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Original scientific paper

Resistance of Cylindrical Sandwich Panels with Aluminum Foam under Blast Loading

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Abstract: In this research, cylindrical sandwich panels with aluminum foam core and aluminum face-sheets under explosive loading are simulated by Abaqus software. The Sandwich panel with aluminum foam core was laminated and simulated in seven cases with different densities by keeping the mass and total thickness constant. The displacement and energy results were evaluated. The results showed that the laminated foam core has a significant effect on the amount of energy absorption and displacement of the panel. The displacement of the model with the optimal laminated core was reduced by 59,8% compared to the model with an equal mass and thickness of core. It was found that reducing the density of the core along the thickness could produce higher explosive resistance. Also, the effect of parameters such as the thickness of the face-sheet and the curvature of the sandwich panel on energy absorption was investigated. According to the parametric study, it has been shown that with increasing the curvature and thickness of the face-sheet, the blast resistance of the sandwich panels increases.

Keywords: aluminum foam; blast resistance; energy absorption; laminated core; sandwich panel

1 INTRODUCTION

Cellular sandwich structures have been used in the aerospace industry due to their high energy absorption and impact resistance [1]. Sandwich structures usually consist of two thin reinforcing plates and a thick core [2-3]. Curved panels have a much stronger and stiffer structure than other shapes and perform better under different loads because they can neutralize external loads more effectively due to their curvature [4]. Lin Jing et al. experimentally investigated the deformation and dynamic response of sandwich panels with aluminum foam cores subjected to blast-loaded air. Experimental results showed that in the modes of deformation and dynamic response, sandwich panels are sensitive to the amount of impact caused by the explosion [5]. The dynamic responses of sandwich panels with aluminum foam cores under air blast loading were investigated by Chen et al.

Numerical simulations showed that increasing the thickness of the front cover sheet led to a significant reduction in total energy. In contrast, the effect of the back cover sheet thickness was negligible [6]. Qi et al. used a group of sandwich panels with aluminum foam cores as armor in vehicles against explosion loads. They analyzed their dynamic responses with different combinations of surface sheet materials [7]. Using finite element simulations, Liu et al. examined the dynamic responses and resistance of explosion of all-metal sandwich panels with laminated aluminum foam cores. They compared them with ungraded single-layer sandwich panels.

They observed that when exposed to the same air blast load, the blast resistance of laminated sandwich panels is better than that of ungraded ones [8]. Li et al. investigated the dynamic responses of spherical sandwich panels with laminated aluminum foam cores under internal blast loading. They analyzed the deformation and energy absorption of each core layer. The arrangement of core layers with different relative densities significantly affected the dynamic plastic reactions of spherical sandwich panels [9].

Shen experimentally investigated curved sandwich panels with aluminum foam cores under different explosive loads and analyzed the deformation and failure modes of the classified specimens [10]. Sandwich structures with aluminum foam cores are good absorbers for impact protection. Hou et al. investigated the effect of impact velocity and shell thickness parameters on ballistic and energy absorption. Throwing object blanter creates a larger petal area and increases the ballistic limit and energy loss [11]. Bezazi et al. presented a comparison between static properties against acoustic compressive loading, acoustic-free density, and conventional foams. Also, a special acoustic feature compared to other foams wasted significant energy [12].

Zhu et al. examined the response of square sandwich panels with aluminum foam cores under blast loading; they conducted a parametric study of the energy absorption performance of sandwich panels. Their results show that foam cores play a major role in energy dissipation, and thinner sheets can increase total internal energy. In contrast, denser and thicker cores can increase some of their energy dissipation [13]. Wang et al. studied the dynamic behavior of sandwich panels with homogeneous and laminated foam cores under blast loading. They comprehensively studied the blast resistance of sandwich panels based on developed numerical models. Their results showed that reducing the core density over the thickness could effectively reduce the stress transferred to the backing sheet, thus creating a higher explosive resistance [14].

In this research, the proposed models of cylindrical sandwich panels with laminated aluminum foam core with variable density and aluminum face sheets have been investigated under explosive loading. The aluminum foam core of the sandwich panel was laminated in layers and simulated in seven cases with different densities by keeping the mass and thickness of the whole core and the sandwich panel constant. The displacement and energy absorption results of the sandwich panels were evaluated.

2 SIMULATION

2.1 Model Geometry

The schematic of the cylindrical sandwich panel is shown in Fig. 1. It consists of two cylindrical aluminum face-sheets and a cellular foam core.

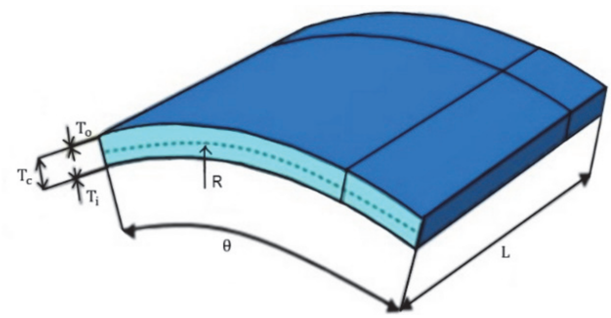

Figure 1 Schematic of cylindrical sandwich panel dimensions

The panel is completely fixed and exposed to the load resulting from the explosion of 25 grams of TNT, equivalent to a distance of 100 mm from the outer face-sheet along the centerline of the panel. Fig. 2 shows a model of a cylindrical sandwich panel with an aluminum foam core.

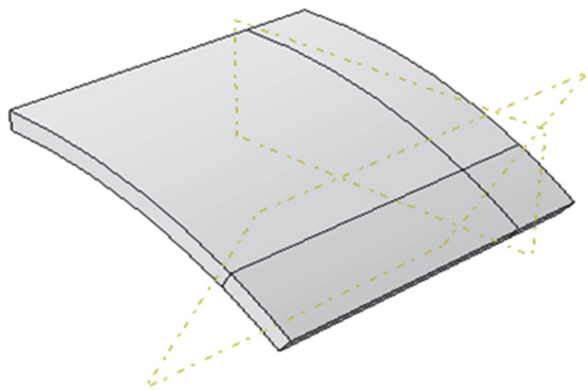

Figure 2 Cylindrical sandwich panel model

2.2 Boundary Conditions and Contact Modeling

Numerical simulation was performed with Abaqus/Explicit finite element software. Only a quarter of the panel was simulated due to reducing the solution time and symmetry. The constraints on the two symmetrical planes are defined, while the other edges are completely fixed, as shown in Fig. 3.

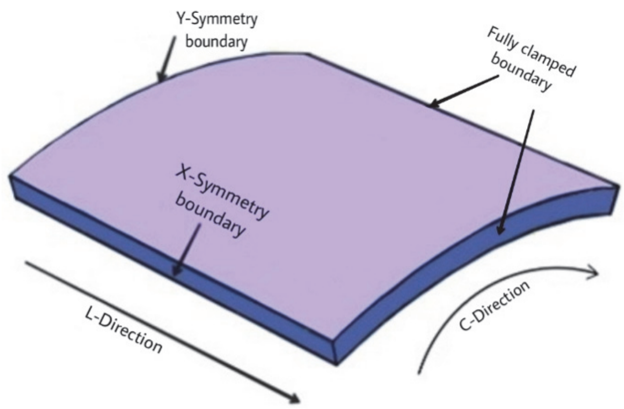

Figure 3 Loading and boundary conditions and cell description for quarter of the sandwich panel

The foam core is grided by the C3D8R element, and the element size is considered to be 1 mm by a convergence study. It is assumed that the top face-sheets are completely enclosed by the upper and lower levels of the core. Normal contact face-sheets with the core were defined using the surface contact formulation.

2.3 Aluminum Face-Sheet

In this research, the top face-sheet of 2024 aluminum alloy was considered, and its mechanical properties are given in Tab. 1.

Table 1 Mechanical properties of aluminum [15]

Material	Density ρ / kg/m^3	Young's modulus E / GPa	Yield stress σ_y / MPa	Poisson's ratio ϑ	Tangent modulus $E_{\tan}$ / GPa
Al-2024	2680	72	75,8	0,33	0,737

2.4 Aluminum Foam

The plastic performance of the aluminum foam core is formed using the options of crushable foam and crushable foam hardening in the Abaqus package. Deshpandeand Fleck [16] used the description of the plastic crushable behavior for the aluminum foam core in Abaqus. Criteria for the aluminum foam was defined as Eq. (1):

$$\varnothing = \hat{\sigma} - \sigma_y \tag{1}$$

where σ_y yield stress and $\hat{\sigma}$ equivalent stress are defined as Eq. (2):

$$\hat{\sigma}^2 = \frac{1}{\left[1+\left(\alpha/3\right)^2\right]}\left[\sigma_e^2 + \sigma^2\sigma_m^2\right] \tag{2}$$

In Eq. (2) σ_e is the von Mises stress, and σ_m is the mean stress. The parameter α, which controls the shape of the yield surface, is a function of the plastic Poisson ratio ϑ_p [17]:

$$\alpha^2 = \frac{9\left(1-2\vartheta_p\right)}{2\left(1+\vartheta_p\right)} \tag{3}$$

For the aluminum foam, ϑ_p is equal to zero and $\alpha = \sqrt{9/2}$, and the yield stress can be expressed as Eq. (4):

$$\sigma_y = \sigma_p + \gamma\frac{\hat{\varepsilon}}{\varepsilon_D} + \alpha_2 \ln\left[\frac{1}{1-\left(\hat{\varepsilon}/\varepsilon_D\right)^{\beta}}\right] \tag{4}$$

where $\hat{\varepsilon}$ is equivalent strain; σ_p, E_p, α^2, γ, β, and ε_D are the parameters of the material and can be related to the density of the foam according to Eqs. (5) and (6):

$$\left(\sigma_p . \alpha_2 . \gamma . \frac{1}{\beta} . E_p\right) = C_0 + C_1\left(\frac{\rho_f}{\rho_{f0}}\right)^4 \tag{5}$$

$$\varepsilon_D = -\ln\left(\frac{\rho_f}{\rho_{f0}}\right) \tag{6}$$

where ρ_f is the density of the foam, and ρ_{f0} is the density of the base material. C_0, C_1, and k are the constants that are listed in Tab. 2.

Table 2 Material constants for aluminum foam [18, 19]

	σ_p / MPa	α / MPa	$1/\beta$	γ / MPa	E_p / MPa
C_0 / MPa	0	0	22,0	0	0
C_1 / MPa	590	140	320	42	0,33E6
k	21,2	45,0	66,4	42,1	45,2

2.5 Explosive Charge Modelling

In this study, Hemp algorithms were first proposed by Randers-Pehrsonand Bannister [20], in which they calculate the angle of impact reflected by the combination of pressure and the amount of impact pressure. The pressure can be calculated by the following expression:

$$P_{\text{load}} = P_{\text{reflected}} \cdot \cos^2\theta + P_{\text{incident}} \cdot (1+\cos^2\theta - 2cos\theta) \tag{7}$$

As θ is the collision angle, P_{incident} is the collision pressure. $P_{\text{reflected}}$ pressure is reflected. Explosive loading in software was created by Conwep. The Conwep model [21] in Abaqus Explicit has two parameters: mass equivalent to TNT and stand off distance. In this experiment, cylindrical TNT is used, while the load shape used in the Conwep model is spherical. To obtain the mass equivalent to the spherical load of TNT for the Conwep, Li [22] proposed a numerical method. In this method, the blast load pressure on the structure is simulated by a cylindrical TNT load that explodes at the standoff distance using the commercial Auto-dyne software. To create the maximum spherical load of TNT applied on the front face-sheet as a cylindrical TNT load, the mass equivalent to the spherical load of TNT is calculated by experimental Eq. (8) [23].

$$\Delta P = \frac{6,1938}{Z} + \left(\frac{0,3262}{Z^2}\right)\left(\frac{2,1324}{Z^3}\right) \tag{8}$$

where ΔP is the maximum excess pressure against the shock wave (kg/cm^2) and Z is the scaled distance (m/kg$^{1/3}$).

3 VALIDATION

In this research, to ensure the accuracy of the simulation method, numerical results are compared with the results presented by Jing et al. [5]. The blast responses of the curved sandwich panels were simulated with an aluminum foam core and the results were compared with experimental data by Jing et al. These sandwich panels consist of two aluminum face-sheets and an aluminum foam core. Explosive loading was applied to the model by blasting a TNT at a fixed position from a distance of 100 mm. The characteristics of the sandwich panels and the results of the central deviations of the inner face-sheet are given in Tab. 3. By comparing the results of this study, the top face-sheet deflection is compared numerically in Tab. 3. The analysis was performed assuming no damage or rupture in the sandwich panels components.

Table 3 Characteristics of curved sandwich panels and experimental and numerical results

Number of specimens	Radius / mm	Foam relative density / kg/m^3	Core thickness / mm	Face-sheet thickness / mm	Mass of TNT charge / g	Inner face central deflection / mm		
						Jing [18]	Present	Error / %
1	250	150	10	0,8	20	17,55	17,93	2,2 %

According to the result of Tab. 3 it was shown that numerical result of the inner face central deflection is very close to the result of reference 18. In Tab. 3, the values of inner face central deflection obtained from the current research was compared with the reference 18; as it can be seen, the error value is very low, so it can be said that the simulation performed is valid. After the analyses the numerical results are extracted. By using the mentioned results, the inner face central deflection for all the models was extracted and the relevant values are given below.

4 DESIGNED MODELS

After validating the simulation method, seven models according to Tab. 4 were considered by the layered foam core with different densities to investigate the effect of changes in the core density. For this purpose, assuming the constant mass and thickness of the foam core, seven different models with laminated core were considered. Therefore, the total core thickness was considered 15 mm for all the models. Tab. 4 shows the specifications of foam density of the core layers of each model. Fig. 4 shows a schematic of the laminated sandwich panel model.

Table 4 Foam density for seven laminated models

Model	1	2	3	4	5	6	7
Top_Foam / kg/m^3	350	150	150	350	350	550	550
Middle_Foam / kg/m^3	350	350	550	150	550	150	350
Bottom_Foam / kg/m^3	350	550	350	550	150	350	150

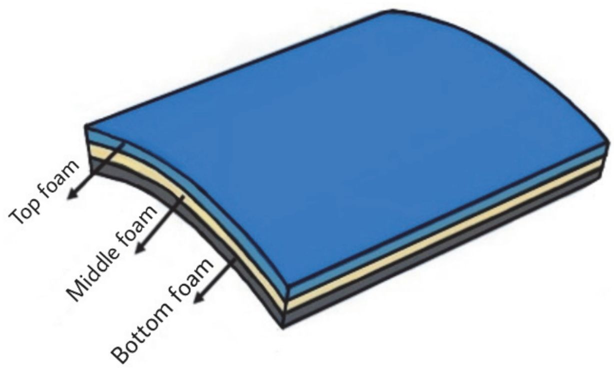

Figure 4 Laminated foam core of the cylindrical sandwich panels

5 RESULTS AND DISCUSSION

After performing the desired simulations and obtaining the results in order to evaluate the proposed models, the results of different models were compared with each other and the optimal model was introduced. In the following, various parameters such as thickness and amount of curvature of the face-sheets on the amount of displacement and energy absorption by the sandwich panel were investigated.

5.1 Deformation and Energy Absorption

By comparing the results of sandwich panel models, it can be seen that model number seven, by reducing the density of the core along the thickness, creates a higher resistance to explosion and shows better results and less deformation. Therefore, model number seven was introduced as the optimal model. Fig. 5 shows the deformation modes of three different models (1, 2 and 7).

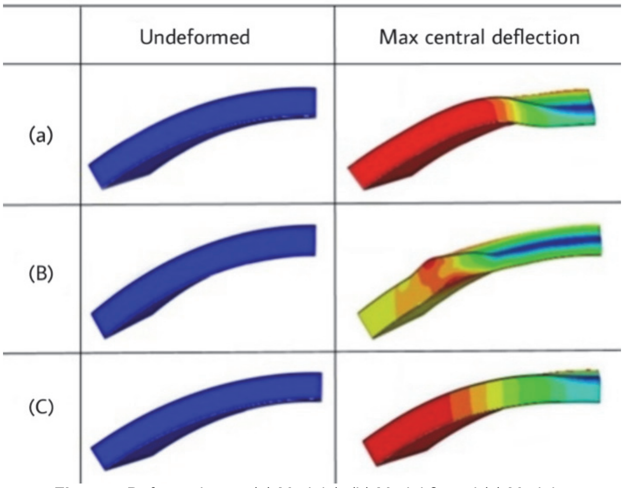

Figure 5 Deformed state (a) Model 1; (b) Model 2; and (c) Model 7

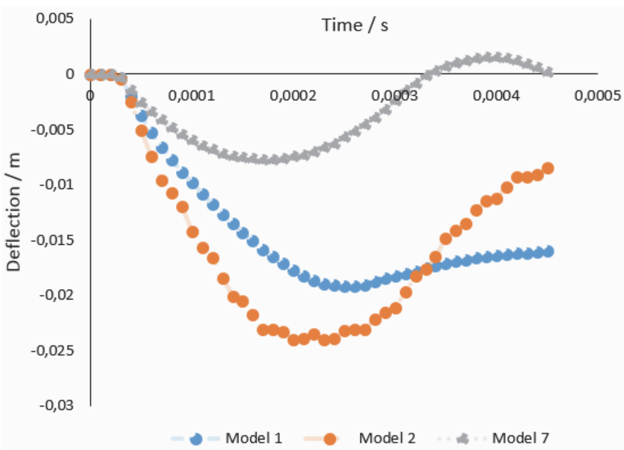

Figure 6 Displacement diagrams of different models 1, 2 and 7

The diagram of the deformation and displacement of the bottom face-sheet is shown in Fig. 6. Also Fig. 7 shows the energy absorption diagram of three different models. The deformation process can be divided into three stages: the loading stage, the compaction stage and the return stage. In the loading stage, the blast load accelerates the top face-sheet in a very short time, and the core layer shows almost no compressive deformation.

In the compaction step, the top face-sheet gradually compresses the core layer to maximize the deformation of the bottom face-sheet. In the return stage, the sandwich panels turn back and vibrate for a certain period. According to the Fig. 6, it is clear that the displacement of the model 7 (optimal model) is reduced by 59,6% compared to the model 1, which means that the model 7 shows better resistance against the explosion.

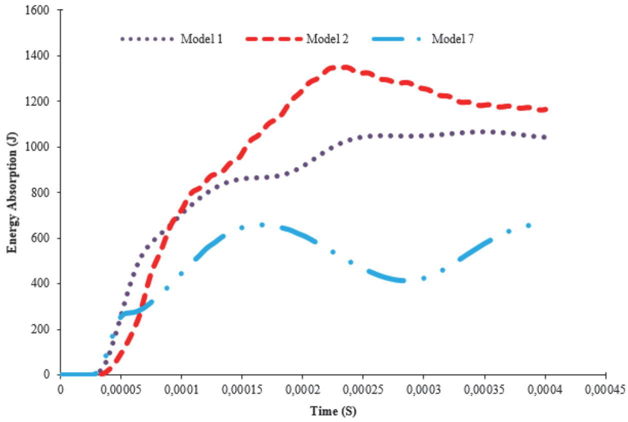

Figure 7 Energy diagrams of models 1, 2 and 7

Also, considering the diagrams in Figs. 6 and 7, it can be concluded that, in general, grading the density of the foam core leads to better performance of the sandwich panel against explosive loading. If the core density decreases along the thickness, the resistance of the sandwich panel increases under explosive loading.

5.2 The Effect of Face-Sheet Thickness in the Optimal Model

To investigate the effect of face-sheets thickness for the optimal model, two groups are considered in Tab. 5. Five different thicknesses of face-sheets are considered. T_i is the thickness of the bottom face-sheet, and T_o is the thickness of the top face-sheet. Increasing the thickness of the bottom and top face-sheets has different effects on the sandwich structure that was mentioned below.

Table 5 Thicknesses of the face-sheets related to 1 and 2 groups

Group 1	T_i / mm	3	2,5	2	1,5	1
	T_o / mm	1	1	1	1	1
Group 2	T_i / mm	1	1	1	1	1
	T_o / mm	3	2,5	2	1,5	1

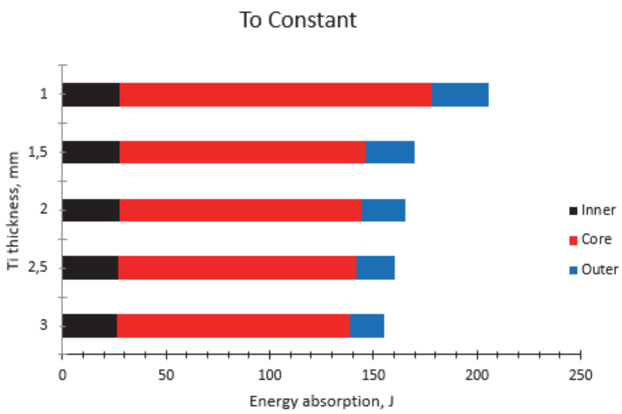

Figure 8 Energy absorption rate of group 1

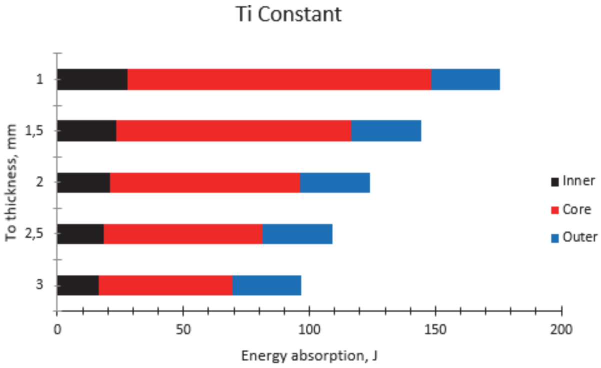

Figure 9 Energy absorption rate of group 2

The results for the considered states in Tab. 5 are shown in Figs. 8 and 9. As it is known, with increasing the thickness of the top and bottom face-sheets, the absorbed energy decreases. So that by increasing the thickness of the top and bottom face-sheets, the energy absorbed by the sandwich panel gradually decreases. It is also observed that sandwich panels are more sensitive to increasing the thickness of the top face-sheet, because increasing the thickness of the top face-sheet leads to increasing the stiffness of the whole panel.

5.3 The Effect of Face-Sheet Thickness in the Optimal Model

Five different curvature values for the optimal model (Model 7) were considered to analyze the effect of curvature of the sandwich panel on the explosive resistance.

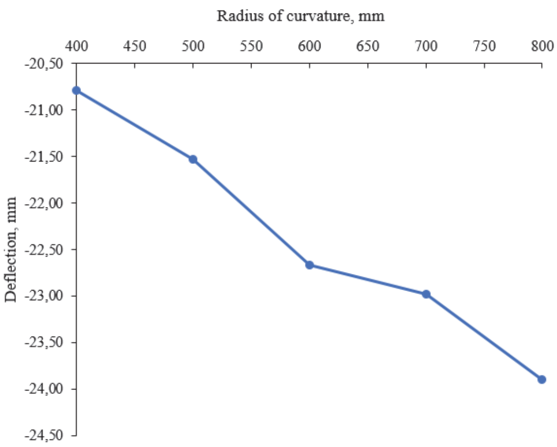

Figure 10 The effect of curvature on displacement

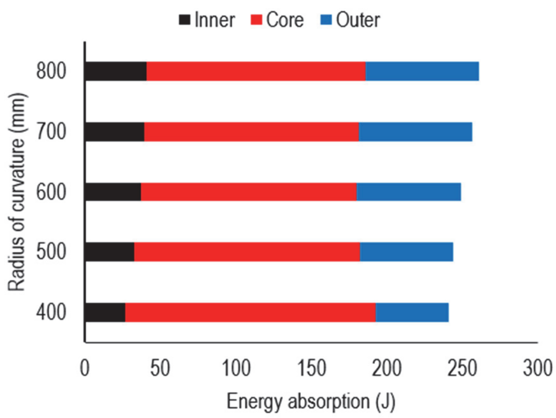

Figure 11 The effect of curvature on energy absorption

As shown in Fig. 10, increasing the radius of the sandwich panels with a constant thickness of the top and bottom face-sheets leads to a reduction in the displacement. Also, the energy absorption capacity of the sandwich panel increases with increasing curvature value, which is shown in Fig. 11.

6 CONCLUSION

In this study, the dynamic response of cylindrical sandwich panels with aluminum foam core and aluminum face-sheets under external explosive loading was investigated. The Sandwich panel with aluminum foam core was laminated and analyzed in seven cases with different densities by keeping the mass and total thickness constant. Then the displacement and energy absorption results were evaluated. The summary of the most important results is as follows:

1. It can be shown that curved structures show better performance than their normal states and with increasing curvature value, sandwich panels show better explosive resistance.
2. Lamination of the foam core has a significant effect on the amount of energy absorption and displacement of the panel.
3. The displacement of the model with the optimal laminated core was reduced by 59,8% compared to the model with an equal mass and thickness of core.
4. It was found that reducing the density of the core along the thickness could produce higher explosive resistance.
5. In terms of energy absorption and displacement, the model with a laminated foam core shows better results than the model with the same density of core layers.
6. Sandwich panels are more sensitive to increasing the thickness of the top face-sheet.

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