Blast Resistance of Sandwich Plate with Auxetic Anti-tetrachiral Core

Jakub MICHALSKI
Poznan University of Technology, Institute of Applied Mechanics
ul. Jana Pawła II 24, 60-965 Poznan
jakub.ja.michalski@doctorate.put.poznan.pl

Tomasz STREK
Poznan University of Technology, Institute of Applied Mechanics
ul. Jana Pawła II 24, 60-965 Poznan
tomasz.strek@put.poznan.pl

Abstract

Auxetic structures exhibit unusual behavior not only when subjected to static loads but also in case of dynamic events. However, their response to transient loads still requires further research. In this article, the blast resistance of auxetic and non-auxetic sandwich plates was compared using the finite element method. The first stage of works, that consisted of the analyses of plates with homogenized core with different values of Poisson's ratio subjected to blast load, proved that auxetic core may increase the resistance to this kind of load. In the next step, two sandwich plates were compared – one with auxetic anti-tetrachiral core and one with a non-auxetic hexagonal honeycomb core. Obtained results indicate that auxetic plate has superior blast resistance when compared with the regular sandwich panel.

Keywords: auxetics, sandwich plate, blast resistance, explicit dynamics, finite element method

1. Introduction

Auxetic materials and structures have unique properties because of their negative Poisson's ratio. Unlike regular materials, they become thicker when subjected to tension and thinner when subjected to compression. Their existence was confirmed in 1920 but the term "auxetic" (from Greek "auxetikos" – meaning "the one that tends to increase") was introduced only in 1991 [1].

Since 1980s auxetics are becoming an increasingly popular topic of research. This is because of the growing number of potential applications of these materials – from sports equipment through medical stents to satellite components. Various microstructures with negative Poisson's ratio were already developed by scientists. The most common one is the re-entrant honeycomb introduced by Gibson et al in 1982. In 1982 Lakes described a new method of turning regular foams into auxetic ones. This method utilizes the fact that proper mechanical and thermal handling of the foams leads to the change in their microstructure in such a way that they become auxetic [1].

So far most works focused on static behavior of auxetics but currently, there is an increasing number of articles that discuss their dynamic response to different loads. It was already proven that auxetic structures may have increased fatigue strength and fracture resistance. The authors compared re-entrant and hexagonal honeycomb unit cells.

The results of their simulation suggest significant differences in favor of the auxetic structure [2,3].

Blast resistance of auxetics is among the topics regarding the dynamic behavior of these materials that still require further research. Only a few works are discussing this aspect. In 2017 Imbalzano et al. [4] compared sandwich panels with re-entrant core and with hexagonal honeycomb core in terms of their blast resistance. The authors performed numerical simulations and concluded that auxetic structure has a higher resistance to this type of load. They explained that unusual local deformation of the auxetic structure is the reason for this difference – re-entrant cells stiffen the area affected by the blast. These results suggest that auxetics can be used in various protection equipment, such as armor of military vehicles. Also, Al-Rifaie et al. [5] tested graded auxetic dampers applied to blast-resistant gates. They found that such structures can reduce gate deformations significantly. Another work in this field was carried out by Novak et al. [6]. Authors carried out experimental an numerical testing of sandwich panels with chiral auxetic core. Large potential of such structures in blast loading conditions was confirmed. Double curved shallow shells with auxetic honeycomb core subjected to blast were analyzed by N. Dinh Duc et al. [7]. Analytical solution was developed. Moreover, H. Jopek [8] tested fibrous composite with auxetic reinforcement in terms of rigidity and indentation resistance. It was found that fibers with negative Poisson's ratio have positive impact on these properties of the composite.

2. Blast waves and their modeling

Explosions can be defined as rapid physical, chemical, or nuclear reactions accompanied by the transition of potential energy into mechanical work done by expanding gases. The main component of the explosion is fuel or charge. After ignition, it suddenly releases energy in the form of heat and pressure wave. This wave (also called blast wave) propagates in the air with a specific pressure pattern (Figure 1). The front part of the blast wave is known as shock wave and it has the highest pressure. Shock wave consists of highly compressed air that propagates radially outwards from the source with supersonic speed. When it reaches an obstacle, it reflects. Reflections increase the pressure significantly. Negative phase causes suction but its extreme pressure is significantly lower than in the positive phase. Thus, the negative phase has negligible impact on the deformation of objects affected by the blast and can be ignored in calculations [9].

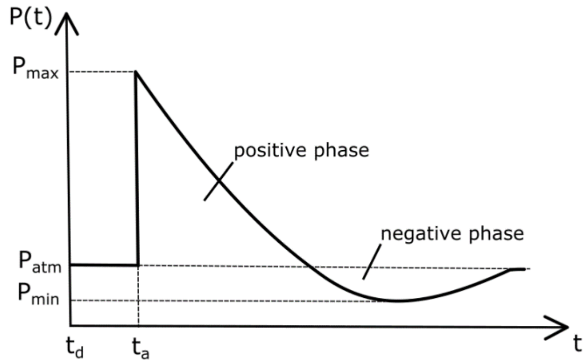

Figure 1. Ideal blast wave pressure variation in time at a distance from the source (P_{atm} – atmospheric pressure, t_d – detonation time, t_a – arrival time) [9]

Different explosives can be compared in terms of power using TNT equivalence [7]:

$$\alpha_{TNT} = \frac{\eta Q}{\eta_{TNT} Q_{TNT}} \tag{1}$$

where: η – coefficient depending on the type of explosive, Q and Q_{TNT} – the heat of detonation of explosive and TNT, respectively.

For numerical modeling of blast waves, one can use the ConWep program. It utilizes Friedlander's equation to describe pressure changes in time [9]:

$$P(t) = P_{so}\left[1 - \frac{t - t_A}{t_o}\right] \cdot e^{-A\frac{(t-t_A)}{t_o}} \tag{2}$$

where: P_{so} – peak positive overpressure [kPa], t_o – duration of the positive phase [ms], A – waveform constant [-], t_a – arrival time [ms].

The negative phase is ignored and all calculations are designed for TNT. However, the aforementioned TNT equivalence can be used for other types of explosives. Time-varying pressure calculated by the ConWep program is applied directly to the surface of the model. Abaqus software uses ConWep for blast loading calculations [9,10].

3. Numerical results

For the article numerical simulations were performed in Abaqus 2020 software. Explicit dynamics finite element solver was used. In the first stage of the works, the sandwich plate model was prepared and meshed with solid elements. The model consisted of two face sheets and a homogenous core between them. Several different values of Poisson's ratio were assigned to the core and each version of the plate was subjected to blast loading. Plates were clamped on all sides and authors assumed perfect bonding between the face sheets and the core (tie constraint was used). The results of these simulations are presented in the form of top plate displacement history for various core Poisson's ratios in the plot below (Figure 2).

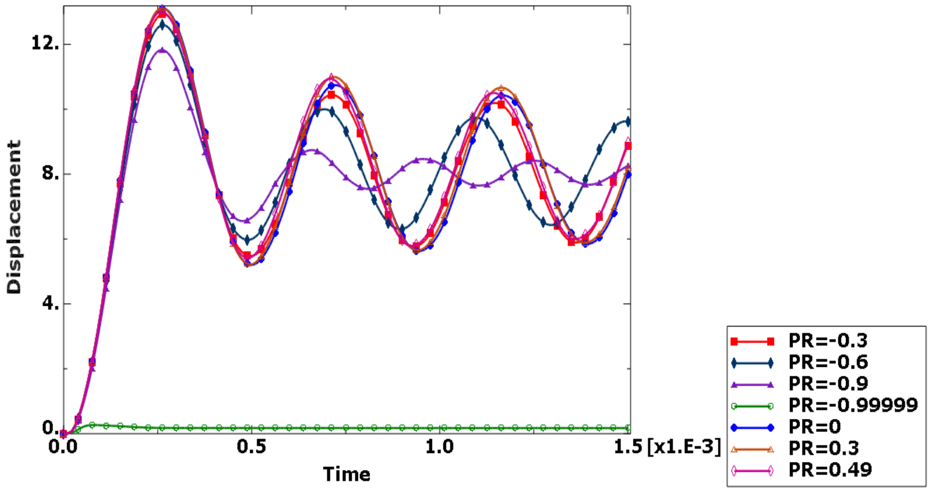

Figure 2. History of the vertical displacement of the top plate for various core Poisson's ratios

As can be seen from the plot, the differences are small for all variants apart from the one where Poisson's ratio was equal to -0.99999. In this extreme case the deflection is close to zero because of the fact that such a low value of assigned Poisson's ratio results in a very stiff structure. There is a visible pattern for most cases – the lower the Poisson's ratio the lower the resulting displacement. These results suggest that auxetics may have improved blast resistance when compared with regular materials. Because this property of auxetics relies mostly on their ability to deform in such a way that localized stiffening is observed, additional testing was required. New models were created similarly as in the previous stage but their cores were not homogenized. Structures that form them were modeled using shell elements. For non-auxetic core hexagonal honeycomb was chosen while the auxetic one was anti-tetrachiral structure. An attempt has been made to make the overall size and unit cell dimensions almost identical in both cases. However, some deviation was unavoidable due to the different geometry of both types of unit cells. Relative densities of both cores were also different for the same reason. Each composite plate's size was about 305x305x75 mm (including two 5 mm thick face sheets). Approximate external dimensions of unit cells were equal to 26 mm.

Face sheets were meshed with C3D8R solid elements (reduced integration first order hexahedrons) while for the cores S4R shell elements (reduced integration first order quadrilaterals) were used. The total number of elements reached 80906 for the non-auxetic plate and 79910 for auxetic one. Meshed geometries of both sandwich panels are shown in the picture below (Figure 3).

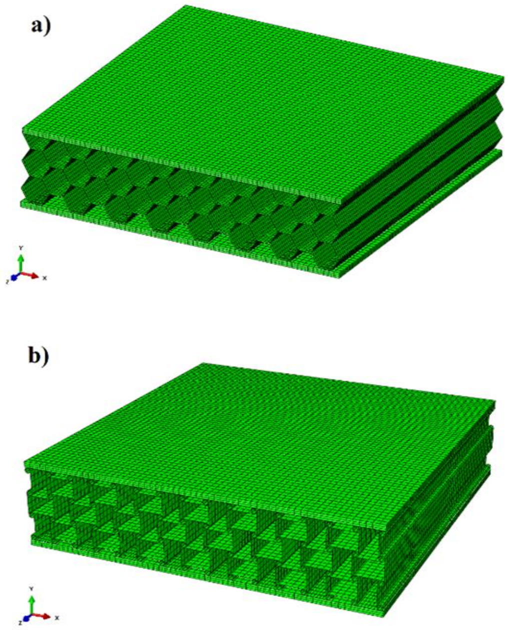

Figure 3. Meshed sandwich panels with: a) hexagonal honeycomb core,
b) anti-tetrachiral core

A quarter model of the plate with symmetry boundary conditions could be used in this case but authors decided to use the full model because of sufficient computational resources and to avoid any mistakes. The same analysis settings were used in both cases. Plates were clamped on all sides and the reference point representing charge (1 kg of TNT) was placed 70 mm above the center of each plate's top surface. Face sheets were connected with core structures using tie constraints resulting in perfect bonding. A general contact algorithm was used to account for interactions between different parts of the core.

It was assumed that all parts of the plates (face sheets and cores) are made of high ductility stainless steel AL-6XN. Material properties included [10]:
- density: 7850 kg/m3,
- Young's modulus: 161 GPa,
- Poisson's ratio: 0.35,
- plasticity with Johnson-Cook hardening model: A=400, B=1500, n=0.4, m=1.2, $T_{melting}$=1800 K, $T_{transition}$=293 K,
- strain-rate dependence (Johnson-Cook model): C=0.045, ε_0=0.001,
- specific heat: 452 J/kg*K.

The initial temperature for whole models was set to 273 K. The analysis time was 1.5 ms. The results of the simulations are shown in the pictures below (Figure 4-5).

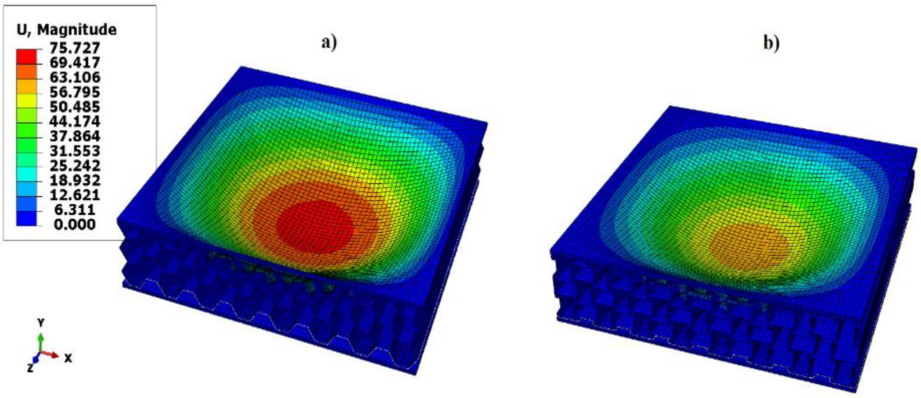

Figure 4. The total displacement of the panel with: a) hexagonal honeycomb core, b) anti-tetrachiral core

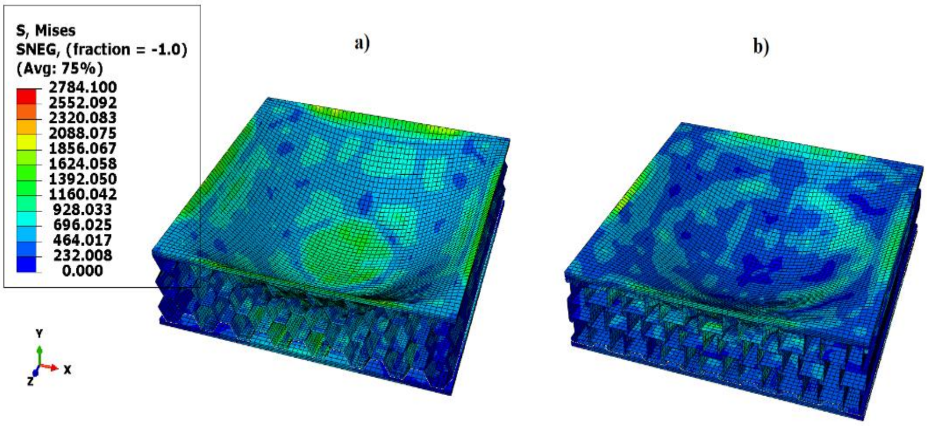

Figure 5. Von Mises stress in the panel with: a) hexagonal honeycomb core, b) anti-tetrachiral core

Obtained results indicate that auxetic core may reduce the total displacement of the plate subjected to blast. Stresses were also lower in the case of the anti-tetrachiral core. The differences are not large but still significant. As mentioned before, plates were not exactly the same in terms of dimensions and relative densities of the cores. However, based on the research experience, it is expected that impact of these factors on the obtained results is small enough to keep the conclusion of auxetic core superiority in terms of blast resistance valid.

4. Conclusions

Results of the simulations performed in the first stage of works showed that the core's Poisson's ratio influences the displacement of the sandwich plate subjected to blast. Additional studies were required to account for the influence of local stiffening effects. These extended analyses confirmed the observation from the first stage.

Acquired results indicate that the anti-tetrachiral core provides superior blast resistance when compared with the hexagonal honeycomb one. Thus the structure could be used in applications requiring improved resistance to shock waves created by explosions. Such usage examples include various civilian and military equipment – armored vehicles, walls, and other forms of explosion protection.

The authors compared the non-auxetic sandwich plate with one type of auxetic structure. Results from previous articles suggest that different kinds of auxetics may also exhibit improved blast resistance. In the future, more unit cell geometries should be compared to provide broad insight on this property of auxetics.

Numerical simulations introduce various simplifications and potential sources of errors to the process of blast resistance verification. The finite element method itself is an approximate way of solving differential equations. Also mesh density has significant impact on results. Material models are not fully accurate as well. Another source of errors is the approach used by ConWep to model explosions. This numerical program was designed to provide correct empirical data, especially when trinitrotoluene is used as an explosive material, but some factors cannot be accounted for when performing analyses with ConWep. Thus, as explained above, there are several sources of errors in the process of blast load modelling. However, this type of testing is very expensive, requires significant effort, and can be even dangerous when carried out experimentally. Because of that numerical simulations may be particularly useful in this field. Some authors compared the afforementioned approach with experiments and found that results are in very good agreement. This also refers to the discussed case of sandwich plate. Interestingly, the difference between numerical and experimental results are higher for larger charges. This is most likely caused by too stiff clamped boundary conditions and debonding occurring between the core and plates during physical experiment [10].

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