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Improving the Performance of the Sandwich Panel with the Corrugated Core Filled with Metal Foam: Mathematical and Numerical Methods

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ABSTRACT

A new type of composite structure with a metal foam is reinforced by the metal corrugated core, called metal-foam-filled sandwich panel with a corrugated or V-frame core, is modelled, simulated, and studied in this article. All types of samples with different relative densities of the foam are tested and analyzed under the drop hammer load. The sandwich panel included two aluminium face-sheet, aluminium foams, and aluminium corrugated or V-frame cores. Mathematical and finite element models were also been developed to predict the effects of the relative density of the foam and other geometric parameters on the energy absorption. In addition, the mathematical equations based on a mass-spring-damper problem with two degree-of-freedom (DOF) were derived to evaluate the kinetic and kinematic parameters of the sandwich panel, such as velocity, acceleration, contact force, and energy absorption. It was found that the models could represent the dynamic response of the sandwich panel. Finally, in order to improve the performance of the sandwich panel, an optimization method was utilized for finding the optimum parameters which play an important role.

1. Introduction

Sandwich panels have been widely used for constructing bridge decks, temporary landing mats and thermal insulation wall boards due to better performance in comparison to other structural materials in terms of enhanced stability, higher strength to weight ratios, better energy absorbing capacity and ease of manufacturing and repair. In sandwich panels, low-density material, known as the core, is usually adopted in combination with high stiffness face-sheets to resist high loads. The main functions of core materials are absorbing energy and providing resistance to face-sheets to avoid local buckling [1]. In sandwich panels with corrugated cores, it has been envisioned that this may be achieved if proper lateral support to core members against plastic yielding and buckling is supplied. To this end, recently, Yan et al. [2] inserted high porosity close-celled aluminium foams into the interstices of corrugated sandwich panels made of 304 stainless steel. A combined experimental and numerical study of the hybrid-cored sandwich was carried out under quasi-static compressive loading. It was found that the foam filling into the core of an empty corrugated sandwich could increase the compressive strength and energy absorption capacity of the hybrid sandwich by 211% and 300%, respectively, and the specific energy absorption by 157%. Yan et al. [3] theoretically and experimentally studied the behaviour of sandwich beam with aluminium foam-filled corrugated cores under three-point bending.

The bending stiffness, initial failure load, and peak load of the sandwich structure were predicted

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by theoretical analysis. They concluded that the filling of aluminium foams would lead to dramatically increase of bending stiffness, initial failure load, peak load, and sustained load-carrying capacity relative to an unfilled corrugated sandwich panel. Yu et al. [4] investigated the crushing response and collapse modes of metallic corrugate-cored sandwich panels filled with close-celled aluminium foams using Finite Elements Method. They showed that at low compression velocities, the foam-filled panel was more efficient in energy absorption compared to the empty panel due to the lateral support provided by the filling foam against strut buckling if the foam relative density was sufficiently large.

Yazici et al. [5] experimentally investigated the influence of foam infill on the blast resistivity of corrugated steel core sandwich panels and numerically studied through the Finite Elements Method. After verifying the finite element model, numerical studies were conducted to investigate the effect of face-sheet thickness, corrugated sheet thickness, and boundary conditions on the blast performance. Experimental and numerical results were found to be in good agreement with R2 values greater than 0.95. The greatest impact on the blast performance came from the addition of foam infill, which reduced both the back-face and front-face deflections by more than 50% at 3 [ms] after blast loading at a weight expense of only 2.3%. Foam infill benefits were more prominent for Simple Supported edge case than encastre Supported edge case.

Han et al. [6] explored the physical mechanisms underlying the beneficial effect of filling aluminium foams into the interstices of corrugated plates made of stainless steel with finite element simulations. Relative to unfilled corrugated plates of equal mass, this effect was assessed based on elevated peak stress and enhanced energy absorption under quasi-static out-of-plane compression. Upon validating the FE predictions against existing measurements, the influence of key geometrical and material parameters on the compressive response of foam-filled corrugated plates was investigated. Four new buckling modes were identified for foam-filled corrugations.

Based upon these deformation modes of post-buckling, collapse mechanism maps were constructed. Due to the additional resistance provided by foam filling against buckling of the corrugated plate and the strengthening of foam insertions due to complex stressing, both the load bearing capacity and energy absorption of foam-filled sandwiches were greatly enhanced.

Recently, Damghani et al. [7-9] the numerically and experimentally studied the energy absorption in aluminium foam and corrugated core sandwich panel structures by drop hammer test.

In this article, the effect of the core density on the energy absorption of the foam-filled corrugated core sandwich panels through the mathematical model and numerical simulations has been investigated. In addition, the effects of the foam relative density are evaluated by the mathematical model. Thus, the kinematic and kinetic parameters could be predicted by this model. The result of the theoretical and numerical studied have good agreement with each other. Also, an optimization method was used to improve the performance of the sandwich panel, such as minimizing the maximum peak of the contact force and maximizing the internal energy (energy absorption).

In summary, in this study, first, the mathematical model would be derived. Second, the model will be validated by comparing its results to those obtained by the numerical method. Third, the optimum values of the important parameters would be found in order to improve the performance of the sandwich panel.

2. Mathematical Model

2.1. Dynamic Stiffness of Top Face-Sheet of the Corrugated core Sandwich Panel

Rigidly supported sandwich panels would experience only local deformation of top face-sheet. Many of the theoretical methods for determining the local deformation involve Hertzian contact methods [10]. Since the local deformation causes transverse deflections of the entire top face-sheet and core crushing, those Hertzian contact laws are inappropriate for finding local indentation response. Other methods for determining the local deformation and core compression include modelling the top face-sheet on a deformable foundation [11, 12].

Turk and Hoo Fatt [13] presented a theoretical solution for the local indentation of a rigidly supported composite sandwich panel by a rigid, hemispherical nose cylinder. They modelled the sandwich composite as an orthotropic membrane resting on a rigid-plastic foundation model. The solution was found to be within 15% of experimental results that involved face-sheet indentations that were several times the face-sheet thickness [13]. Abrate [14] gave an expression for the local indentation of a simply supported plate on the elastic foundation.

When the panel is clamped around the edges, it experiences two types of deformations [14]. First, local deformation of the top face-sheet into the core material, δ, and second, global panel bending and shear deformation, Δ. The local deformation is the local indentation of the top face-sheet as the core crushes. The global deformation is understood as the bending and shear deformation of a sandwich panel that has not experienced any local face-sheet indentation and core crushing. Both the local and global deformations are coupled [15].

The principle of minimum potential energy is again to derive approximate solutions for simply supported panels. Using the actual series solution for the deformations is not practical because a very large number of terms would have to be retained before the convergence of the series solution. So, the local load-deflection response is [16]:

$$\boldsymbol{P = K_g \Delta} \tag{1}$$

where the local stiffness is [16]:

$$\boldsymbol{K_g = [(4F_1F_5 - F_4^2)(4F_3F_5 - F_6^2) + (2F_2F_3 - F_4F_6) \times (F_4F_6 - 2F_2F_5)] / \left[2F_5\left(4F_3F_5 - F_6^2\right)\right]} \tag{2}$$

which the F_i , $(i = 1, \dots, 6)$ are ratios derived by minimizing the energy [17]. The following section describes the simple dynamic models for the impact response. Regarding Fig. 1, the equations of the motion for the 2-DOF mass-spring-damper system are [16]:

$$\boldsymbol{(M_0 + m_f)(\ddot{\Delta} + \ddot{\delta}) + K_{1d}\delta + Q_d = 0} \tag{3}$$

where $\boldsymbol{Q_d}$ is the dynamic crushing resistance of the core that can be experimentally evaluated. $\boldsymbol{m_f}$ is the effective mass of the top face-sheet, and $\boldsymbol{m_s}$ is the effective mass of the sandwich. Furthermore, $\boldsymbol{K}_{\text{gd}}$ is the dynamic global stiffness of the sandwich panel. $\boldsymbol{K_{1d}}$ is the dynamic local stiffness of top face-sheet. In addition, it can be assumed that the mass of the sandwich panel is negligible compared to the mass of the projectile for simplicity. Therefore, the solution for δ given by [15, 16] is:

$$\delta = \frac{\dot{\delta}}{\omega} \sin \omega t + \frac{Q_d}{K_{1d}} \cos \omega t - \frac{Q_d}{K_{1d}}, \quad , \omega = \sqrt{\frac{K_{1d}K_{gd}}{(K_{1d} + K_{gd})M_0}} \tag{4}$$

The velocity and acceleration of top face-sheet are found by differentiating Eq. (4). Consequently, the impact force given by [15, 16] is:

$$\boldsymbol{F(t) = -M_0(\ddot{\Delta} + \ddot{\delta}) = -M_0\left(1 + \frac{K_{1d}}{K_{gd}}\right)\ddot{\delta}} \tag{5}$$

The maximum impact force occurs when $\boldsymbol{\frac{dF}{dt} = 0}$, given by [15, 16] is:

$$F_{max} = \frac{M_0}{K_{gd}} \frac{(K_{gd} + K_{1d})\omega}{\sqrt{(Q_d\omega)^2 + (\dot{\delta}_0 K_{1d})^2}} \times \left(\dot{\delta}_0{}^2 K_{1d} + \frac{Q_d^2\omega^2}{K_{1d}}\right) \tag{6}$$

Maximum impact force occurs when:

$$\boldsymbol{t_{max} = \frac{1}{\omega} \tan^{-1}\left(\frac{\delta_0 K_{1d}}{Q_d \omega}\right)} \tag{7}$$

Maximum strain rate is also given by:

$$\dot{\varepsilon}_{max} = \frac{\varepsilon_{cr}\omega}{\tan^{-1}\left(\frac{\dot{\delta}_0 K_{1d}}{Q_d \omega}\right)} \tag{8}$$

2.2. Global Deformation of the Corrugated Core Sandwich Panel

Fig. 2 shows a sandwich panel with a corrugated core or V-frame. The core density of triangular sandwich structure is formulated respectively as [18]:

$$\rho_c = \frac{2t_1}{L \sin 2\omega} \rho \tag{9}$$

where ρ is the density of the base material of the core sheets, $L = H_c / \sin\theta$ for the triangular core as shown in Fig. 3. Thus, the relative density for the triangular core could be expressed as [19]:

$$\boldsymbol{\bar{\rho} = \frac{2t}{l \sin 2\theta}} \tag{10}$$

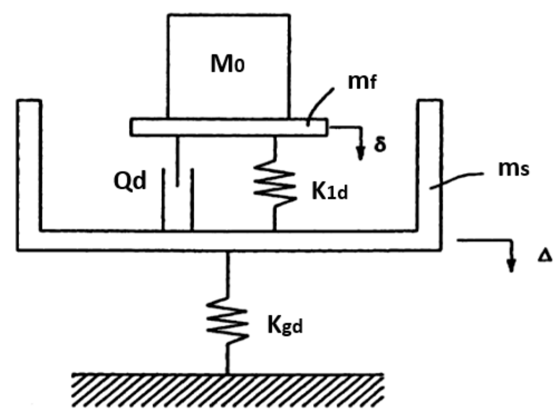


Fig. 1. A discrete model of projectile impact on the simply supported panel [16]

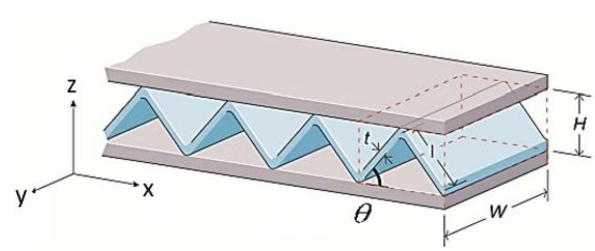


Fig. 2. Corrugated lattice sandwich structure unit cell dimensions [18]

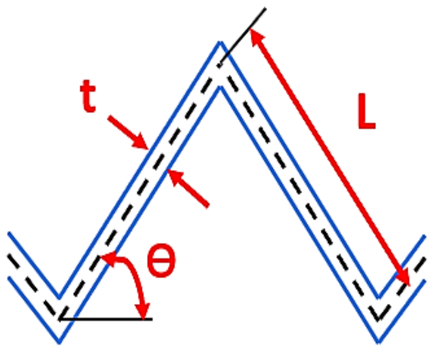


Fig. 3. The geometry of the triangular core

In addition, in a foam-filled corrugated core, the total average density of the sandwich core may be expressed as [2]:

$$\boldsymbol{\rho_{total} = \rho_c v_c + \rho_f (1 - v_c)} \quad (11)$$

where v_c is the volume proportion of the core occupied by corrugated plate and ρ_f is the density of the foam. Then, the total average density of the sandwich core can be written as:

$$\boldsymbol{\rho_{total} = \frac{2t_1}{l \sin 2\theta} v_c + \rho_f (1 - v_c)} \quad (12)$$

Based on the static relationship [20], the overall shear deflection of the Web-Foam core is the sum of the web and foam shear deflections:

$$\tau_{xy} = \tau_w V_w + \tau_f V_f \quad (13)$$

in which, τ_{xy}, τ_w and τ_f are the shearing stress of web-foam core, web, and foam, respectively. Also, V_w and V_f are the volume ratio of web and foam, respectively. The geometrical relationship is:

$$\boldsymbol{\gamma_{xy} = \gamma_w = \gamma_f} \quad (14)$$

where γ_{xy},γ_w and γ_f are the shear strain of web-foam core, web, and foam, respectively. By using Hooke's law, the corresponding stresses are:

$$\boldsymbol{\tau_{xv} = \gamma_{xv} G_{xv}, \quad \tau_w = \gamma_w G_w, \quad \tau_f = \gamma_f G_f} \quad (15)$$

in which, G_{xy}, G_w and G_f are the shear modulus of web-foam core, web, and foam, respectively. Consequently, the elastic modulus of the corrugation when loaded in x_3 direction can be expressed as [21]:

$$E_3 = E_s \bar{\rho} \sin^4 \theta \quad (16)$$

where E_s is Young's modulus of the parent material. By using the same method, the effective shear modulus of the corrugated core G_1 can be expressed as:

$$\boldsymbol{G_1 = \frac{E_s \bar{\rho} \sin^2 2\theta}{4} = \frac{E_s \sin^2 2\theta}{4} \left(\frac{2tv_c}{l \sin 2\theta} + \rho_f (1 - v_c)\right)} \quad (17)$$

In a foam-filled corrugated core, the elastic modulus is given by:

$$\boldsymbol{E_{total} = E v_c + E_f (1 - v_c) = \frac{2tE_s \sin^4 \theta}{l \sin 2\theta} v_c + E_f (1 - v_c)} \quad (18)$$

Compressive strength, σ_3 as well as transverse shear strength, σ_1 of the corrugated core are:

$$\boldsymbol{\sigma_3 = \sigma_c \bar{\rho} \sin^2 \theta = \sigma_c \sin^2 \theta \left(\frac{2tv_c}{l \sin 2\theta} + \rho_f (1 - v_c)\right)}$$

$$\boldsymbol{\sigma_1 = \sigma_c \frac{\bar{\rho}}{2} \sin 2w = \frac{\sigma_c}{2} \sin 2w \left(\frac{2tv_c}{l \sin 2\theta} + \rho_f (1 - v_c)\right)} \quad (19)$$

then:

$$\boldsymbol{\sigma_c = (\sigma_3 + \sigma_1) \times \left[\left(\frac{2tv_c}{l \sin 2\theta} + \rho_f (1 - v_c)\right)\right) \times \left(\left(\sin^2 \theta + \frac{\sin 2w}{2}\right)\right]^{-1}} \quad (20)$$

The dynamic stiffness is given by [15] and substituting it in Eq (2), where:

$$\begin{aligned}
F_1 &= \frac{2240}{1575}\left(\frac{4tE_s \sin^4 \theta}{l \sin 2\theta} v_c + 2E_f (1 - v_c)\right), \\
F_2 &= \frac{1344}{1575} a \left(\frac{2tE_s \sin^4 \theta}{l \sin 2\theta} v_c + E_f (1 - v_c)\right), \\
F_3 &= \frac{1}{1575}\Big(204\Big[a^2 \frac{2tE_s \sin^4 \theta}{l \sin 2\theta} v_c + E_f (1 - v_c)\Big] + 2016\Big[\frac{2tE_s \sin^4 \theta}{l \sin 2\theta} v_c + E_f (1 - v_c)\Big] + 2040\Big[\frac{4tE_s \sin^4 \theta}{l \sin 2\theta} v_c + 2E_f (1 - v_c)\Big]\Big), \\
F_4 &= \frac{1344}{1575} a\left(\frac{2tE_s \sin^4 \theta}{l \sin 2\theta} v_c + E_f (1 - v_c)\right), \\
F_5 &= \frac{1}{1575}\Big(204a^2\Big[\frac{2tE_s \sin^4 \theta}{l \sin 2\theta} v_c + E_f (1 - v_c)\Big] + 2016\Big[\frac{2tE_s \sin^4 \theta}{l \sin 2\theta} v_c + E_f (1 - v_c)\Big] + 2040\Big[\frac{2tE_s \sin^4 \theta}{l \sin 2\theta} v_c + E_f (1 - v_c)\Big]\Big), \\
F_6 &= \frac{4032}{1575}\left(\frac{4tE_s \sin^4 \theta}{l \sin 2\theta} v_c + 2E_f (1 - v_c)\right)
\end{aligned} \quad (21)$$

Consequently, the final stiffness and deformation by substituting Eq. (21) in Eq. (11) and Eq. (2) would be obtained. In addition, velocity and force or acceleration in terms of time could be derived by Eq. (6) and making a derivative from Eq. (4).

3. Numerical Study

4.1. Numerical Modelling of Corrugated-Core Sandwich Panels

This section is intended to give a brief review on the capabilities of LS-DYNA finite element code for simulation of an impact event. The numerical simulation is used for interaction between a rigid impactor and a sandwich panel with a corrugated core during impact. The impactor is modelled and meshed using quad elements with material type 20 (rigid), [7-9]. Material constants for the steel impactor are presented in Table 1.

The face-sheets and sandwich cores were made of Aluminium, and the detailed material parameters are summarized in Table 2. The corrugated core members were meshed by structural shell element S4R and quadratic structural element. With symmetry boundary conditions, displacement-controlled quasi-static uniaxial compression was applied to the top face-sheet while the bottom face-sheet was fixed. A plastic-kinematic model with material number 3 is used for Aluminium Plate Plastic-kinematic model with material number 3 is used for Aluminium plate [7-9].

It does not take much for finite element analysis to produce results. However, for results to be accurate, we must demonstrate that results converge to a solution and are independent of the mesh size. Mesh convergence determines how many elements are required in a model to ensure that the results of an analysis are not affected by changing the size of the mesh. System response (stress, deformation) will converge to a repeatable solution with decreasing element size. Following convergence, additional mesh refinement does not affect results. At this point, the model and its results are independent of the mesh.

Convergence studies vary the sizing and configuration of the FEA mesh. Using an iterative method, the size of elements increased along each side and solved the simulation. The complexity of the model vs. response was recorded. For us, complexity is the size of elements and the subsequent degree of freedom. Our response of interest is the maximum Von Mises stress. We can then plot the maximum Von Mises stress vs. the size of elements in the model. At a point, the response of the system converges to a solution. Refinement of the mesh (the addition of more elements) has little or no effect on the solution. We also can plot the solved time and Von Mises stress vs. the size of elements. The addition of elements increases the solution time. At a point, more elements increase solution time with no refinement in solution. Refinement past this point is an inefficient application of FEA. The results of an FEA model must be independent of the mesh size. A convergence study ensures the FEA model captures the behavior of the system while reducing solving time [7, 21].

According to Fig. 4 and upon performing a mesh sensitivity study, an element size on the order of 1.5 was shown to be sufficiently refined for ensuring the accuracy of the numerical results. The upper indenter was simulated using eight-node solid elements, and the lower platform was defined to be rigid.

An automatic surface-to-surface contact was defined between the upper indenter and the sandwich panel. Meanwhile, an automatic single surface contact was considered to simulate self-contact of core sheets during deformation. An automatic one-way surface-to-surface contact was defined between the face-sheets and core members. For this reason, a speed of 2 m/s was adopted in the simulation [7-9]. Scale factors used for Fig. 5.b is 10 while for Fig. 7.b, it is 12.

FE model of the triangular corrugated sandwich panel is shown in Fig. 5. Also, Fig. 6 shows the kinetic and kinematic parameters of the sandwich panel.

Table 1. Properties of steel impactor [7-9]

Material property	ρ (kg/m^3)	E (GPa)	ν	σ_Y (MPa)
Value	7800	210	0.3	400

Table 2. Properties of Aluminum [7-9]

Material property	ρ (kg/m^3)	E(GPa)	ν	σ_y (MPa)	σ_u (MPa)	ε_D
Value	2700	70	0.3	117	124	0.2

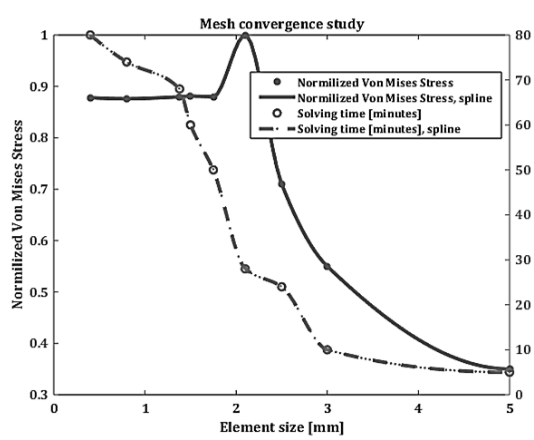
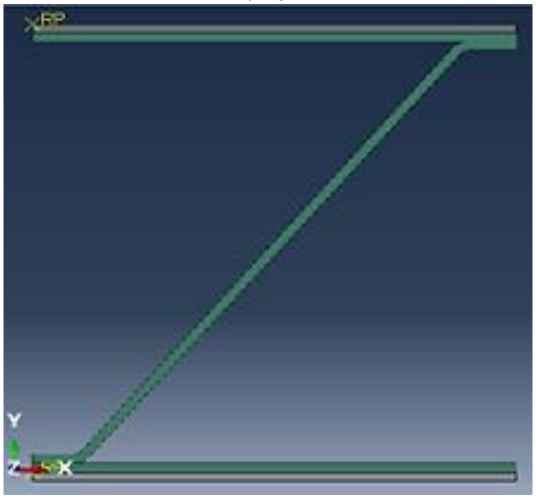
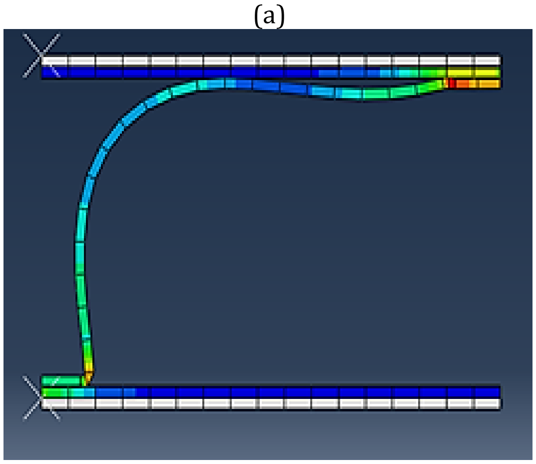


Fig. 4. Mech convergence study for element size and solving time.



(a)



(b)

Fig. 5. a) undeformed. b) deformed finite element model of the triangular corrugated sandwich panel.

According to Section 4, the derived theoretical model was verified by comparing with the numerical methods. As can be seen in Fig. 5, we just modelled and simulated the sandwich panel with face-sheet and corrugated core, and the result is a good agreement with the theoretical model (Fig. 6). In the next sections, we are going to consider the results of the theoretical model in other types of the cores, such as foam-filled core and foam-filled with the corrugated or V-frame core.

4.2. Numerical Modelling of Sandwich Panels with Foam Core

In this section, the numerical simulation is used for interaction between a rigid impactor and a sandwich panel with foam core during impact. Aluminium foam is modelled using the Deshpande-Fleck foam model by choosing material number 154 in LS-DYNA, [22-24]. Fig. 7 shows the model of the sandwich panel with Aluminium Foam. The material constants for the Aluminium foam are presented in Table 3, [7-9].

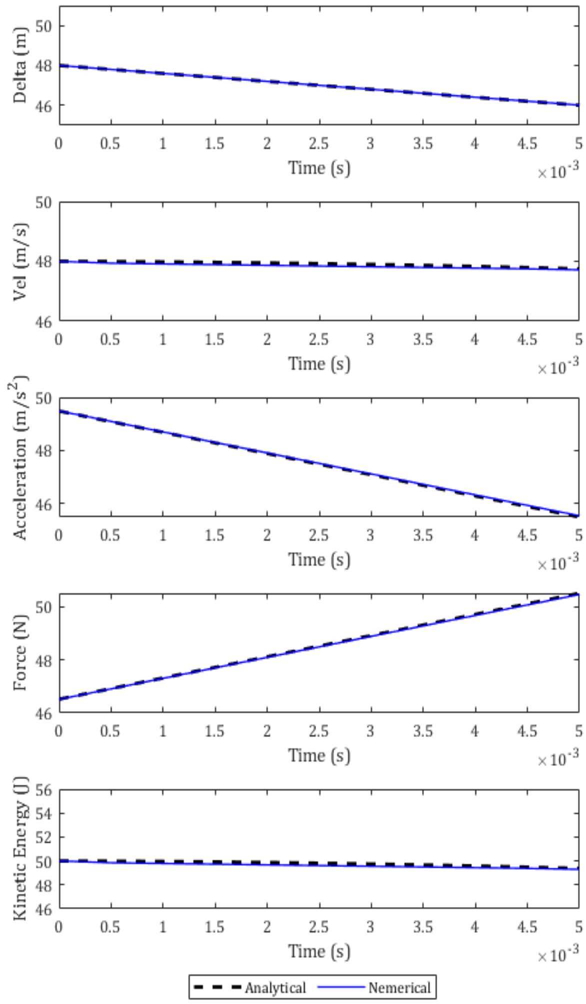
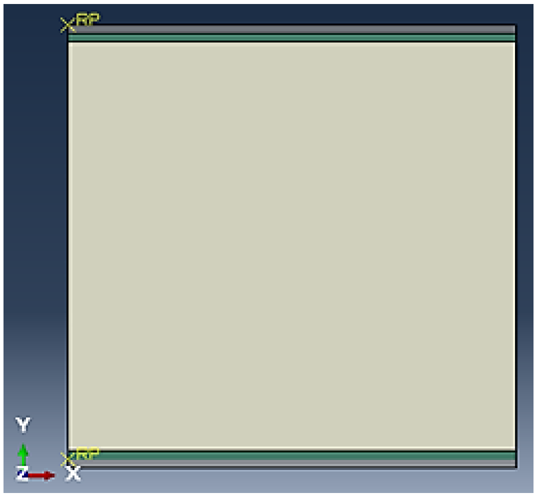


Fig. 6. Time-series of impactor displacement, velocity, and acceleration, imposed force of impactor, and impactor kinetic energy for a triangular corrugated-core sandwich panel.

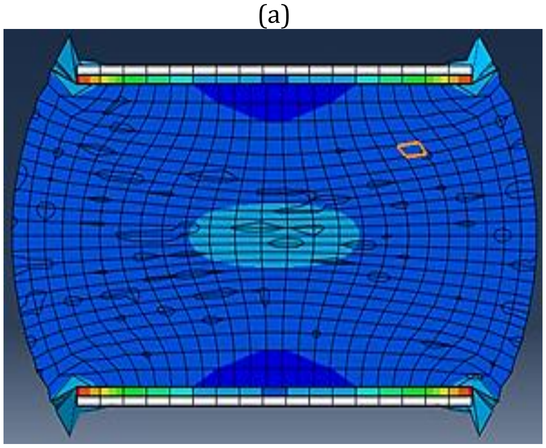
In some models such as Deshpande-Fleck foam model, it may be not possible to reduce the step time. To solve this problem in LS-DYNA, the element erosion method is used to remove the heavily distorted elements. Several criteria are used to this end. Although, in the present work, the maximum strain criterion is utilized, the maximum stress criterion is applicable [22].

For the case of Aluminium foam, the maximum strain of 0.3 is used from the experimental results. "MAT-add-erosion" is an auxiliary tool to remove the elements of the impressed [25-28].

According to Figs. 8 to 10, there is good agreement between the numerical method and theoretical model of the sandwich panel with the foam-filled core in three conditions of the relative density of the foam.



(a)



(b)

Fig. 7. a) undeformed. b) deformed finite element model of foam-core sandwich panel.

Table 3. Properties of Aluminum foam [7-9]

	Relative Density		
Material property	(18%)	(23%)	(27%)
E (MPa)	1500	1660	1800
υ_P	0.05	0.05	0.05
α	2.1	2.1	2.1
γ (MPa)	4.3	5.26	7
ε_D	1.63	1.48	1.33
α_2 (MPa)	48	55	65
B	5.5	4.6	3
σ_{pl} (MPa)	3.8	4.7	5.4
ε_{cr}	0.1	0.1	0.1

4.3. Numerical Modelling of Metal-Foam-Filled Sandwich Panels with a Corrugated or V-Frame Core

In this section, we are going to compare the numerical method and theoretical model in the metal-foam-filled sandwich panels with a corrugated or V-frame core (Fig. 11). In the case of the foam-filled panel, the symmetry boundary condition was applied on the two side-faces of the foam insertion.

Also, both the front and back face-sheet of the sandwich panel was assumed to be stiff enough to be modelled as rigid bodies. The foam insertions, the face-sheets, as well as the struts, were also perfectly bonded at the interface [7-9].

According to Figs. 12 to 14, there is good agreement between the numerical method and theoretical model of the sandwich panel with the corrugated foam-filled core in three types of the relative density of the foam. In the next step, we are going to use an optimization method to improve the performance of the sandwich panel and find the optimum parameters which play an important role.

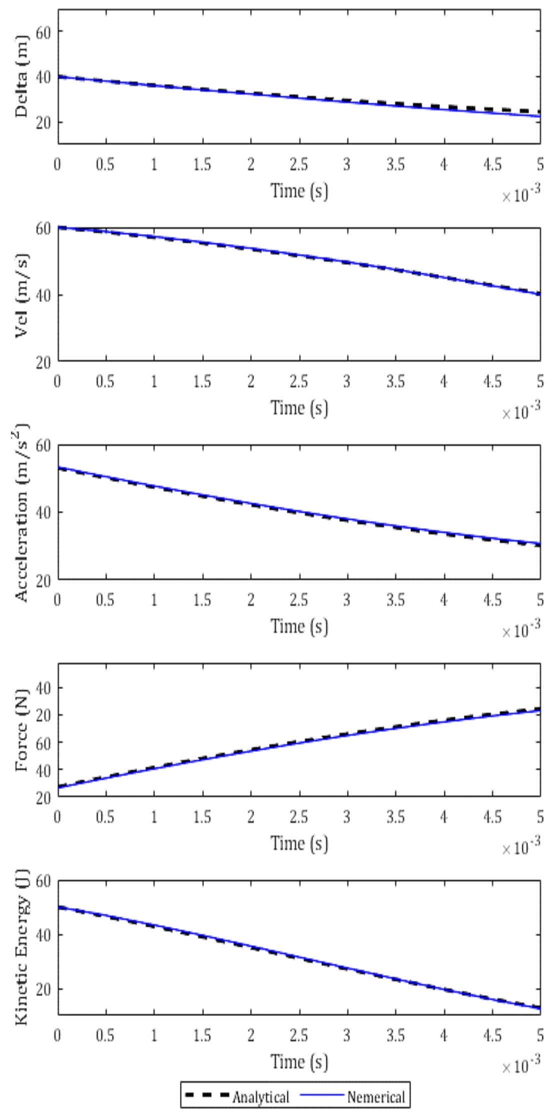


Fig. 8. Time- series of impactor displacement, velocity, and acceleration, imposed force of impactor, and impactor kinetic energy for the foam-core relative density of 18%.

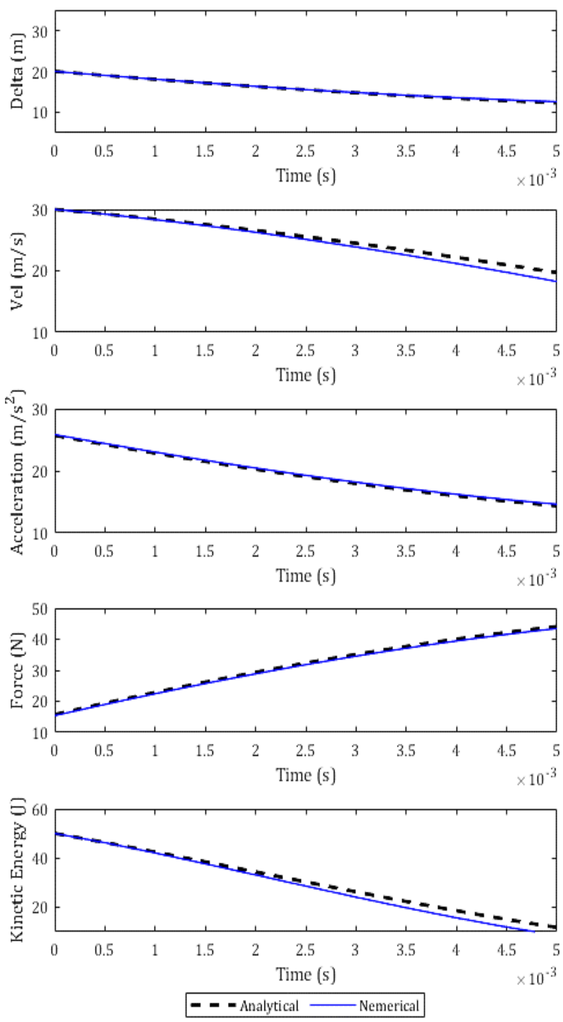


Fig. 9. Time- series of impactor displacement, velocity, and acceleration, imposed force of impactor, and impactor kinetic energy for the foam-core relative density of 23%.

4. Optimization

This part of the article aims to investigate the optimum parameters of the sandwich panel in order to improve the performance. We used a nonlinear optimization method, genetic algorithm (GA) algorithm provided in MATLAB, to minimize the energy absorption as the objective function in the crashworthiness optimization.

For the planar impact, we found from the curves of response vs. time that the peak of the contact force and internal energy both increases as the wall thickness t increases, and then, a multi-objective optimization problem was performed.

Before running the optimization, to make more sense, we were trying to find the relationship between the parameters and the objective functions, internal energy and the peak of the contact force, which are provided in Figs. 15 to 20.

Therefore, we formulated the design problem in the penalty function as a multi-objective optimization framework:

$$\begin{cases} \textbf{Maximize}: \ \boldsymbol{Internal\ Energy} \\ \textbf{Minimize}: \ \boldsymbol{Peak\ Force} \\ \textbf{Or totaly Minimize}: \ \boldsymbol{penalty\ functi} \\ \boldsymbol{1e9} \quad \boldsymbol{< E\ core\ and\ foam <} \\ \textbf{Constraints}: \ \boldsymbol{1e-3} \quad \boldsymbol{< thikness <} \\ \boldsymbol{10} \quad \boldsymbol{< angle <} \end{cases} \tag{22}$$

where:

$$\text{Penalty Function} = |(w1 - |Internal\ Energy|)| + w2 \times |Peak\ Force|$$
$$Internal\ Energy = Area\ of\ the\ contact\ force\ vs.\ displacement, \tag{23}$$
$$Peak\ Force = \max(contact\ force),$$
$$w1 = 20,\ w2 = 0.01, which\ are\ the\ weight\ numbers$$

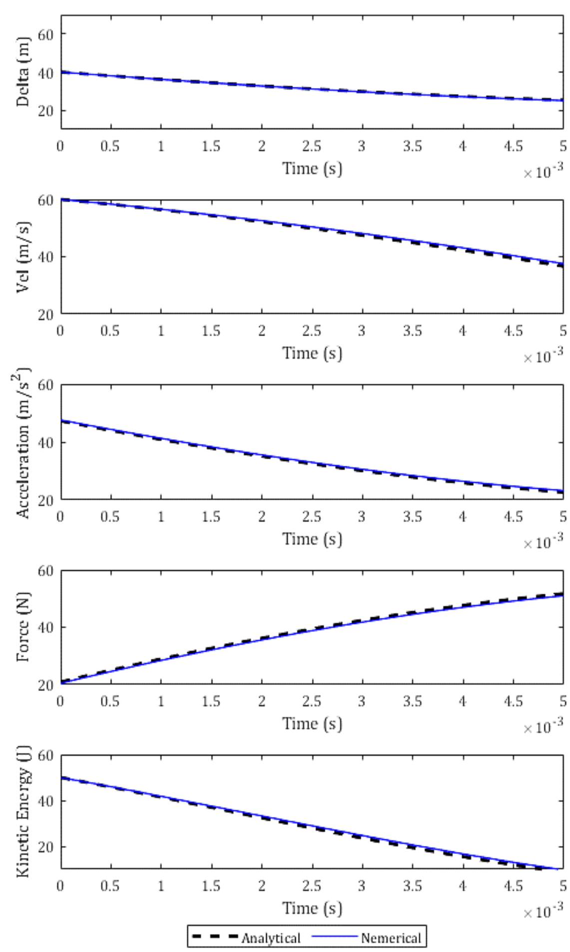
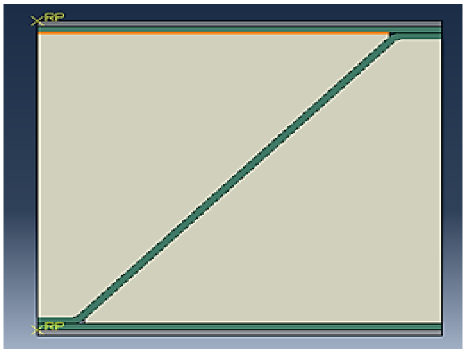
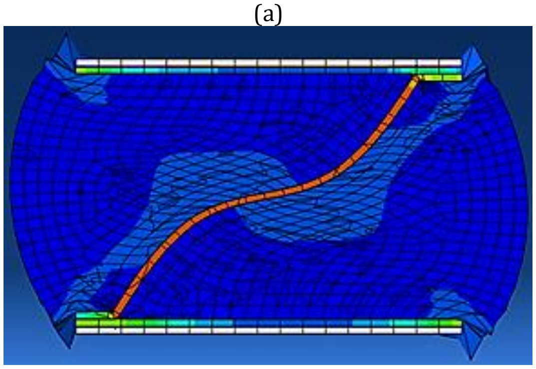


Fig. 10. Time- series of impactor displacement, velocity, and acceleration, imposed force of impactor, and impactor kinetic energy for the foam-core relative density of 27%.



(a)



(b)

Fig. 11. a) undeformed. b) deformed finite element model of the sandwich panel with the corrugated foam-filled core

Fig. 21 shows the history of the optimization method to reach the best value of the multi-objective function, which means the value of the maximum contact force and internal energy. As can be seen in the plot, after around 50 iterations, the function converges to 63.95, and the optimal design variables are:

$$\begin{aligned} E_{core} &= 10^9 \text{ [Pa]} \\ E_{foam} &= 10^9 \text{ [Pa]} \\ t &= 0.005 \text{ [m]} \\ \theta &= 65.7415 \text{ [deg]} \end{aligned} \tag{24}$$

The maximum energy absorption (internal energy) is 11.0854 J, and the maximum contact force is 5.504^3 N.

5. Discussions

Fig. 6 plots the crushing force vs. time and internal energy vs. time curves. From the comparison with Hou et Al. [18] and Damghani et al. [7-9], it is known that the deformation patterns to a certain extent, determine the energy-absorption and the peak crushing force. For the low-velocity impact load, all the core cells were deformed, which lead to high internal energy absorption. Obviously, much bigger crushing force is needed for the latter to make the structure completely deform than for the former to make it deform locally. So, the plot has a good agreement with the statement. In addition, in Fig. 8, we see much bigger crushing force is needed for the sandwich panel with a core-foam, and it will be increasing by increasing the foam density. This trend has a good agreement in comparison with results obtained by Damghani et al. [7], Hoo et al. [15-17], and Turk et al. [13]. Fig. 21 shows the errors of the optimization during each iteration, which its trend has a good agreement with Hou et Al. [18]. Therefore, it could be concluded that after approximately 20 iterations, the convergence of the penalty function would be satisfied.

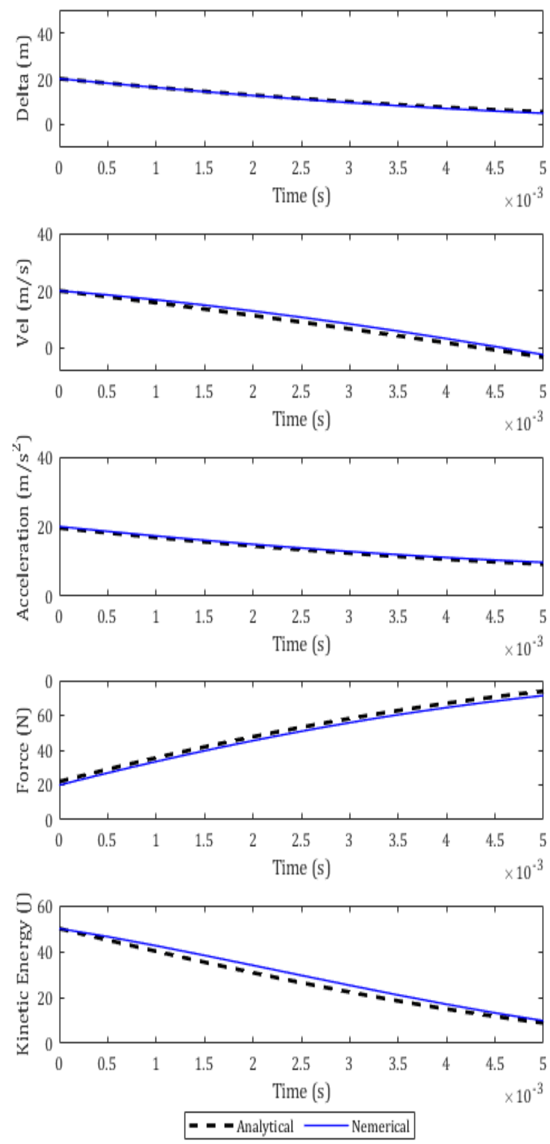


Fig. 12. Time- series of impactor displacement, velocity, and acceleration, imposed force of impactor, and impactor kinetic energy for a sandwich panel with the corrugated foam-filled core with a relative density of 18%.

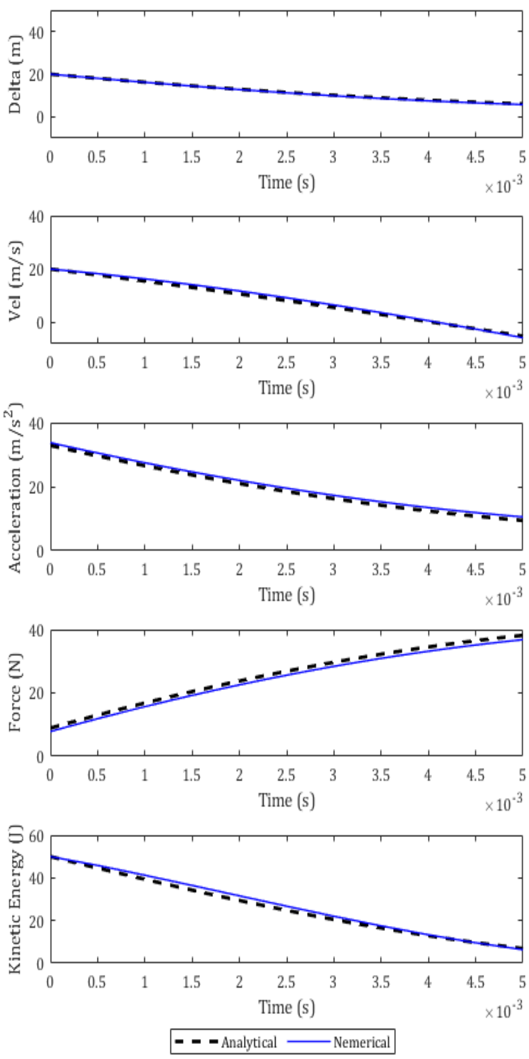


Fig. 13. Time- series of impactor displacement, velocity, and acceleration, imposed force of impactor, and impactor kinetic energy for a sandwich panel with corrugated foam-filled core with relative density of 23%.

6. Conclusions

This article aims to investigate the effects of the key shape and dimensional parameters on the crashing behavior of corrugated sandwich panels and optimize the sandwich cores for crashworthiness criteria. Mathematical and numerical methods were used to characterize the failure response of foam-filled corrugated core sandwich panels under the low-velocity impact. A two-degree-of-freedom is used to theoretically predict the local and global deformation behavior of a simply supported panel. The results revealed a good correlation between the theoretical and numerical predictions; Furthermore, the kinematic and kinetic parameters of the metal-foam-filled sandwich panels with a corrugated core were predicted. The effect of foam-core relative density on the impact properties of sandwich panels showed that the impact resistance and rate of energy absorption would be increased by densifying the foam-core. When the face sheets thicknesses, core height, and core density were kept constant, the core cell shape has a relatively small effect on the low-velocity local impact responses, but they have significant influences on the planar impact responses. The optimal core cell shapes were obtained using energy absorption as the objective function in the crashworthiness optimization. It was found that there is a close relationship between the deformation process and the crushing force vs. time history curve.

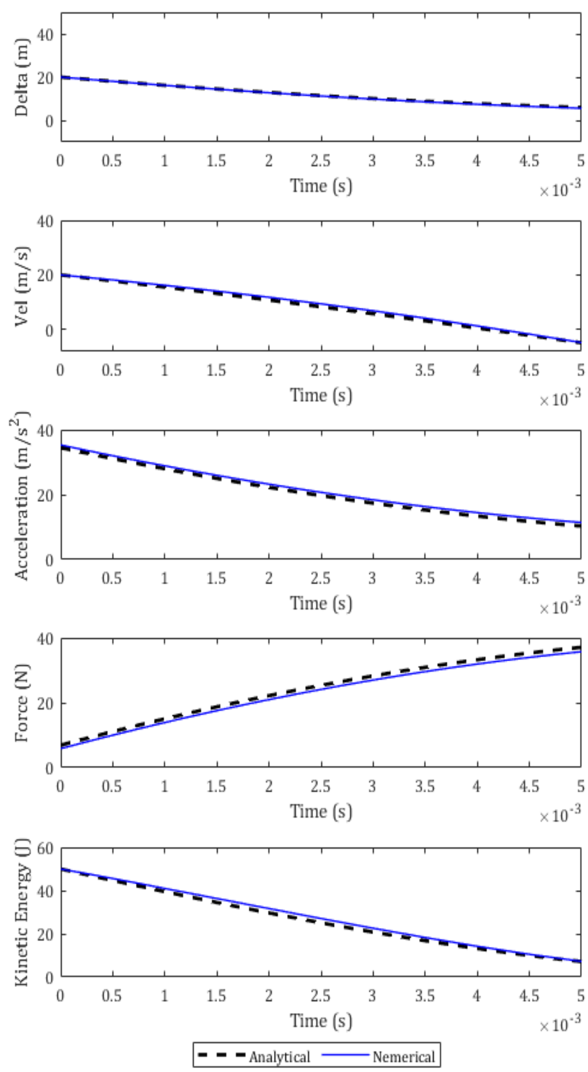


Fig. 14. Time- series of impactor displacement, velocity, and acceleration, imposed force of impactor, and impactor kinetic energy for a sandwich panel with corrugated foam-filled core with a relative density of 27%.

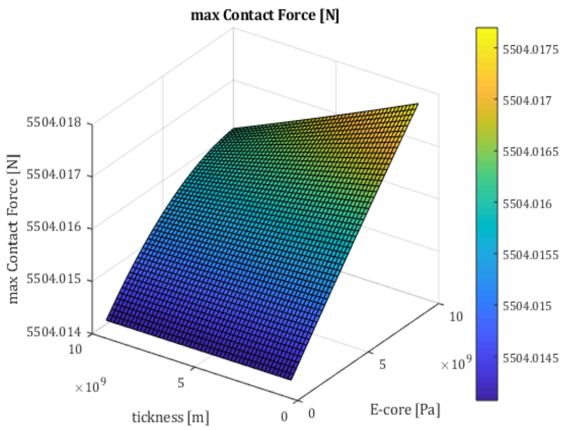


Fig. 15. maximum contact force vs. the elastic modulus and the thickness of the core 18%

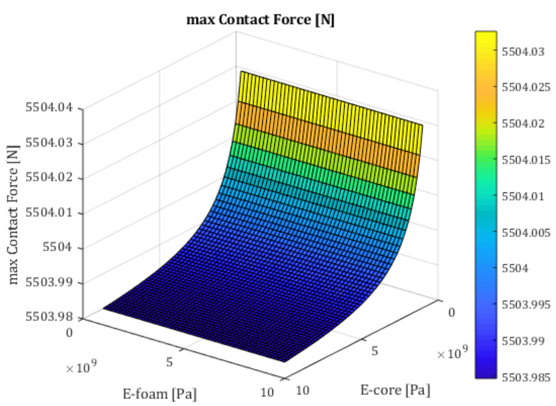


Fig. 16. maximum contact force vs. the elastic modulus of the core and foam 18%

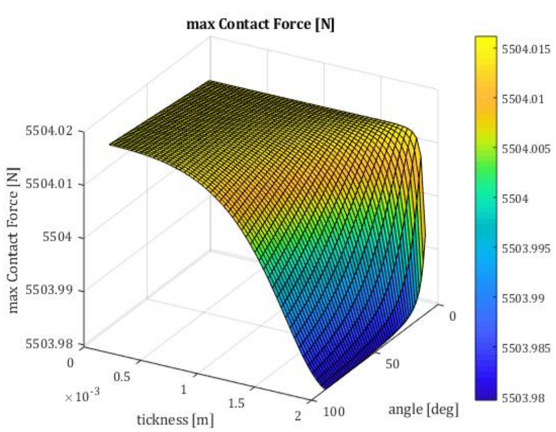


Fig. 17. maximum contact force vs. the angle and thickness of the core 18%

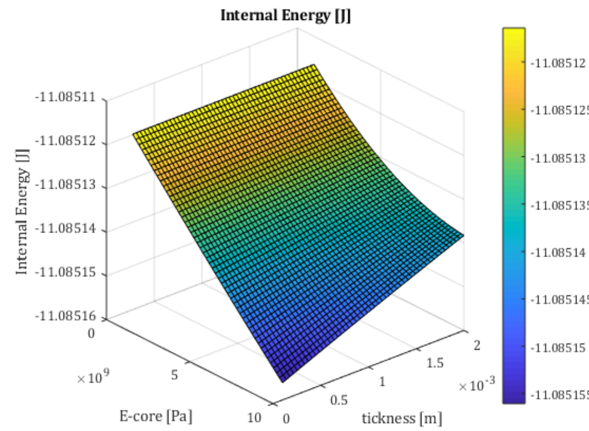


Fig. 18. Internal energy vs the elastic modulus and the thickness of the core 18%

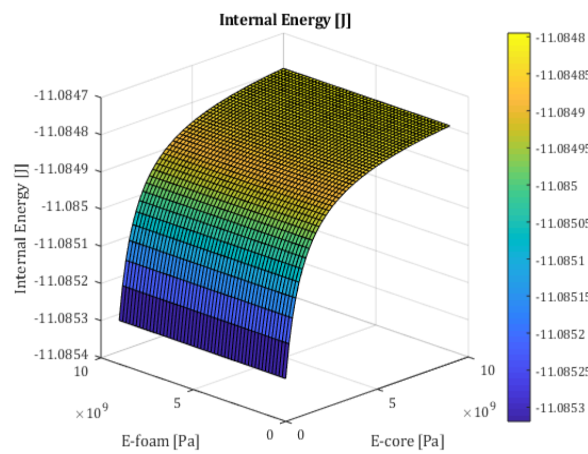


Fig. 19. Internal energy vs. the elastic modulus of the core and foam 18%

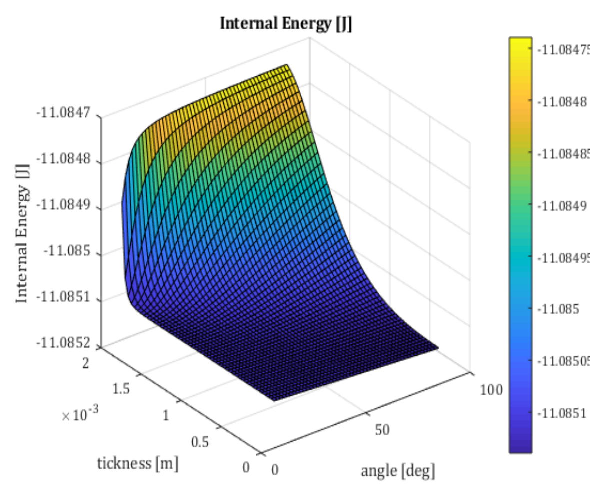


Fig. 20. Internal energy vs. the angle and thickness of the core 18%

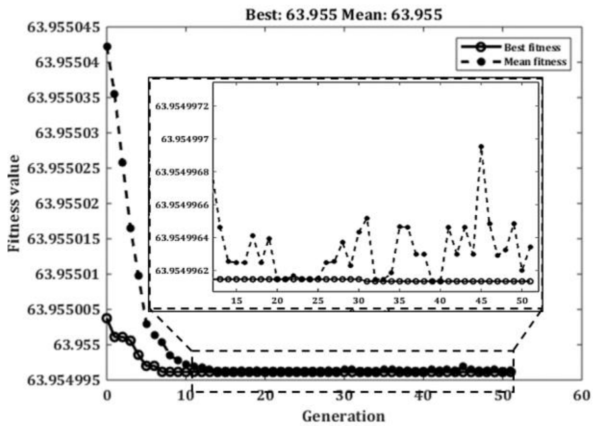


Fig. 21. convergence history of the optimization method

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References

[1] Wu Z, Liu W, Wang L, Fang H, Hui D. Theoretical and experimental study of foam-filled lattice composite panels under quasi-static compression loading. *Compos Part B: Engin* 2014; 60: 329-40.

[2] Yan LL, Yu B, Han B, Chen CQ, Zhang QC, Lu TJ. Compressive strength and energy absorption of sandwich panels with aluminum foam-filled corrugated cores. *Compos Sci & Tech* 2013; 86: 142-8.

[3] Yan LL, Han B, Yu B, Chen CQ, Zhang QC, Lu TJ. Three-point bending of sandwich beams with aluminum foam-filled corrugated cores. *Mater Des* 2014; 60: 510-9.

[4] Yu B, Han B, Ni CY, Zhang QC, Chen CQ, Lu TJ. Dynamic Crushing of All-Metallic Corrugated Panels Filled With Close-Celled Aluminum Foams. *J Appl Mech* 2015; 82(1).

[5] Yazici M, Wright J, Bertin D, Shukla A. Experimental and numerical study of foam filled corrugated core steel sandwich structures subjected to blast loading. *Compos Struc* 2014; 110: 98-109.

[6] Han B, Yan L, Yu B, Zhang Q, Chen C, Lu T. Collapse mechanisms of metallic sandwich structures with aluminum foam-filled corrugated cores. *J Mech Mat Struc* 2014; 9(4): 397-425.

[7] Nouri Damghani M, Mohammadzadeh Gonabadi A. Numerical study of energy absorption in aluminum foam sandwich panel structures using drop hammer test. *J Sandw Struct Mater* 2017; 21(1): 3-18.

[8] Damghani MN, Gonabadi AM. Numerical and Experimental Study of Energy Absorption in Aluminum Corrugated Core Sandwich Panels by Drop Hammer Test. *Mech Mater Sci Eng* 2017; 8.

[9] Damghani M, Gonabadi A. Experimental Investigation of Energy Absorption in Aluminum Sandwich Panels by Drop Hammer Test. *Mech Mater Sci Eng* 2016; 7: 123-41.

[10] Yang S, Sun C. Indentation law for composite laminates. In: Proceedings of the Composite Materials: Testing and Design (6th Conference); 1982. ASTM International.

[11] Noori-Damghani M, Rahmani H, Mohammadzadeh A, Shokri-Pour S. Comparison of Static and Dynamic Buckling Critical Force in the Homogeneous and Composite Columns(Pillars). *Int Rev Mech Eng* 2011; 5(7): 1208-12.

[12] Thomsen OT. Theoretical and experimental investigation of local bending effects in sandwich plates. *Compos Struc* 1995; 30(1): 85-101.

[13] Türk MH, Fatt MSH. Localized damage response of composite sandwich plates. *Compos Part B Eng* 1999; 30(2): 157-65.

[14] Abrate S. Localized Impact on Sandwich Structures With Laminated Facings. *Appl Mech Rev* 1997; 50(2): 69-82.

[15] Hoo Fatt MS, Park KS. Dynamic models for low-velocity impact damage of composite sandwich panels – Part A: Deformation. *Compos Struc* 2001; 52(3-4): 335-51.

[16] Dobyns AL. Analysis of Simply-Supported Orthotropic Plates Subject to Static and Dynamic Loads. *Am Inst Aeronaut Astronaut* 1981; 19(5): 642-50.

[17] Hoo Fatt MS, Park KS. Dynamic models for low-velocity impact damage of composite sandwich panels – Part B: Damage initiation. *Compos Struc* 2001; 52(3-4): 353-64.

[18] Hou S, Zhao S, Ren L, Han X, Li Q. Crashworthiness optimization of corrugated sandwich panels. *Mater Des* 2013; 51: 1071-84.

[19] Biagi R, Bart-Smith H. In-plane column response of metallic corrugated core sandwich panels. *Int J Solids Struct* 2012; 49(26): 3901-14.

[20] Wang L, Liu W, Wan L, Fang H, Hui D. Mechanical performance of foam-filled lattice composite panels in four-point bending: Experimental investigation and analytical modeling. *Compos Part B Eng* 2014; 67: 270-9.

[21] George T, Deshpande VS, Wadley HNG. Hybrid carbon fiber composite lattice truss structures. *Compos Part A: Appl Sci Manufact* 2014; 65: 135-47.

[22] LS-DYNA. Keyword User's Manual. *Version* 2006; 960: 1-2.

[23] Hanssen AG, Hopperstad OS, Langseth M, Ilstad H. Validation of constitutive models applicable to aluminium foams. *Int J Mech Sci* 2002; 44(2): 359-406.

[24] Deshpande VS, Fleck NA. Isotropic constitutive models for metallic foams. *J Mech Phys Solids* 2000; 48(6-7): 1253-83.

[25] Damghani M, Gonabadi M. Investigation of Energy Absorption in Aluminum Foam Sandwich Panels By Drop Hammer Test: Experimental Results. *Mech Mater Sci Eng* 2017; 7.

[26] Rajendran R, Prem Sai K, Chandrasekar B, Gokhale A, Basu S. Preliminary investigation of aluminium foam as an energy absorber for nuclear transportation cask. *Mater Des* 2008; 29(9): 1732-9.

[27] Rajendran R, Moorthi A, Basu S. Numerical simulation of drop weight impact behaviour of closed cell aluminium foam. *Mater Des* 2009; 30(8): 2823-30.

[28] Damghani M, Gonabadi M. Investigation of Energy Absorption in Aluminum Foam Sandwich Panels By Drop Hammer Test: Experimental Results. *Mech Mater Sci Eng* 2017; 7: 123-41.