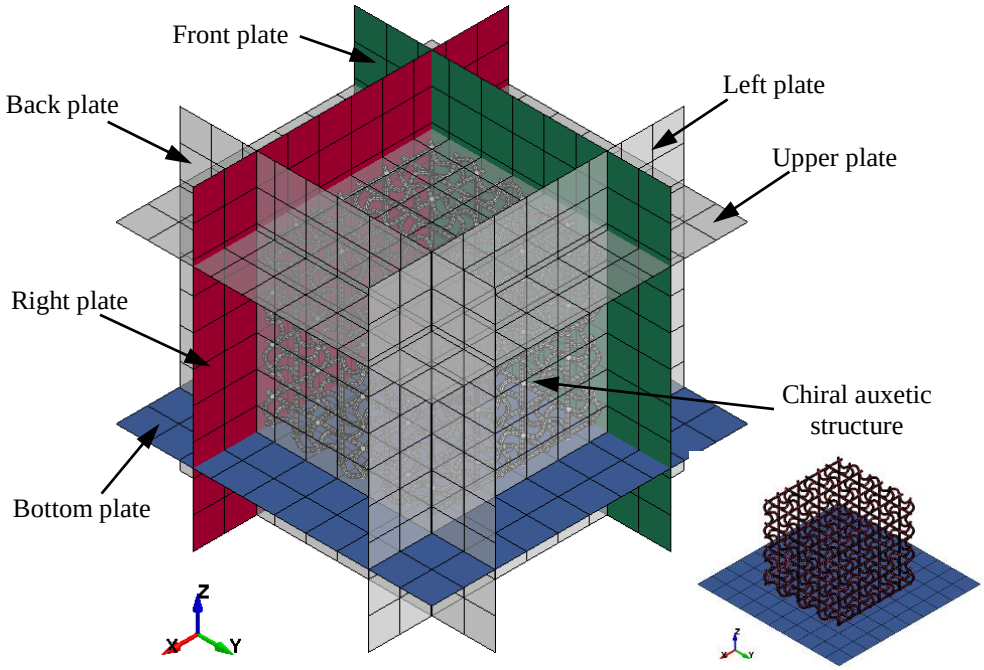


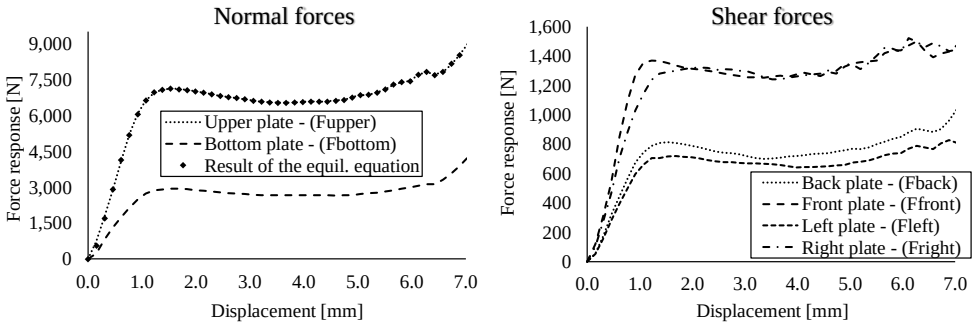
Fig. 2: Computational model

The contact between auxetic structure and plates was formulated in normal and transverse direction with consideration of static and dynamic coefficient of friction. In this parametric study, the value of static coefficient of friction was $\mu_{fr,stat} = 0.36$ and dynamic coefficient of friction was $\mu_{fr,dyn} = 0.34$. The general contact with friction was defined also between struts (beam finite elements) [2].

3 Computational results and parametric study

3.1 Multiaxial loading

The computational model for multiaxial loading of chiral auxetic structure was built based on the successfully validated computational model presented in [2]. In this study the effect of different amplitude of chiral auxetic structures on mechanical response was studied. Computational results of the geometric case #5 of chiral auxetic structure are presented in Fig. 3. Computational results have shown that the force response is the same for each pair of the compression plates, therefore only the force response at the upper and bottom panels is described in the subsequent analysis. Fig. 3a shows absolute values of the force response at the upper and bottom plates in a loading direction (z – direction). The difference between force response at the upper and bottom plates is a consequence of a coefficient of friction between structure and plate surface. The consequence of coefficient of friction is reflected as shear forces in z – direction at the other four plates (left, right, front and back plates), which are shown on Fig. 3b.



a) **Fig. 3**: Computational results b)

In the computational analysis it was assumed that the normal force at the upper plate is equal to the sum of all shear forces and normal force at the bottom plate which leads to the following equilibrium equation:

$$\sum F = 0 \quad \rightarrow \quad |F_{\text{upper}}| = \left|\sum F_{shear\ forces}\right| + |F_{\text{bottom}}| \tag{1}$$

On Fig. 3a the result of the equilibrium equation is presented. From the computational results it is evident that the friction coefficient has a large impact on the mechanical response. Therefore, the friction coefficient analysis between structure and plate surface is performed in the next paragraph.

3.2 Friction coefficient analysis

In this paragraph, the mechanical response of the chiral auxetic structure under quasi-static loading conditions was studied to determine the impact of the friction coefficient on the force response between upper and bottom plates. In parametric study, five computational simulations were performed with different friction coefficients. The values of the friction coefficients are given in Table 3.

Table 3: Material parameters for plates

Simulation 1		Simulation 2		Simulation 3		Simulation 4		Simulation 5	
$\mu_{fr,stat}$ [-]	$\mu_{fr,dyn}$ [-]	$\mu_{fr,stat}$ [-]	$\mu_{fr,dyn}$ [-]	$\mu_{fr,stat}$ [-]	$\mu_{fr,dyn}$ [-]	$\mu_{fr,stat}$ [-]	$\mu_{fr,dyn}$ [-]	$\mu_{fr,stat}$ [-]	$\mu_{fr,dyn}$ [-]
0	0	0.1	0.1	0.2	0.2	0.3	0.3	0.36	0.34

Fig. 4 shows the force response between upper and bottom plates dependence on the friction coefficient. The force response at the upper and bottom plates are the same in the case, when the value of static and dynamic friction coefficient were equal to zero. In this case, the shear forces at the other four plates (left, right, front, back) are also equal to zero. With increase of the friction coefficient, the reaction force at the upper plate increased and shear forces at the other four plates appeared.

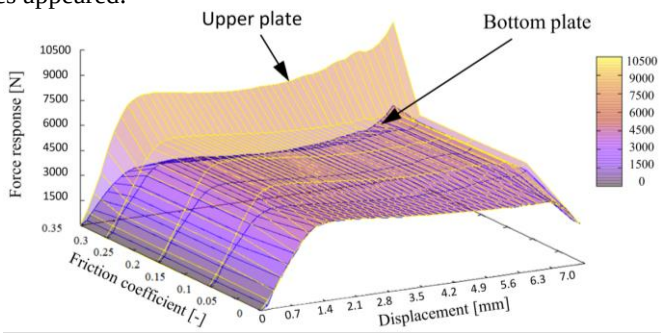


Fig. 4: The impact of the friction coefficient on the mechanical response

3.3 Parametric study

In this section, the computational model was used to study the geometry effect of the unit cell on the fracture behaviour of analysed chiral auxetic structures. A parametric study was carried out for seven geometric cases. The difference between the geometric cases are in amplitude of the unit cell of the chiral auxetic structure. The amplitude of the unit cell varied between 0 mm to 1.5 mm with step of 0.25 mm (Fig. 1). Values of the static ($\mu_{fr,stat}$ = 0.36) and dynamic ($\mu_{fr,dyn}$ = 0.34) friction coefficient were taken from [2].
Fig. 5 shows the computational results of the fracture behaviour of the three different geometric cases. From computational results the differences of the fracture behaviour can be seen. In the geometric case #1 where the amplitude of the unit cell is equal to zero, the struts fracture appears at the external edges of the structure while in the geometric cases #4 and #7 where the amplitude of the unit cell is greater than zero, the struts fracture appears inside the structure.

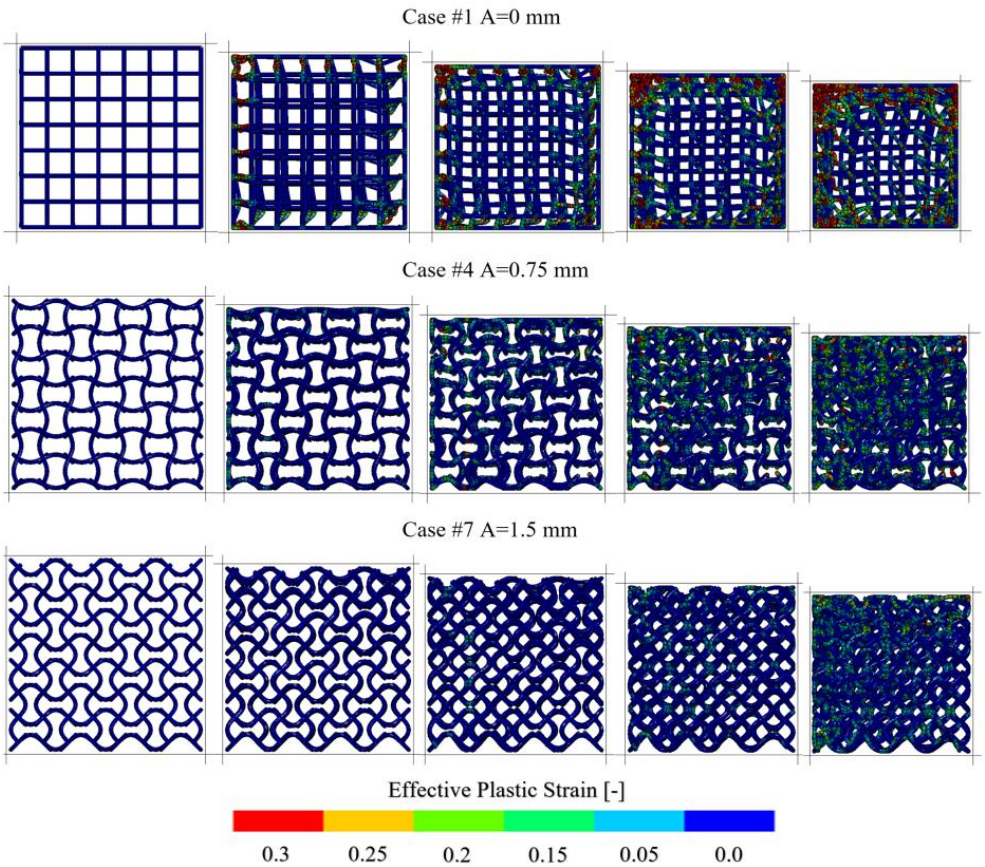


Fig. 5: The computational results of the fracture behaviour for three different cases (strain increment 5 %)

Fig. 6 shows the stress response dependence on the amplitude of the unit cell. The stress response was calculated from reaction force at the upper plate and nominal surface, which is different for each cases. The nominal surface was calculated with the following equation:
$S=N_c \cdot L_{hor} + 2 \cdot A_i + d$, where N_c is the number of unit cells in line, L_{hor} is the nodal distance in horizontal direction, A_i is the amplitude and d is the strut thickness.
Computational results show, that the highest stress response is in the case #1, when the amplitude of the unit cell of the chiral auxetic structure is equal to zero. This is due to the

fact that some struts are oriented normal to the loading plate and increase the stiffness with intense buckling instead of bending as it is the case for other geometries. From Fig. 6 is evident that the stress response decreases with increasing the amplitude of the unit cell while the Poisson's ratio of the chiral auxetic structure increases.

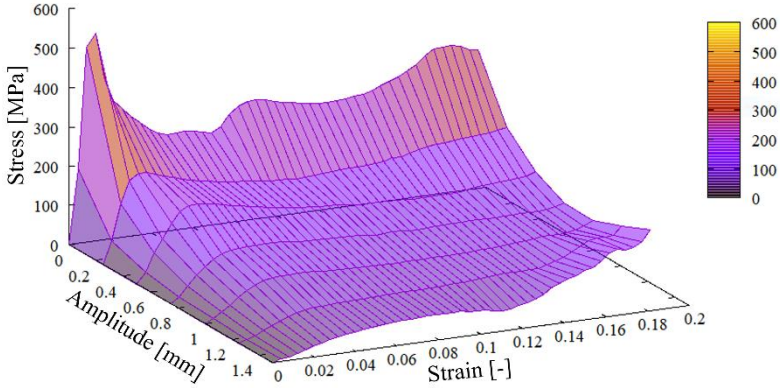


Fig. 6: The impact of the amplitude on the mechanical response

In a preliminary study [2], the deformation behaviour of the chiral auxetic structures was studied to determine the Poisson's ratio. In parametric study, 35 geometries of chiral auxetic structures were analysed. The geometries of the structures were different in the amplitude of the unit cell and the cell length. In parametric study, the values of the Poisson's ratio are in the range from –0.14 to –0.26 [2]. The auxetic effect is more intensive in the case, when the higher the amplitude and the smaller the cell length while the auxetic effect is small in the case where the amplitude is low and the cell length large [2].

4 Conclusions

The computational model for multiaxial loading of chiral auxetic structure was built based on the successfully validated computational models presented in previous work [2]. The validated computational model was used as a basis for the further computational investigation of a fracture behaviour of 3D chiral auxetic structure under multiaxial loading conditions. In this study, the effect of different amplitude of chiral auxetic structures on mechanical response was analysed. A parametric study was carried out for seven geometric cases. The difference between the geometric cases is in amplitude of the unit cell of the chiral auxetic structure.

The difference between reaction force at the upper and bottom plates is evident from computational results, which is a consequence of friction coefficient between structure and plate surface. Therefore, the friction coefficient analysis between structure and plate surface was performed. In friction coefficient analysis, five computational simulations were performed for different friction coefficients. Computational results showed that the force response at the upper and bottom plates are the same in the case, when the value of static and dynamic friction coefficient were equal to zero. In this case, the shear forces at the other four plates (left, right, back, front) are also equal to zero. With increase of friction coefficient value, the reaction force at the upper plate increased and shear forces at the other four plates appeared.

Furthermore, parametric study of multiaxial loading of chiral auxetic structures was performed. Computational results showed that the amplitude of the unit cell of chiral auxetic structure significantly influence on the stress response. The higher stress response is in the case, when the amplitude of the unit cell of the chiral auxetic structure is equal to zero. The

stress response decrease with increasing the amplitude of the unit cell while the Poisson's ratio of the chiral auxetic structure increase.

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