Blast and ballistic loading study of auxetic composite sandwich panels with LS-DYNA

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1 Introduction

Response of novel structures designed for impact, blast and ballistic protection can be enhanced using composite sandwich panels, which are able to extend the energy absorption capabilities [1]. Cellular metals offer very good energy absorption to weight ratio and are consequently used as the core of such composite structures [2]. One of the most promising for this kind of application are auxetic cellular structures, which are modern metamaterials with some unique and superior mechanical properties [3]. They exhibit a negative Poisson's ratio, i.e. they get wider when stretched and thinner when compressed, as a consequence of their internal structure deformation. The effect of negative Poisson's ratio is useful for many different applications to enhance properties in density, stiffness, fracture toughness, energy absorption and damping [3]. In case of impact the auxetic material moves towards the impact zone and thus increases the penetration resistance. The conventional cellular materials with a positive Poisson's ratio in contrast move away from the impact area. The benefits of using auxetic materials as core layers in sandwich panels are obviously crucial to increase the impact energy absorption capability.

Three different methods for blast loading of auxetic composite panels were analysed and compared in this study, based on validated computational models with LS-DYNA. Furthermore, the computational models for ballistic loading of composite sandwich panels were developed and validated based on the experimental testing. For blast loading, **`*LOAD_BLAST_ENHANCED`** (Conwep method), Smooth Particle Hidrodynamics (SPH) method and Multi-Material Arbitrary Lagrange-Eulerian (MMALE) method [4] were investigated. All blast loading computational models were compared to the published experimental results [5]. The most appropriate method was then used for subsequent simulations of composite sandwich panels. The Design Of Experiments (DOE) study was performed based on the validated computational models, focusing on auxetic composite panels using different geometry parameters of cover plates and auxetic cores. The maximum displacement of composite panels and Specific Energy Absorption (SEA) were evaluated and discussed for evaluation of the energy absorption capabilities of different sandwich composite panel geometries. In the case of ballistic loading, the Fragment Simulating projectiles were used to evaluate the behaviour of auxetic composite panel under ballistic loading conditions and to compare behaviour of composite panels to behaviour of monolithic plate with the same weight.

2 Experimental testing

Chiral auxetic cellular structures [6] were fabricated by the Selective Electron-Beam Melting (SEBM) method from Ti-6Al-4V alloy powder at the Joint Institute of Advanced Materials and Processes (ZMP), University of Erlangen-Nürnberg, Germany. Quasi-static compressive testing of auxetic specimens was performed up to the densification to determine complete mechanical behaviour of the fabricated specimens. The geometry of chiral auxetic cellular structures is shown in Figure 1. Auxetic chiral structures analysed in this work had following parameters: L_{ver}, $L_{\mathrm{hor}} = 5$ mm, $A = 1$ mm and $d = 0.57$ mm. Tensile tests of aluminium cover plate's base material were performed on the universal testing machine INSTRON 8801. Ballistic testing of the monolithic plates made of aluminium (AL 7075-T651) and titanium alloy (Ti-Gr.37) (dimensions: 100 mm x 100 mm x 3 mm) was performed using a gas gun device at Georgia Institute of Technology, Atlanta, USA. The standard Fragment Simulating Projectile (FSP) was used in all tests to simulate the fragment impact during the explosion of grenades [7]. The FSP's were fabricated from grade 4340 steel, with diameter of 7.52 mm, length 8.64 mm and weight of 2.85 g. The loading velocities were in the range of 300 m/s.

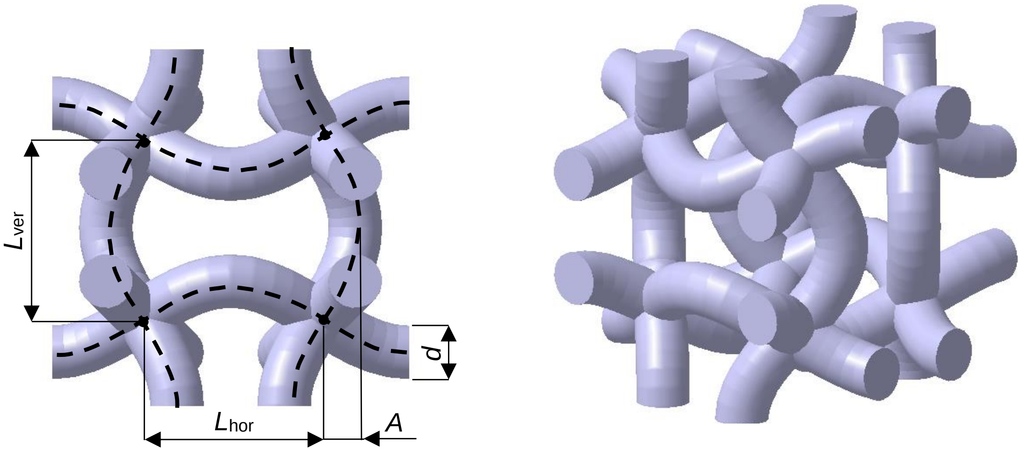

Fig.1: Unit cell geometry of chiral auxetic cellular specimen

3 Computational models

3.1 Compression testing of auxetic cellular structures and tensile testing of cover plates

The results of experimental testing were used to validate the developed discrete computational models of chiral auxetic cellular structures represented with the beam finite elements. The Hughes-Liu beam finite elements with cross-section integration (2x2 Gauss quadrature) were used to model the tubular struts of the auxetic specimens. The node to surface contact formulation with friction ($\mu_{fr,stat} = 0.36$ and $\mu_{fr,dyn} = 0.34$) was defined between the plates and the auxetic core. The general contact (`*CONTACT_AUTOMATIC_GENERAL`) with friction was defined between struts (beam finite elements).

Comparison between the experimental and computational results is shown on Fig. 2, where very good agreement can be observed. The validated computational model of the chiral cellular structure was used as the core in the auxetic sandwich panel [8].

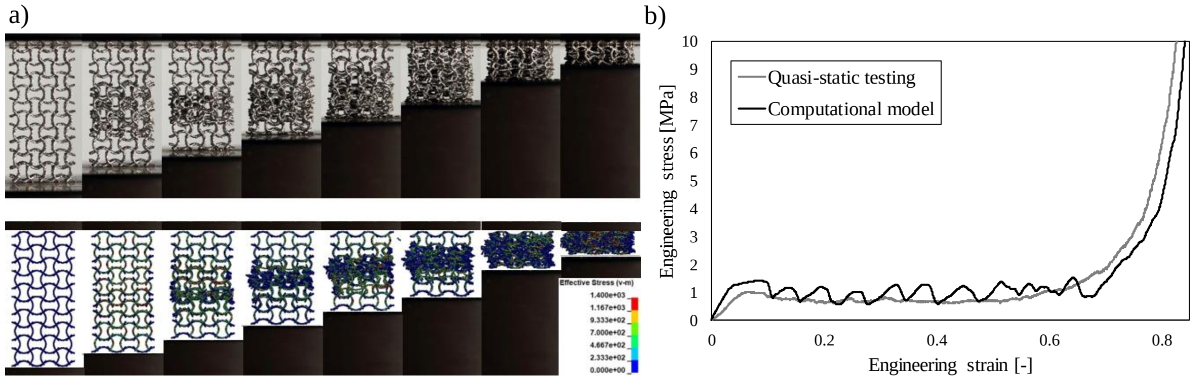

Fig.2: Experimental and computational deformation of auxetic cellular structure under compression (strain increment 10%) – (a) and (c) comparison of mechanical response

The computational model of the tensile testing in LS-DYNA software was used for validation of material model for aluminium alloy 7075-T651 cover plates. The computational model of plates was built from linear volume finite elements with the same global size as they were further used in the simulations of ballistic loading. The appropriate size of the finite elements was determined beforehand with sensitivity studies. The computational displacements were monitored at the same positions as was the position of the extensometer in experiments. The comparison between the computational and experimental deformation behaviour is shown in Fig. 3, where a very good correlation in the deformation pattern and collapse behaviour can be observed.

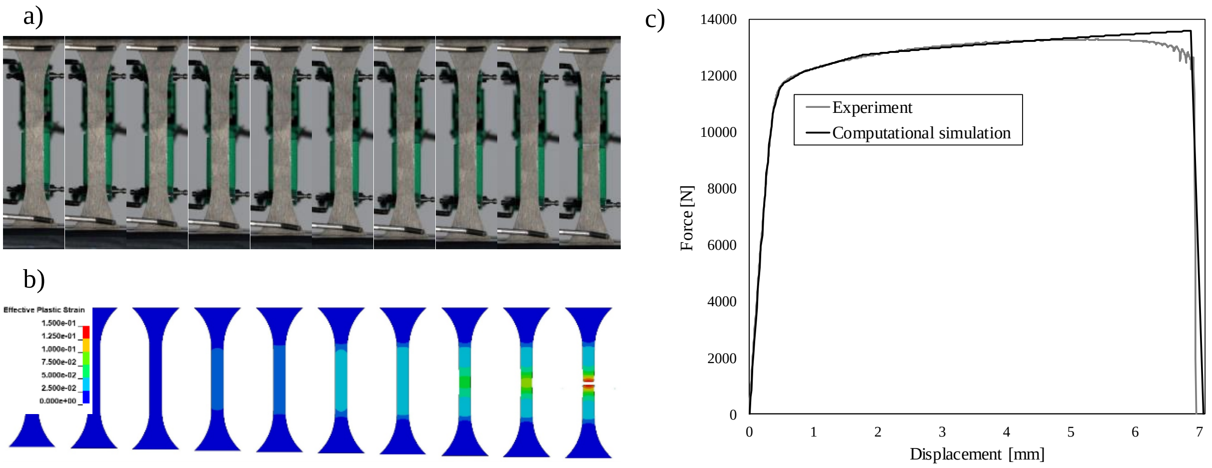

Fig.3: Comparison of experimental (a) and computational (b) results of uniaxial tensile testing of aluminium alloy 7075-T651 (displacement increment 0.8 mm) and (c) comparison of mechanical response

3.2 Blast loading

Computational models for blast loading were validated based on the experimental data [5] using three different computational approaches (ConWep, SPH and MMALE), Table 1. The Belytschko-Tsay shell finite elements, with 2 through shell thickness integration points were used to model the cover plates of sandwich panels.

The used material data and Jones-Wilkins-Lee (JWL) Equation Of State (EOS) for explosive (***MAT_HIGH_EXPLOSIVE_BURN**) in the case of ConWep, SPH and MMALE methods are listed in Tables 1-2. The air domain was described with ***MAT_NULL** in the case of the MMALE method. The model parameters of explosive and air domain are the following: density ρ, detonation velocity D, Chapman-Jouget pressure P_{CJ}, detonation energy per unit volume E_0, and initial relative volume V_0. The parameters A, B, R_1, R_2, and ω of the explosive were taken from [9].

ρ [kg/m^3]	D [m/s]	P_{CJ} [GPa]
1590	6930	2.1 E^{10}

Table 1: Explosive material model for TNT

A [GPa]	B [GPa]	R_1 [-]	R_2 [-]	ω [-]	E_0 [J/m^3]	V_0 [-]
3.712	3.231	4.15	0.95	0.3	7.0 E^9	1

Table 2: JWL Equation of state

The comparison of computed normalized maximal deflection of the plate for three different methods of blast loading is shown in Table 3. The SPH method assures the smallest discrepancy between experimental and computational results, and was therefore chosen as the most appropriate approach for further blast loading simulations.

			δ/t Normalized maximal deflection of the plate [-]			
Test	W [kg]	h [m]	Experiment [5]	ConWep	SPH	MMALE
#1	1.094	0.065	7.45	8.07	7.21	6.65
#2	1.094	0.1	4.85	6.93	4.62	3.88
#3	0.468	0.1	2.60	2.69	2.13	1.96

Table 3: Comparison between different computational approaches of blast loading (W weight of TNT explosive, h distance between the TNT and plate)

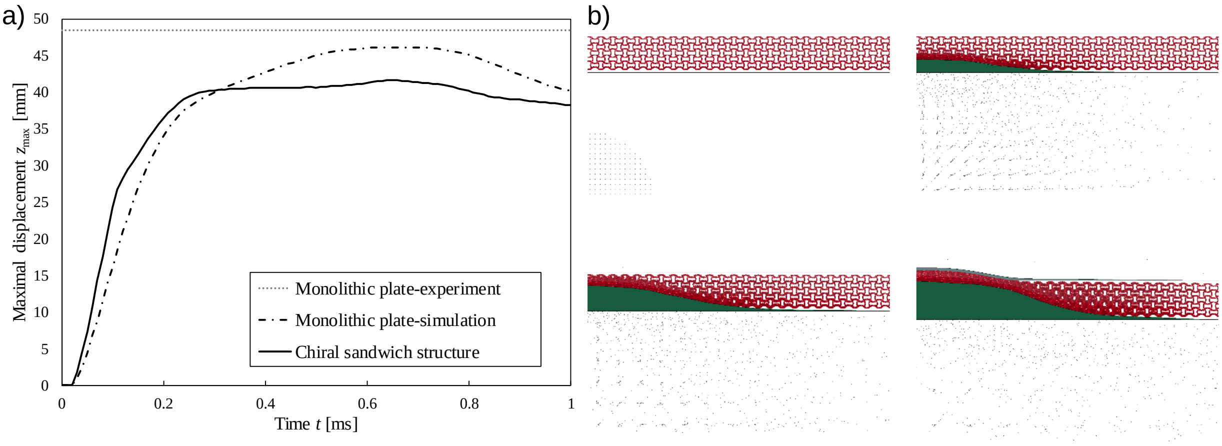

Fig.4: Comparison between experimental results and results from computational simulation of monolithic and sandwich plate (a) and deformation behaviour of auxetic sandwich panel (b) [8]

Figure 4a shows the beneficial influence of using a sandwich panel in comparison to a monolithic plate of the same weight, where a lower maximum displacement of auxetic sandwich structure in comparison to monolithic plate can be observed. After successful validation of the FE model, a Design of Experiments (DOE) study was performed to determine the influence of the auxetic composite panel's geometry on the deformation response of the composite panel under blast loading. The DOE of the composite sandwich panel under blast loading conditions was divided into three case studies: i) the influence of the cover plates` thickness, ii) the influence of the auxetic core geometry, and iii) the influence of the graded porosity on the maximum displacement and specific energy absorption (SEA). In the first analysed case, the thickness of the bottom and top plates varied in a range from 2 mm to 6 mm with the step of 0.5 mm. The auxetic structure geometry was the same as the experimentally tested specimens under compression loading conditions with 88.3 % of core porosity. The results of the top and bottom cover plate thickness influence the maximal displacement and SEA of the composite panel after more than 150 finite element simulations were carried out are presented in Fig. 5. As expected, the minimum observed plate displacement is 36 mm in the case where both plates had the maximum analysed thickness of 6 mm, while the maximum displacement was 63.7 mm in the case where both plates had the lowest thickness of 2 mm.

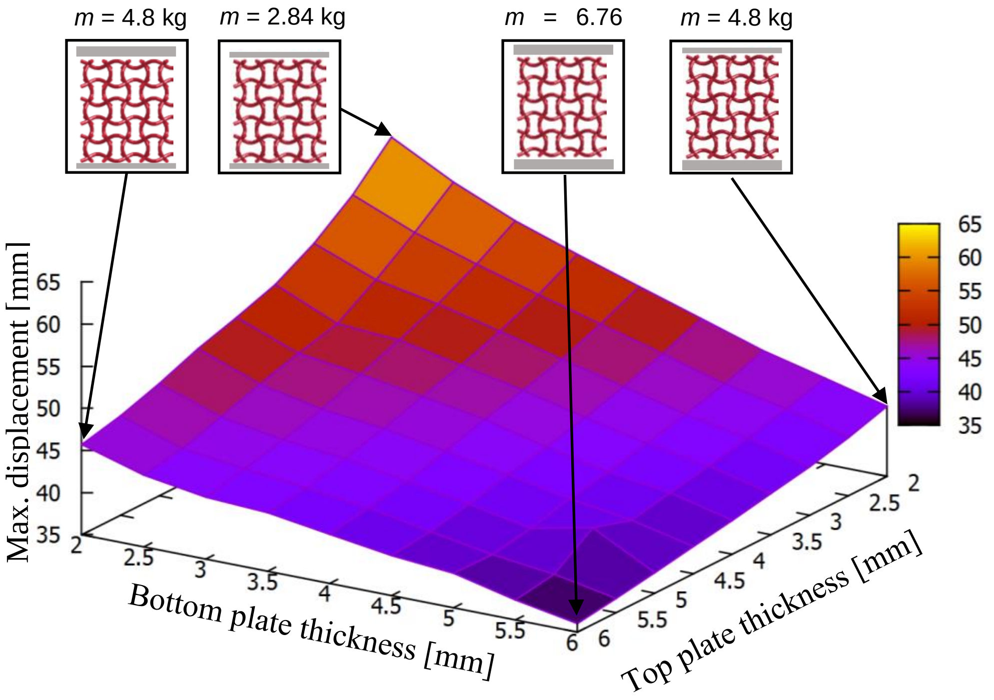

Fig.5: Maximum displacement for different bottom and top cover plates thicknesses

In the second case, the auxetic structure geometry parameters were changing (Fig 1), while the cover plates` thickness was kept constant. The amplitude of the auxetic cellular structure varied from 0.5 mm to 2 mm with the step of 0.1 mm and the cell length from 5 mm to 10 mm with the step of 1 mm. Both cover plates had a thickness of 4 mm. The porosity of the core was in the range from 85.5 % to 97.3 %. From the SEA analysis shown on Figure 6 it can be observed that the core with a larger cell length can absorb more energy, while the amplitude has a minor influence on the SEA, especially at larger cell lengths.

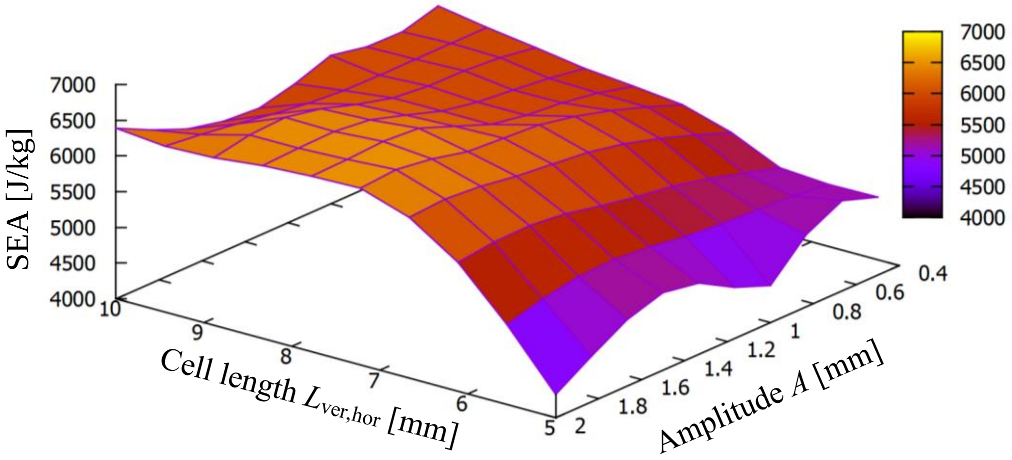

Fig.6: SEA of the core for different core geometries and constant cover plates` thickness

3.3 Ballistic loading

Computational models for ballistic loading were validated based on the experimental results for two different cover plate's materials (titanium and aluminium). The comparison between the experimental and computational behaviour of cover plates is shown in Figure 7a. Validated computational models were then further used to simulate the ballistic loading of auxetic composite sandwich panel, which consist of two cover plates with 3 mm thickness and the auxetic core with 25 mm thickness.

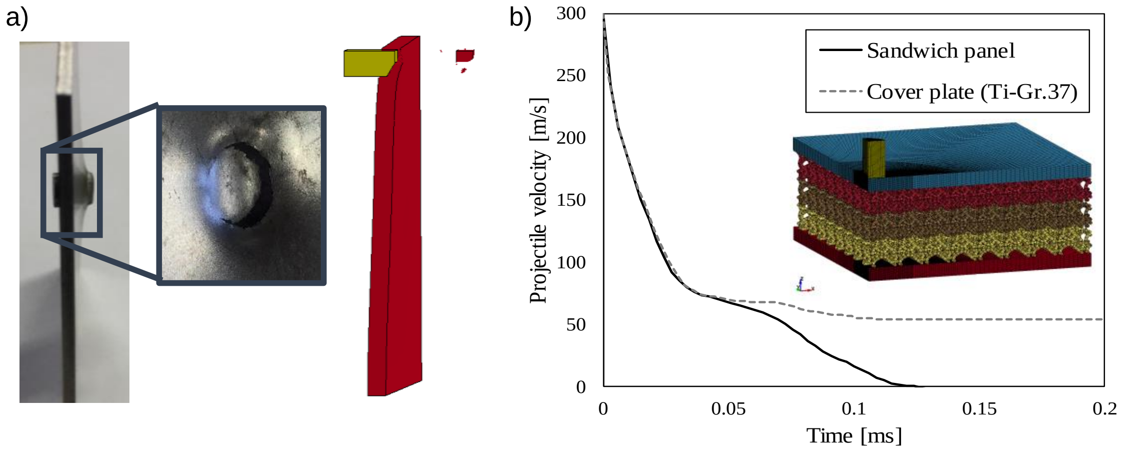

Fig.7: Results of the experimental and computational ballistic testing of titanium cover plate at 275 m/s (a) and velocity of the projectile in the case of the cover plate and sandwich structure (b).

The comparison between the projectile's velocity, when penetrating through the cover plate only and the whole auxetic sandwich structure, considering a projectile's initial velocity of 300 m/s, is shown in Figure 7b. In the case of the monolitic cover plate, there is 50 m/s of residual velocity after projectile penetrates the plate, while in the case of the sandwich structure the projectile got stuck in the first cover plate. This is a consequence of the core, which bends and fractures under ballistic loading at larger strains, providing additional support to the top plate. It was found out that the use of the sandwich panel increases the ballistic velocity only by 5 % due to localised deformation of the top cover plate. It is possible to overcome this by using more ductile or strain-rate sensitive material for the cover plates. Different fillers can also be added to the cellular structure to enhance the mechanical properties of the core, as shown in [10].

4 Summary

The chiral auxetic cellular structures were manufactured using the SEBM method and tested experimentally under quasi-static and dynamic loading conditions. The experimental results were further used for the development and validate the computational models in LS-DYNA. Three different methods (ConWep, SPH, MMALE) were compared and validated for the blast loading. The Smooth Particle Hydrodynamics method was chosen as the most appropriate and was further used for simulating the blast loading of the sandwich composite panels. A Design of Experiments study was performed to analyse the influence of the sandwich panel's geometry on the maximum displacement of the composite panels. It was proven, that when using a composite sandwich panels it is possible to increase the specific energy absorption capabilities under blast loading conditions.

The uniaxial tensile and ballistic experimental testing and simulation of aluminium and titanium cover plates was performed next. In the case of ballistic testing, the plates were loaded with Fragment Simulating Projectile. Based on the validated computational models of cover plates and chiral auxetic cellular structure, the computational model of auxetic composite panel was assembled (two cover plates and auxetic cellular core). The model was used for simulations of ballistic testing, which showed that the auxetic core can increase the ballistic velocity.

5 Literature

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