Proceedings of the Sixth International Conference on
Soft Computing, Machine Learning and Optimisation in
Civil, Structural and Environmental Engineering
Edited by: P. Iványi, J. Lógó and B.H.V. Topping
Civil-Comp Conferences, Volume 5, Paper 5.1
Civil-Comp Press, Edinburgh, United Kingdom, 2023
doi: 10.4203/ccc.5.5.1

# Shedding light on the impact-resisting mechanism of tension-torsion coupling metamaterials

**L. Meng and M. Zhong**

**School of Mechanical Engineering,**
**Northwestern Polytechnical University, China**

## Abstract

Tension-torsion coupling (TTC) metamaterials are man-made architectures demonstrating a counterintuitively rotational deformation under unidirectional load. Since their emergence in 2017, numerous studies have been carried out to verify the unique static properties originating from the twisting effect of TTC metamaterials. From the perspective of dynamic properties, even though the distinct advantage in impact resisting has been experimentally observed, the underlying mechanism remains unrevealed, and related investigations are conspicuously scarce. Herein, first-principle simulations are performed to provide a quantitative analysis of energy flow during the impact procedure and to shed light on the mechanism of energy damping and impact resistance. We demonstrate that the twisting effect of cellular material generally leads to weakened stiffness, and this is advantageous particularly for the improvement of impact mitigation. Also, we reveal that the unique chiral features of TTC metamaterials allow more strain energy to be stored during the impact, and this portion of the energy is ultimately dissipated by after-impact vibration. Lastly, energy dissipation by friction between lateral struts or ligaments, despite occupying a less significant position, is proven to be comprehensively enhanced in TTC metamaterials.

**Keywords:** TTC metamaterial, energy absorbing, impact-resisting, additive manufacturing.

# 1 Introduction

Sandwich structures cored by either random foams or periodic honeycomb/lattice structures have been widely employed in protective systems in marine, aerospace and transportation industries. Among different types of sandwich cores, lattice structure is at the cutting edge of research interest given the ultra-low density and high specific stiffness/strength [1, 2]. Enabled by the advanced additive manufacturing (AM) technique, the feature scale of lattice structure spans a wide range and the resulting mechanical properties characterize an excellent tunability [3, 4]. As such, lattice structures are recognized significant potentials in multifunctional applications and enjoy an overwhelming popularity in particular in impact resistant structure design [5].

A concise literature review shows that most, if not all, of the lattice structures rest their energy absorbing capacities mainly on either the plastic deformation and/or the crush damage of constituent struts [6]. In this consideration, Ma et al. [7] designed a pre-folded origami pattern and increased the energy absorption up to 29.2% by introduce stationary plastic hinges along the creases of the pattern. Similarly, a three-layered tube with pre-folded cores has been conceived in [8], and the reported results revealed an enhenced energy absorpiton capacity, in comparison with either the standalone composite circular tube or the stand-alone composite pre-folded tubes. More recently, metamaterials, one of the top ten advances in materials science over the past three decades [9], are reshaping the landscape of impact resistant sandwich structures. By tailoring the geometric configurations of architected lattice, new deformation modes have been introduced to various metamaterials and distinct energy absorbing mechanisms are triggered as well [10, 11]. Of particular interest in the research field is the negative Poisson's ratio (NPR) metamaterial and the tension-torsion coupling (TTC) metamaterials [12, 13].

Negative Poisson's ratio metamterials, also termed auxetic materials, generally take such popular configurations as re-entrant honeycomb, (double) arrowhead and star-shape and chiral architects [14]. They have been widely used in engineering fields due to its excellent fracture resistance, indentation resistance, sound absorption performance, among others [15, 16]. With regards to the anti-impact properties, some substantiated both numerically and experimentally that the NPR effect leads to an in-plane shrinkage under impact and promotes the flow of material towards the impact center, which by consequence involves more material to bearing the load (greater densification) [17]. However, others elucidated that, due to the irregularities in the auxetic rod, NPR metamaterials are not necessarily advantageous over conventional ones for very high impact and its strength can be rather limiting [18]. Despite the fruitful applications, the mechanism remains somewhat mysterious and further investigations are in urgent demand.

Most recently, the so-called tension-torsion coupling (TTC) metamaterials is gaining an ever-increasing popularity since its emergence in 2017 [19, 20]. Its peculiar deformation mode that transforms axial compression to rotation is intrinsically associated with the introduction of chiral feature [21]. Based on the micro-polar theory, the corresponding mechanical characteristic can be described by independent micro-polar elastic constants and the mechanical properties of 3D chiral metamaterial are further analyzed. Combining with the couple-stress homogenization approach, innovative 3D TTC chiral metamaterials have also be conceived using the advanced topology optimization technique [22].

The distinct energy absorbing capacity has been evidenced by a series of experimental results reported previously. For instance, it has been experimentally disclosed in our previous work [24] that the tension-torsion coupling effect does promote the impact resisting capacity of lattice-cored sandwich, despite that a quantitative relation between the chiral twisting behavior and the energy-absorbing capability of the lattice metamaterial have not yet been built. Qi et al. [25] combined the origami pattern with the chiral lattice, and conceived a pre-folded origami which enhanced the energy absorption capability. Chen et al. [26] explains this as a synergies of contributions from both the negative Poisson's ratio deformation and rotational deformation.

To uncover the mystery behind the impact energy dissipation mechanism of the TTC metamaterial, a reliable numerical model is established in the current work. A proof-of-principle study on 3D-printed architectures are carried out. The unvealed principles that promoting the energy absorbing capability shall open new avenues for impact-resistant architecture designs.

## 2 Methods

### 2.1 Dynamic Finite-element Simulations

In this current work, we start the investigation of the impact resisting mechanism of various lattice structures on account of a limited number of unit cells. Being particularly interested in the TTC metamaterial, we focus on a hyperbolic-chiral TTC lattice while setting the Body-centered-cubic (BCC) lattice as a baseline for comparison. For the sake of more firm conclusions, a quad-chiral TTC metamaterial is included in the investigation [19].

Fig. 1 illustrates the three considered unit cells as well as the stacked-up lattice assemblies, composing respectively of 4 × 1, 4 × 1, and 2 × 1 units. Readers are invited to note that, for comparison reasons, the same material usage is guaranteed for the comparative cases by adjusting the uniform rod diameters (the ligament width for the quad-chiral TTC unit).

Beyond the lattice assembly level, another attempt is made as well to examine a more realistic impact scenario on lattice-cored sandwich panels. Given the prohibitive computing cost, medium-size and full-size sandwich models are respectively investigated, while employing different numerical strategies. Note that the quad-chiral TTC unit and the BCC unit are easily populated along the in-plane directions, while a regular tessellation scheme developed in our previous work is adopted for the hyperbolic-chiral unit [24]. The lattice cores measure the same global dimension of 150 × 100 × 50mm3 . Two 1mm-thick cover sheets are then added to both sides of the lattice core to form the sandwiches, and schematic of the lattice-cored sandwich is presented in Fig.1(e), along which and the geometry of impact punch is presented.

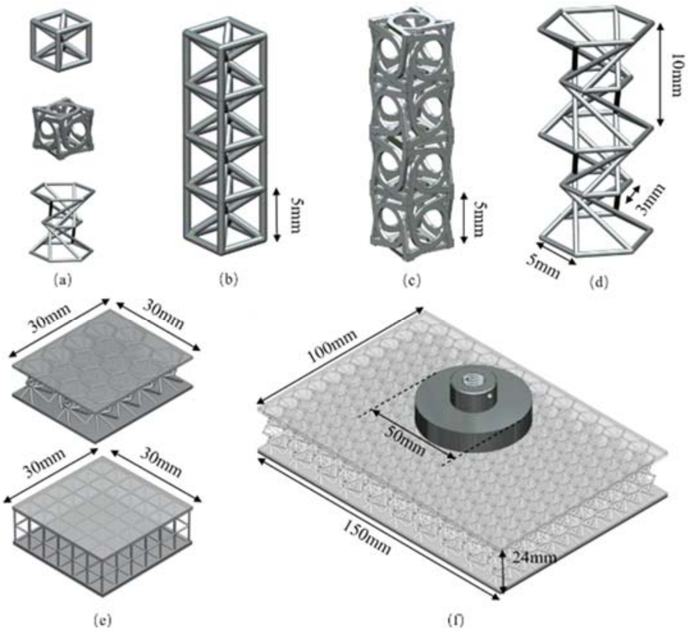

Figure 1: Geometric models of (a) three lattice units and (b)-(d) the corresponding lattice assemblies, composing of 4×1 BCC, 4×1 quad-chiral TTC and 2×1 hyperbolic-chiral TTC unit cells, respectively. (e) medium-size sandwich samples, and (f) full-size lattice-cored sandwich and the drop-weight punch.

## 2.2 Dynamic Finite-element Simulations

In the current work, we investigate the impact-resisting performance of various lattice structures in the scenario of a drop-weight test. As compared to the modelling of the impact punch and the cover sheets, particular attentions are required for the lattice core, given the considerable difference in the length scales of global and local characteristic features.

The choice of finite element shall depend upon the feasibility due to the prohibitive computing costs in impact simulation. In the current work, solid elements will be adopted in discretizing the lattice assemblies and medium size models, while beam elements are specifically chosen for analyzing the impact resistance of various sandwich plates. Such choice balances the accuracy and efficiency brought about respectively by the solid and beam elements, and it provides not only an accurate analysis of the impact-resisting mechanism in unit cell level, but also allows a further validation on a structural level with an affordable computing cost. It is added as well that modelling the truss-based lattice structures with the tapered beam element is advantageous and can be an alternative for the sake of a higher accuracy.

- FE model for lattice units

In this current work, the 10-noded modified quadratic tetrahedron element is adopted to discretize different types of lattice assemblies, and the resultant models are composed of respectively 13.3k, 13.5k and 12.6k solid elements for the BCC, quad-chiral and hyperbolic TTC unit assemblies. The elastic material properties adopted for the lattice are E= 2.2GPa and $\nu$ =0.39, corresponding to that of the photosensitive resin (density 1.15g/cm3 ) amenable to additive manufacturing. The plastic deformation is modelled by the stress-strain relationship obtained in an experimental manner.

The bottom of lattice assemblies are fixed to a rigid base. At the beginning of the impact, the top surface of the lattice assemblies is right in contact with the a rigid surface which models the projectile, and an initial impact speed of 2.2m/s is assigned according to its weight and the desired impact energy (20mJ). A general contact scheme is implemented for the whole model, with normal ‘hard’ contact selected and tangential contact characterized by a friction coefficient of 0.2.

- FE model for medium-size sandwich samples

For the modelling of impact test on the medium-size sandwich samples, the same material property is adopted for both the infilled core and the two cover sheets. Except for an impact energy of 160mJ carefully chosen to maintain a reasonable amount of deformation, the same boundary conditions are employed as to the lattice assembly case. Given the reduced size of the sample, the computing cost when using solid elements is still acceptable, and element type C3D10M is hence preferably adopted considering its accuracy as well as the presented contact behaviour in the model.

- FE model for sandwich plates

For the impact simulation of sandwich structure, a cylindrical punch is modelled by a rigid body of 4kg weight in the drop-weight test, and an impact energy of 15J is used. The initial impact velocity, 2.75m/s, is derived according to energy conversion. To avoid prohibitive dynamic simulations, 2-noded linear beam elements B31 were adopted for the lattice core, while 8-noded linear brick elements C3D8R with reduced integration were chosen for the cover sheets. Typical element size was set as 0.5, which is a compensation of analysis accuracy and efficiency. Mesh convergence for strength was observed at this element size or smaller. Both the cover sheets and the lattice core are modelled as aluminum and elastic constants are chosen to be E = 70GPa, and $\nu$ = 0.33. Plastic behaviour is characterized by the Jackson-cook parameters A = 324.1, B = 113.8, C = 0.002, n = 0.42 and m = 1.34, following [23]. A perfect bounding is assumed between the beam elements of the core structure and the cover panels, and the ‘Tie’ constraint is correspondingly employed. General contact is adopted as previous cases. Since the impact energy is considered so limited to damage the aluminium, no damage criterion is taken into account in this work.

### 2.3 Conservation of energy during the impact

During the impact process, the balance of entire energy E total of the system gives

$$E_{total} = E_v + E_{fd} + E_{ke} + E_i - E_w \tag{1}$$

in which $E_v$ is the viscous energy dissipated by damping mechanisms; $E_{fd}$ is the frictional energy dissipated, $E_{ke}$ is the kinetic energy, and $E_w$ is the work done by the externally applied loads. Notice that the internal energy, $E_i$ , sums up the recoverable elastic strain energy $E_e$ ; the energy dissipated through inelastic process, Ep; the energy dissipated through visco-elasticity or creep, $E_{cd}$ ; and the artificial strain energy, $E_a$, namely

$$E_i = E_e + E_p + E_{cd} + E_a \tag{2}$$

To capture the energy flow status during the impact process, the abovementioned energy quantities will be queried from the whole model for the sandwich core, the face sheets and the rigid punch, respectively.

## 3 Results

### 3.1 Impact results on lattice assemblies

Before turning to the complex sandwich models, we first carry out an investigation on the impact responses of the three lattice assemblies. To evaluate whether the dynamic impact analysis yields an appropriate response, we refer to both the energy flows and the impact curves during the whole simulation procedure.

Fig.2 depicts the impact force evolution queried from the modelled punch during the impact process. For all the three lattice assemblies, as observed, the impact force undergoes severe oscillations, which distinguishes dynamic deformations from static ones. Notably, compared to the non-chiral BCC lattice, both the quad-chiral and the hyperbolic-chiral TTC metamaterials significantly delayed the arrival of the peak impact force. Counting from the contact between the punch and the lattice sandwich panel until their separation, the impact times are hence 0.62ms (Non-chiral BCC), 1.16ms (Quad-chiral) and 6.57ms (Hyperbolic-chiral), respectively for the three lattice assemblies. The extended impact process as well as the mitigated peak impact force, from 150N to under 50N, together confirms the tendency of improved damping effect by the TTC metamaterials. Despite being drawn from the lattice assemblies rather than the lattice-cored sandwich, the conclusion is in perfect accordance with the experimental results in our previous study [24], and preliminarily validates the applicability of the simulation technique adopted in the current work.

Readers are invited to note as well that the impact curve in Fig.2 interprets mainly the behaviour of the impact punch, while that of the lattice assemblies are absent.

Hence, we further compare in Fig.3 and Fig.4 the displacement and stress evolution of diverse lattice assemblies during the impact process, respectively. It is underlined that the percentage values in the figures are adopted to distinguish different stages of the impact according to the vertical displacement of the impact punch, i.e., 0% denotes the initial contact of the punch with the sandwich, and 100% refers to the end of penetration (also the beginning of rebounding).

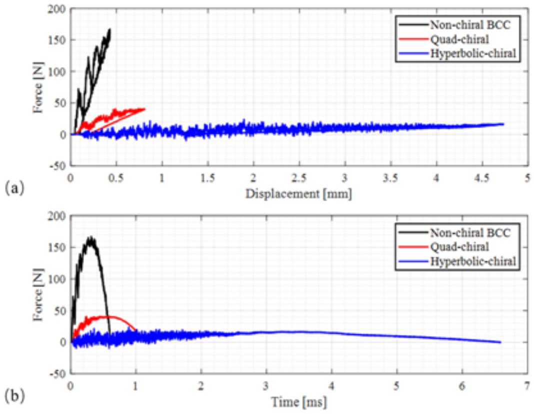

Figure 2: Impact responses of the three lattice assemblies: (a) Force-time curve, and (b) Force-displacement curve.

It can be observed that the non-chiral BCC lattice remains near intact during the process due to a bigger rigidity, and the chiral TTC lattice experienced a remarkable deformation given the compromised stiffness. The maximum penetration depth on the non–chiral BCC, hyperbolic-chiral and quad-chiral TTC lattice assemblies reach 0.43mm, 1.76mm, 4.69mm, respectively.

When referring to the stress evolution history in Fig.4, we notice as well that the chiral TTC metamaterials experience a considerable stress level over an enlarged region caused by the tension-torsion coupling effect, and this probably leads to more material to deform plastically. In sharp contrast, high stress level was observed mainly on the vertical struts as well as the intersection of oblique ones for the BCC lattice, and the global stress level was inferior to that of the TTC metamaterials. This difference could vary the energy absorption properties of different lattice assemblies.

Despite the distinct deformation during the impact process, we are aware that the after-impact behaviour of the lattice assemblies should be helpful for analysing the impact-resisting mechanism. Therefore, the displacements of the upper surfaces are also extracted until around 150% impact time (namely 1ms, 4ms and 10ms, respectively). The averaged vertical displacements of all the surface nodes are plotted against the impact time in Fig.5. It is noticed that, upon the separation of the striker with the lattice assemblies, this latter demonstrates an apparent vibration behavior. Since no damping effect has been included in the model, the amplitude of displacement does not attenuated along with the vibration. Despite that, this portion of energy will ultimately be dissipated in a realistic scenario, and this should be one of the key factors of energy dissipation in chiral lattice structures.

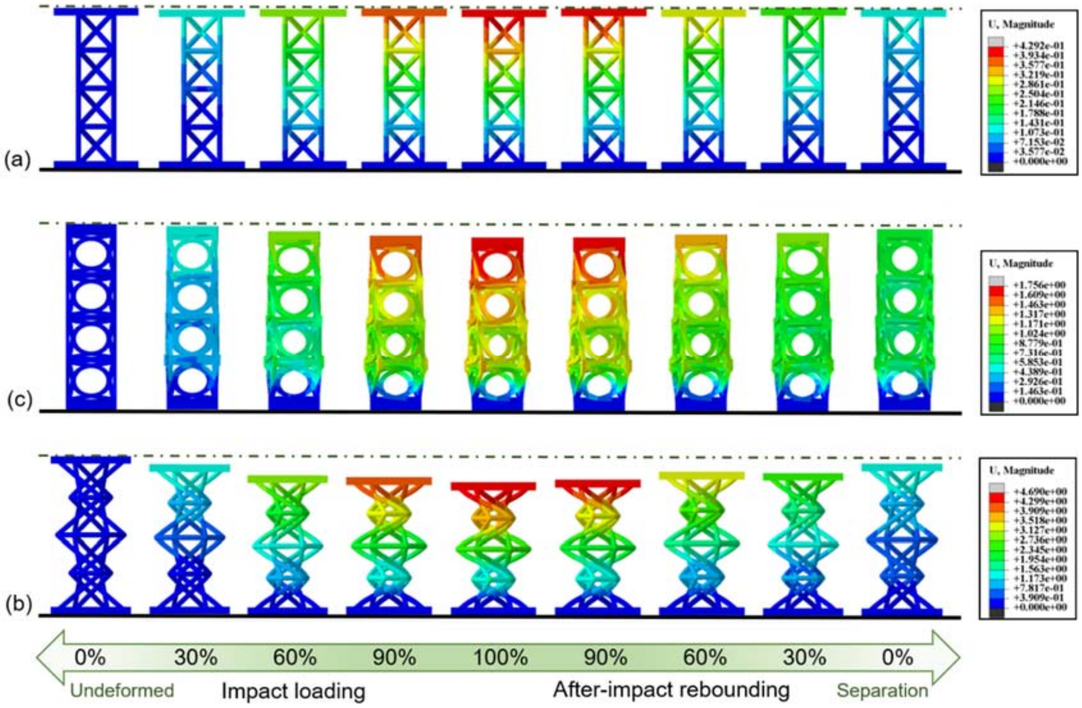

Figure 3: Displacement evolution on diverse lattice assemblies during the impact process: (a) the non-chiral BCC, (b) the hyperbolic-chiral TTC and (c) quad-chiral TTC (The dash-dotted lines indicate the undeformed surface).

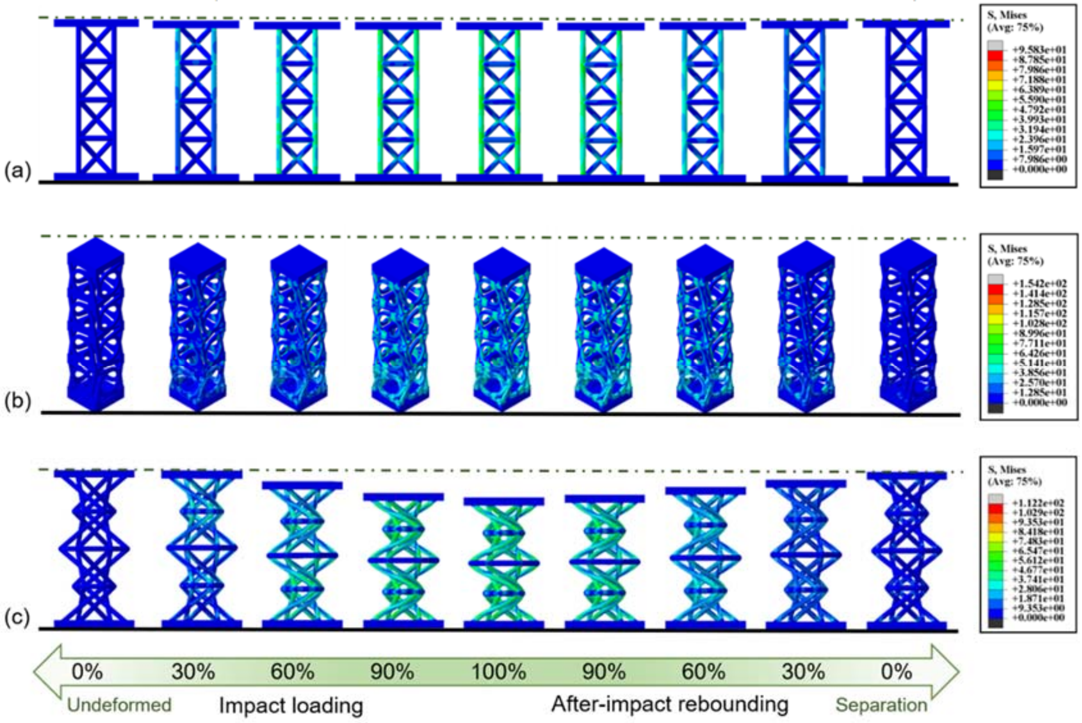

Figure 4: Stress evolution on diverse lattice assemblies during the impact process: (a) the non-chiral BCC, (b) the hyperbolic-chiral TTC and (c) quad-chiral TTC.

## 4 Conclusions and Contributions

In this work, a series of reliable numerical models have been developed to provide physical insights into the impact resisting mechanism of sandwich plates cored by various lattice (meta)materials. The correctness of the finite element models has been confirmed by the comparison with experimentally measured impact responses, i.e., impact force-time curve. Reported results have allowed to identify three principles which enhance the impact-resisting performance: i) the peculiar twisting deformation modes impels more energy absorption in the lattice core of the sandwich; ii) enhanced after-impact vibration by the twisting effect leads to more dissipated energy; and iii) more friction dissipated energy due to the rotational deformation of TTC metamaterial. We insist also that, the capability to store more elastic strain energy through chiral twisting is the hallmark of TTC metamaterials, and it is certain that this design strategy can be harnessed to further improve the impact-resisting performance of sandwich panels. We add lastly that the strain-rates, despite recognized to have a significant effect on the deformation and failure process, is not considered in the present work and should consists another exploration direction in the work to come.

## Acknowledgements

The financial supports from the National Natural Science Foundation of China (12172294, 11902251, 12111530244,12220101002) are acknowledged. The first author would like to give special thanks to Prof. Bin Li (Northwestern Polytechnical University) and Dr. Nan Li (Chinese Academy of Sciences) for the inspiring discussion during the manuscript preparation.

# References

[1] Q. Wu, Y. Gao, X. Wei, D. Mousanezhad, L. Ma, A. Vaziri, J. Xiong, Mechanical properties and failure mechanisms of sandwich panels with ultra-lightweight three-dimensional hierarchical lattice cores, International Journal of Solids and Structures 132 (2018) 171–187.
[2] A. Baykasoglu, C. Baykasoglu, E. Cetin, Multi-objective crashworthiness optimization of lattice structure filled thin-walled tubes, Thin Walled Structures 149 (2020) 106630.
[3] S. Duan, W. Wen, D. Fang, A predictive micropolar continuum model for a novel three-dimensional chiral lattice with size effect and tension-twist coupling behavior, Journal of the Mechanics and Physics of Solids 121 (2018) 23–46.
[4] X. Cao, D. Xiao, Y. Li, W. Wen, T. Zhao, Z. Chen, Y. Jiang, D. Fang, Dynamic compressive behaviour of a modified additively manufactured rhombic dodecahedron 316l stainless steel lattice structure, Thin-Walled Structures 148 (2020) 106586.
[5] F. Sun, C. Lai, H. Fan, D. Fang, Crushing mechanism of hierarchical lattice structure, Mechanics of Materials 97 (2016) 164–183.

[6] G. Zhang, B. Wang, L. Ma, L. Wu, S. Pan, J. Yang, Energy absorption and low velocity impact response of polyurethane foam filled pyramidal lattice core sandwich panels, Composite Structures 108 (2014) 304–310.

[7] J. Ma, D. Hou, Y. Chen, Z. You, Quasi-static axial crushing of thinwalled tubes with a kite-shape rigid origami pattern: numerical simulation, Thin-Walled Structures 100 (2016) 38–47.

[8] K. Huang, H. Ye, Z. Yu, X. Zhou, Energy absorption properties of composite sandwich tubes with pre-folded cores, Composite Structures (2022) 115737.

[9] J. Wood, The top ten advances in materials science, Materials today 11 (2008) 40–45.

[10] T. Frenzel, C. Findeisen, M. Kadic, P. Gumbsch, M. Wegener, Tailored buckling microlattices as reusable light-weight shock absorbers, Advanced Materials 28 (2016) 5865–5870.

[11] X. Tan, S. Chen, S. Zhu, B. Wang, P. Xu, K. Yao, Y. Sun, Reusable metamaterial via inelastic instability for energy absorption, International Journal of Mechanical Sciences 155 (2019) 509–517.

[12] B.-B. Zheng, R.-C. Zhong, X. Chen, M.-H. Fu, L.-L. Hu, A novel metamaterial with tension-torsion coupling effect, Materials & Design 171 (2019) 107700.

[13] M. Ye, L. Gao, F. Wang, H. Li, A novel design method for energy absorption property of chiral mechanical metamaterials, Materials 14 (2021) 5386.

[14] K. E. Evans, A. Alderson, Auxetic materials: functional materials and structures from lateral thinking!, Advanced materials 12 (2000) 617–628.

[15] Q. Lu, D. Qi, Y. Li, D. Xiao, W. Wu, Impact energy absorption performances of ordinary and hierarchical chiral structures, Thin-Walled Structures 140 (2019) 495–505.

[16] X. Wu, Y. Su, J. Shi, In-plane impact resistance enhancement with a graded cell-wall angle design for auxetic metamaterials, Composite Structures 247 (2020) 112451.

[17] L. Hu, M. Z. Zhou, H. Deng, Dynamic indentation of auxetic and nonauxetic honeycombs under large deformation, Composite Structures 207 (2019) 323–330.

[18] T.-C. Lim, Shear deformation in thick auxetic plates, Smart materials and structures 22 (2013) 084001.

[19] T. Frenzel, M. Kadic, M. Wegener, Three-dimensional mechanical metamaterials with a twist, Science 358 (2017) 1072–1074.

[20] M.-H. Fu, B.-B. Zheng, W.-H. Li, A novel chiral three-dimensional material with negative poisson's ratio and the equivalent elastic parameters, Composite Structures 176 (2017) 442–448.

[21] R. Zhong, M. Fu, Q. Yin, O. Xu, L. Hu, Special characteristics of tetrachiral honeycombs under large deformation, International Journal of Solids and Structures 169 (2019) 166–176.

[22] W. Chen, X. Huang, Topological design of 3d chiral metamaterials based on couple-stress homogenization, Journal of the Mechanics and Physics of Solids 131 (2019) 372–386.

[23] I. Boldyrev, I. Shchurov, A. Nikonov, Numerical simulation of the aluminum 6061-t6 cutting and the effect of the constitutive material model and failure

criteria on cutting forces' prediction, Procedia Engineering 150 (2016) 866–870.

[24] L. Meng, J. Shi, C. Yang, T. Gao, Y. Hou, L. Song, D. Gu, J. Zhu, P. Breitkopf, W. Zhang, An emerging class of hyperbolic lattice exhibiting tunable elastic properties and impact absorption through chiral twisting, Extreme Mechanics Letters 40 (2020) 100869.

[25] J. Qi, C. Li, Y. Tie, Y. Zheng, Y. Duan, Energy absorption characteristics of origami-inspired honeycomb sandwich structures under low velocity impact loading, Materials & Design 207 (2021) 109837.

[26] Z. Chen, L. Liu, S. Gao, W. Wu, D. Xiao, Y. Li, Dynamic response of sandwich beam with star-shaped reentrant honeycomb core subjected to local impulsive loading, Thin-Walled Structures 161 (2021) 107420.