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Abstract: In this paper, the non-linear dynamic response of novel steel sandwich panel with hollow I-core subjected to blast loading was studied. Special emphasis is placed on the evaluation of midpoint displacements and energy dissipation of the models. Several parameters such as boundary conditions, strain rate, mesh dependency and asymmetrical loading are considered in this study. The material and geometric non-linearities are also considered in the numerical simulation. The results obtained are compared with available experimental data to verify the developed FE model. Modeling techniques are described in detail. According to the results, sandwich panels with hollow I-core allowed more plastic deformation and energy dissipation and less midpoint displacement than conventional I-core sandwich panels and also equivalent solid plate with the same weight and material.

Keywords: Blast, Dynamic non-linear analysis, Energy dissipation, Sandwich panel.

INTRODUCTION

The demand for lighter and safer structures has increased the importance of novel structural element arrangements and new materials. The sandwich structures are among the most effective structural configurations. These structures have high strength to weight ratio and can bring space savings, vibration control and fire resistance. They are efficient in resisting dynamic loads such as fatigue, impact or blast loads due to their high stiffness and substantial energy dissipation capacity.

The problem of blast effects on metallic sandwich panels has recently received a significant attention. The investigations of blast effects on structures are divided into experimental (Rathbunet al., 2006; Zhu et al., 2008; Nurick et al., 2009; Shen et al., 2010; Dharmasena et al., 2011; Ebrahimi and Vaziri, 2013) and numerical studies (Qiu et al., 2003; Karagiozova et al., 2009; Zhu et al., 2009; Theobald and Nurick, 2007; Shah Mohammadi and Mohammadi, 2010; Shen et al., 2011; Nayak et al., 2013). Xue and Hutchinson (2003) conducted a study to assess the sandwich panel under blast loads. The study suggests that sandwich panels with sufficiently strong cores have the potential to sustain larger impulses than solid plates of the same weight.

One of the experimental studies was carried out by Mori et al. (2009) with the aim of quantifying performance and failure modes of sandwich structures subjected to blast loads. Performance enhancement with respect to solid plates of equal weight was assessed. This study suggested that the

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usage of sandwich structures was useful and that performance enhancements, in terms of maximum displacement, as high as 68% is possible. The study also confirms theoretical analyses suggesting that the use of soft cores maximized the benefits (Mori et al., 2009).

Valdevit et al. (2005) performed an experimental and computational study of the deformations of metallic sandwich panels with corrugated cores in both transverse and longitudinal loading conditions. Panel designs were chosen on the basis of failure mechanism maps constructed using analytic models for failure initiation. The results were verified by experimental measurements and finite element analysis. Limit loads were also examined and found to be sensitive to the failure mechanism. According to the results, when face yielding predominates, appreciable hardening followed the initial non-linearity, rendering robustness. Conversely, for designs controlled by elastic or plastic buckling, initiation of failure was followed by softening. The implication is that, when robustness is a key requirement, designs within the face failure domain are recommended (Valdevit et al., 2005).

The dynamic response of cylindrical sandwich panels with aluminum foam cores subjected to blast loading was numerically investigated by Jing et al. (2013). Numerical results show that the compression strain, which plays a key role on energy absorption of sandwich structures, increases approximately linearly with normalized impulse, and reduces with increasing relative density or the ratio of face-sheet thickness and core thickness (Jing et al., 2013).

Steel I-core sandwich panels with two steel cover plates and vertical webs as internal stiffeners had been widely used in the ship industry, decks and parking houses. These structures have high stiffness and low weight. Although, a large number of steel I-core sandwich panels were designed and built, the effects of their details on their response under blast loading are not well understood. Energy dissipation in blast loaded structures is one of the most important parameters in analysis and design. Considering this fact, the current work seeks to numerically study the validity of soft core hypothesis, using a hollow I-core that allows more substantial plastic deformation and subsequently less back plate deflection. For this purpose, a series of holes were considered in the core elements of conventional I-core steel sandwich panels and potential influences of such configuration was assessed in detail. In this paper, the response of this novel steel I-core sandwich panel under blast loading was numerically investigated. The main aim of this study was to determine the dynamic response of the steel sandwich panel with hollow I-core, considering the effect of the core's elements number, charge weight and strain rate on dynamic response of the panels. Since the details can affect the dynamic response of these panels, several parameters such as boundary conditions, strain rate and asymmetrical blast loading were considered in this study. Special emphasis was placed on the evaluation of midpoint displacements and energy dissipation of models.

FINITE ELEMENT MODEL

Geometry of Models

In this study, two numerical models were considered, as shown in Figure 1. The dimensions of all numerical models were 1500×1500 mm^2. Thickness of face plates in sandwich panels was 8 mm. The dimensions of models are listed in Table 1. The core plate of the sandwich structures was assumed to be hollow. The geometry of the hollow core is shown in Figure 2.

Table 1. Dimension of core and face plates

Model	Thickness of face plates	Thickness of core plates	Number of core plates
1	8 mm	1 mm	4
2	8 mm	0.5 mm	9

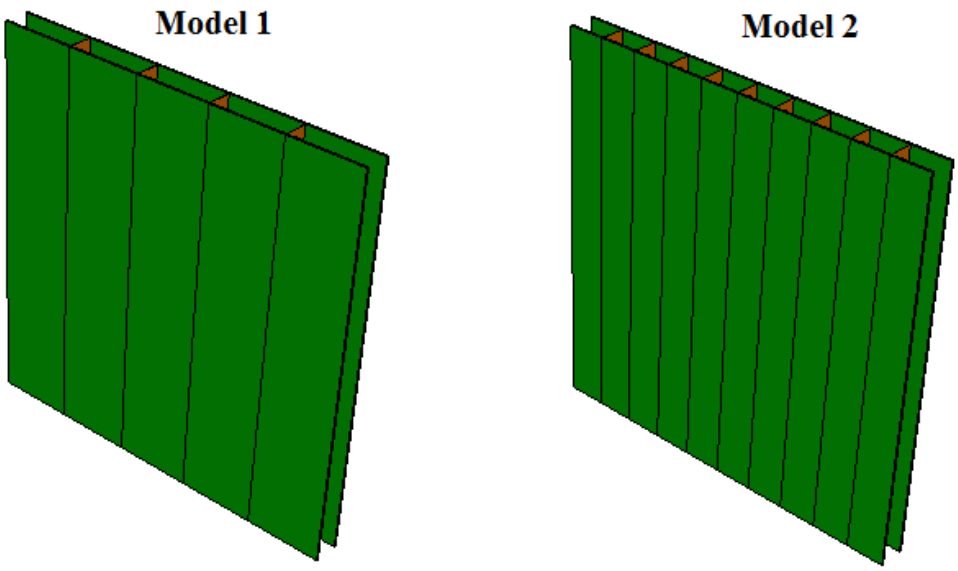

Fig. 1. Geometry of sandwich panel

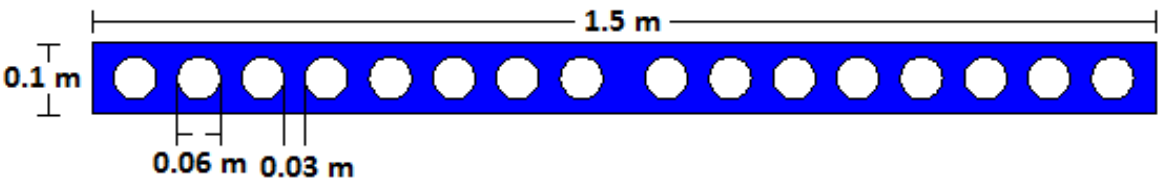

Fig. 2. Geometry of core elements

Material Property

In this study, the elastic part is defined by Young's modulus and Poisson's ratio. The plastic part is defined as the stress and plastic strain. The material will behave as an elastic material up to the yield stress and after this stage, it goes into the strain hardening stage until reaching the ultimate stress. In this paper, the yield stress of all members is 300 MPa and Young's modulus is 210 GPa. Poisson's ratio is 0.3. The plastic part is defined using a curve as shown in Figure 3. It should be noticed that the elastic part is not shown in this figure.

Constructional steel showed an increase in the yield stress with increasing strain rate. In the case of high-rate loading such as blast or impact, strain-rate dependency is likely to be determinant. Strain-rate effects are included by adjusting the material dynamic yield stress at each Gauss point according to Eq. (1) (Jones, 1989).

$$\sigma_y = \sigma_0 \left[1 + \left| \frac{\dot{\varepsilon}}{D} \right|^{\frac{1}{n}} \right] \tag{1}$$

where σ_y and σ_0: are dynamic and static yield stresses, respectively. D and n: are experimentally defined material constants. On the basis of this relation, it is obvious that the static and dynamic yield stress ratio depends on deformation speed. In this numerical study, the 3 sets of values for D and n were adopted: (1) D = 40s^{-1} and n= 5; (2) D = 240 s^{-1} and n = 4.74; (3) D = 6844 s^{-1} and n= 3.91 (Boh et al., 2004; Tavakoli and Kiakojouri, 2014).

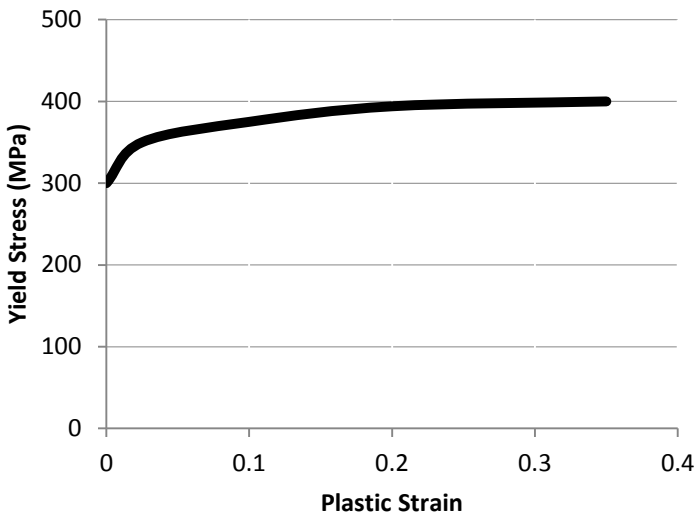

Fig. 3. Plastic property

Loading and Boundary Condition

The threat for the conventional bombs is defined by two variables, charge weight and the stand-off distance between the blast source and the target. Figure 4 shows a typical blast pressure profile. The pressure time-history was divided into a positive and a negative phase. In the positive phase, maximum overpressure, P_s^+, was developed instantaneously and decayed to atmospheric pressure, P_0, in time T^+. For the negative phase, the maximum negative pressure, P_s^-, has lower amplitude than the positive overpressure. The duration of the negative phase, T^-, was longer as compared to the positive duration. The pressure time-history in Figure 4 can be approximated by the exponential Eq. (2) (Ngo et al., 2007).

$$P(t) = P_s^+ (1 - \frac{t}{T^+}) e^{\frac{-bt}{T^+}} \qquad (2)$$

where $P(t)$: is overpressure at time t, P_s^+: is maximum over pressure and b: is an experimental constant.

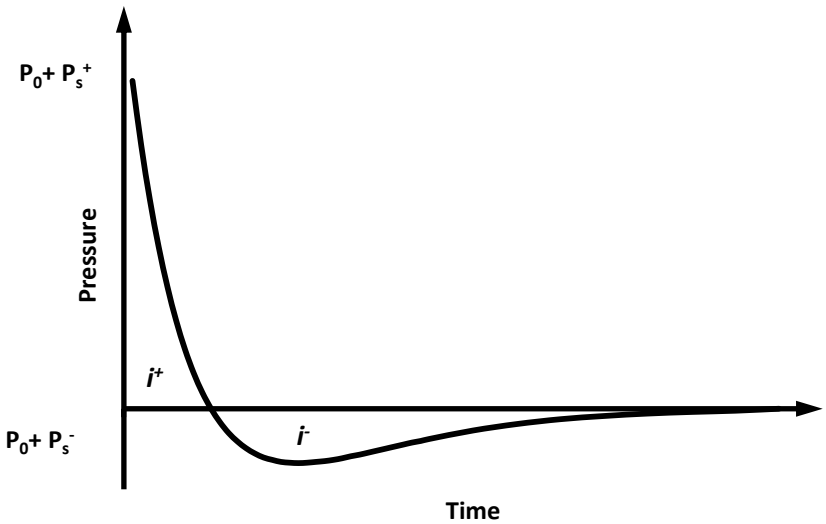

Fig. 4. Blast pressure time-history

The loading effects due to an explosion in air can be defined for spherical incident waves (air blast) or hemispherical incident waves (surface blast), by empirical data provided by the CONWEP model, in conjunction with the incident wave loading definition (Simulia, 2010).

For a given scaled distance, the model provides the following data: the maximum overpressure, arrival time, positive phase duration and the exponential decay coefficient. Using these parameters, the entire time history of both the positive and negative pressure, as shown in Figure 4 can be constructed (Simulia, 2010).

In this study, 1.5, 3, and 4.5 Kg TNT loads were used. The stand-off distance was 500 mm for all models and charges. To study the effects of asymmetrical loading, in addition to symmetrical blast loads (500 mm stand-off distance above center of panels) asymmetrical blast loads were also considered with the blast source above the point (hypocenter) with the 50 cm distance of the perpendicular edges.

Three sets of boundary conditions were used in this study: perfectly fixed (BC1), two edges fixed (the fixed edges and I-core are parallel, BC2) and two edges fixed (the fixed edges and I-core are perpendicular, BC3).These boundary conditions were applied to both cover plates.

In this study, all comparisons were made with reference to perfectly fixed boundary condition and symmetrical blast loading, unless otherwise specified.

Analysis Procedure and Element Type

For dynamic finite element analysis, the explicit method was used because it is more efficient than the implicit integration method for solving extremely short-term events such as blast, explosion and impact. Since thickness of face plates and core was significantly smaller than any other dimensions, shell elements were used to model the plates and core. In this paper, the fourth nodded doubly curved shell element, S4R, was used to model plates and stiffeners. S4R is a 4-node general-purpose shell, quadrilateral, stress/displacement shell element with reduced integration and a large-strain formulation (Simulia, 2010).

VALIDATION

Material and Model

The sandwich panel described by Dharmasena et al. (2008) was used for validation of FE modeling. As shown in Figure 5, sandwich panel consists of a square honeycomb core with vertical webs connected to the top and bottom plates. The overall dimensions of panel are 610×610×61 mm^3. The top and bottom plates are 5 mm thick, and the square honeycomb core webs are 0.76 mm. All parts of the sandwich panel are made of a highly ductile stainless steel alloy comprised of 49% Fe, 24% Ni, 21% Cr, and 6% Mo by weight as described by Nahshon et al. (2007).The mechanical properties of the steel as described in Nahshon et al. (2007) are specified as follows: Young's modulus of 1.61×10^5 MPa, Poisson's ratio of 0.35, density of 7.85×10^{-9} metric tons/mm^3. A Johnson-Cook model was used to model the elastic-plastic behavior with the following parameters: A=400 MPa, B=1500 MPa, C=0.045, n=0.4, m=1.2 and $\mathcal{E}$=0.001s^{-1}.

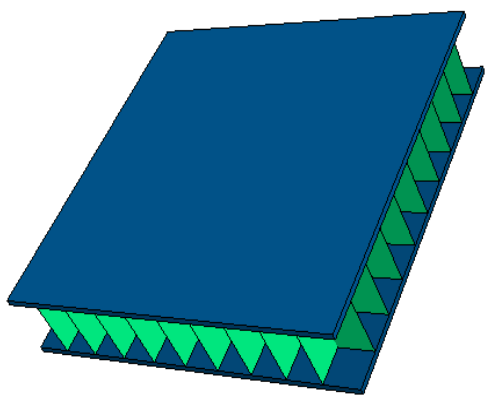

Fig. 5. Square honeycomb core with vertical webs

Here, symmetry behavior was assumed; therefore, only one-quarter of the panel was

modeled. The source of the blast is at a stand-off distance of 100mm vertically above the center of the top surface of the cover plate, as described by Dharmasena et al. (2008). The edges of the structure are fixed. The property of the blast load was specified using charge property. 1, 2, and 3 kg TNT loads were used in this study respectively. General contact was specified in the analysis, including all exterior surface contact interactions. The center deflection after 1.5 milliseconds was considered, so as to compare each case with the experimental results (Dharmasena et al., 2008).

The results were compared within acceptable error with the experimental results. The comparison of results is presented in Figure 6. As described by Dharmasena et al. (2008) at higher loads, it was likely that the edges of the panels used in the test arrangement were actually more flexible than the clamped condition used in the finite element model, causing differences between the numerical and experimental results. Differences in the results could also be due to debonding of the core webs from the top and bottom faces in the experimental set-up (Dharmasena et al., 2008). Figure 7 showed deformed shapes of sandwich panels under different explosive charges.

The panels used by Dharmasena et al. (2008) and the panels presented in this paper are made of different material models. Although, the results show good correlation between the presented numerical model and the experiments carried out in the study of Dharmasena et al. (2008), this does not validate the entire model. In order to validate the materials used in their current model, a circular plate subject to blast loading as a result of the blast of 50 kg of TNT, 0.5 m directly above the center of the plate, as described by Neuberger et al. (2007), was considered. In this part, this blast loaded plate was numerically investigated in order to verify the model structures.

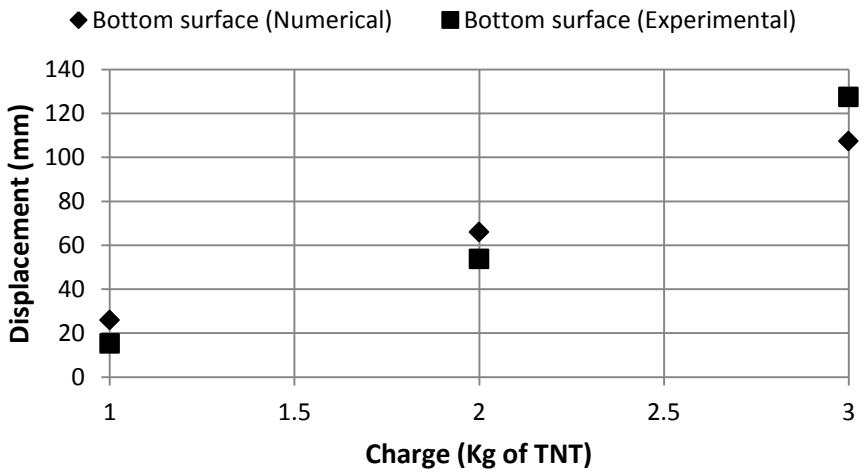

Fig. 6. Comparison of numerical and experimental results

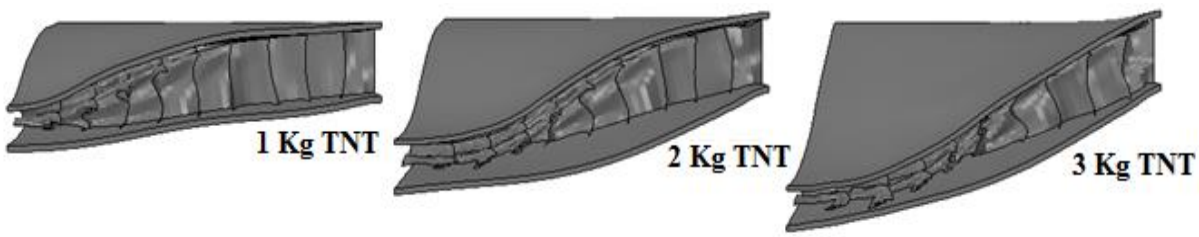

Fig. 7. Deformed shape of sandwich panel subjected to different charges

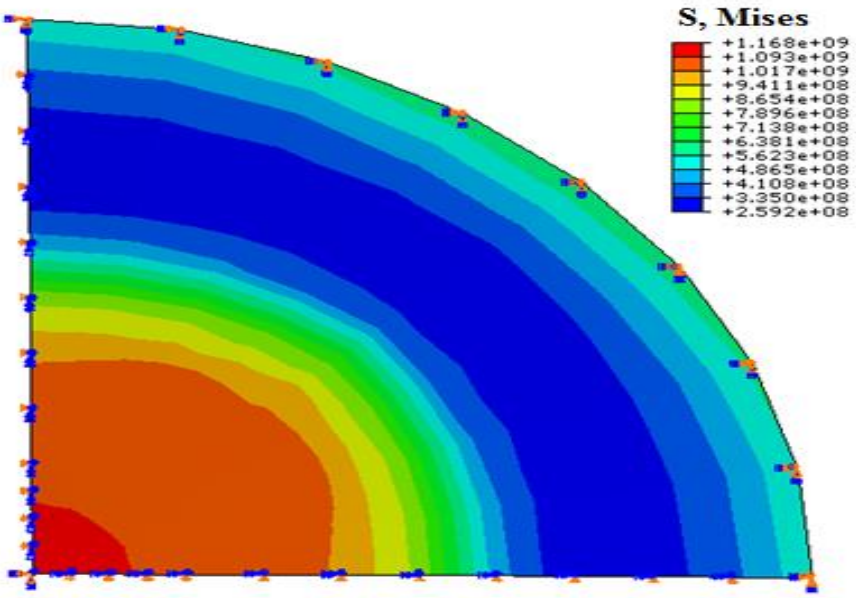

Fig. 8. Mises contours of one-quarter plate

The plate has a radius of 1 m and a thickness of 0.05 m. One-quarter of the plate was modeled using shell elements (Figure 8). Blast loading was applied on the top surface of the plate. The density of the plate material is 7850 Kg/m^3, Young's modulus is 210 GPa and Poisson's ratio is 0.28. The plastic property was modeled with an isotropic hardening bilinear model, with yield stress of 1000 MPa. A non-linear dynamic analysis was performed for a period of 4 milliseconds. The plate was supported by two thick armor steel plates with circular holes tightened together with bolts and clamps. The armor plate that faces the explosive charge has a hole with inclined side walls, to prevent reflection of the blast to the tested plate. The measurement of the maximum dynamic displacement of the plate was achieved by a special comb-like device. The TNT charges were hanged in air using fisherman's net and ignited from the center of the charge (Neuberger et al., 2007).

The time-history of the displacement at the midpoint of the plate was modeled using S4R elements which follow closely the result presented in Neuberger et al. (2007), as shown in Figure 9. The time-history of the Mises stress at the plate center is presented in Figure 10.

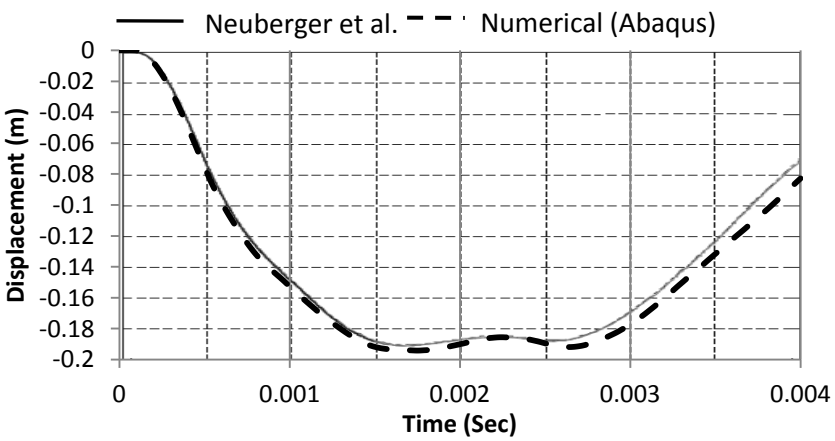

Fig. 9. Time-history of midpoint displacement

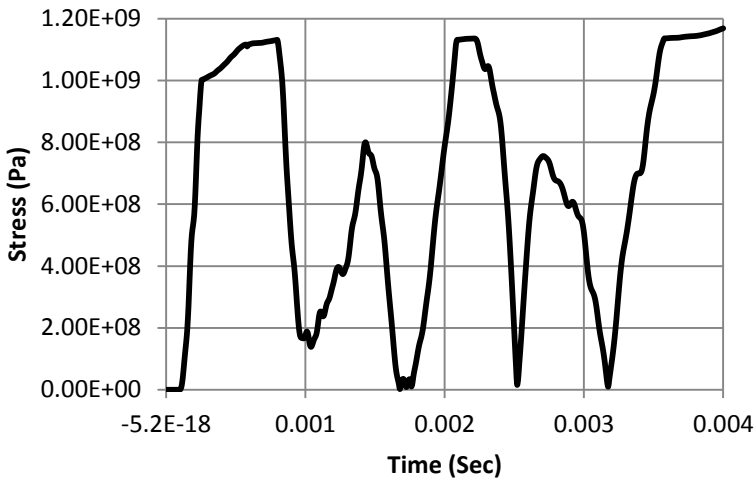

Fig. 10. Time-history of mises stress

Mesh Dependency

It is known that the non-linear analysis depends on mesh configuration. On the other hand, the mesh size was also limited by the computer speed and the dimensions of the numerical model. In non-linear finite element analysis, one of the major features in the numerical simulation of blast loaded structures was the use of an adequate mesh size.

In this study, three different models consisting of shell elements of size 0.03, 0.06 and 0.09 m were used to verify the accuracy of the finite element models. As expected, refining the mesh led to changes in the response of the panel under blast loads, as shown in Figure 11. Results do not change noticeably using meshes finer than 0.03, indicating that this mesh size is adequate and the model has sufficient accuracy. In this study, all other comparisons were made with reference to this mesh to ensure the accuracy of FEA.

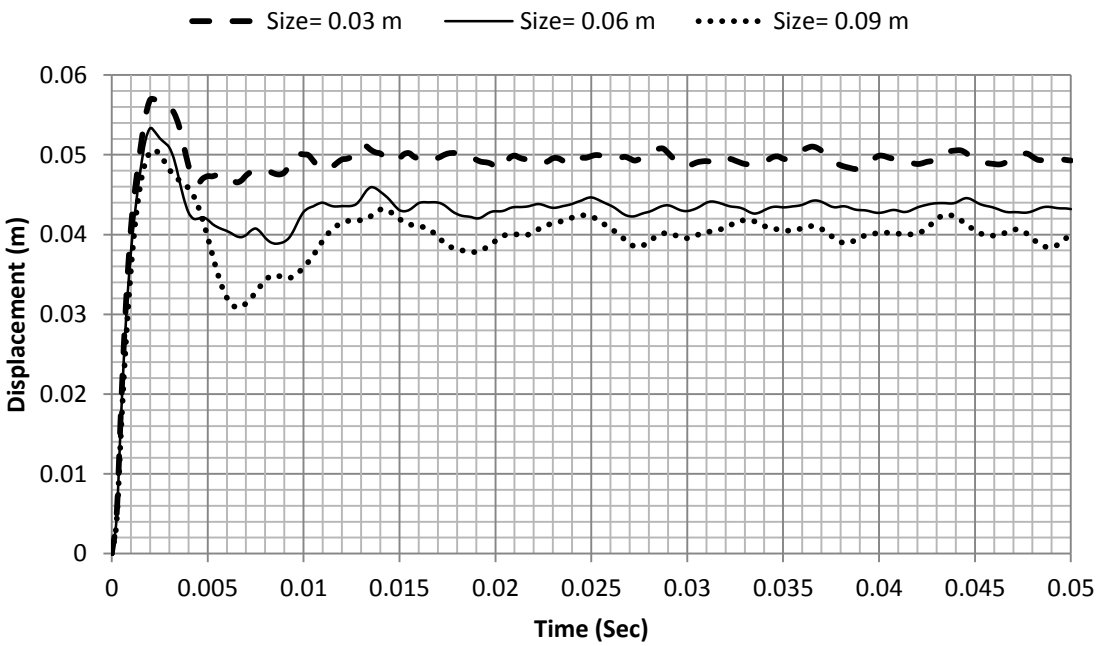

Fig. 11. Influence of mesh size (Model 1, 3 Kg TNT)

RESULTS

Dynamic Response under Different Charge Weights

Figures 12-17 show the midpoint displacements of sandwich panels' front and back plates, under different explosive charges as presented above. As expected, front plates had more displacement than back plates because of energy dissipation in core elements. The differences between displacements of the two cover plates increased as the explosive charge increased. Figure 18 showed displacement counter for the front and back plates of Model 2 subjected to 4.5 kg of TNT.

As shown in Table 1, although, the thickness of cover plates is the same for all models, two different thicknesses were used for the core elements (the numbers of core elements were also changed to keep the total weight intact), (Table 1). According to the results, with increase in the applied blast loads, the effectiveness of numerous thin elements versus fewer and thicker web elements was enhanced.

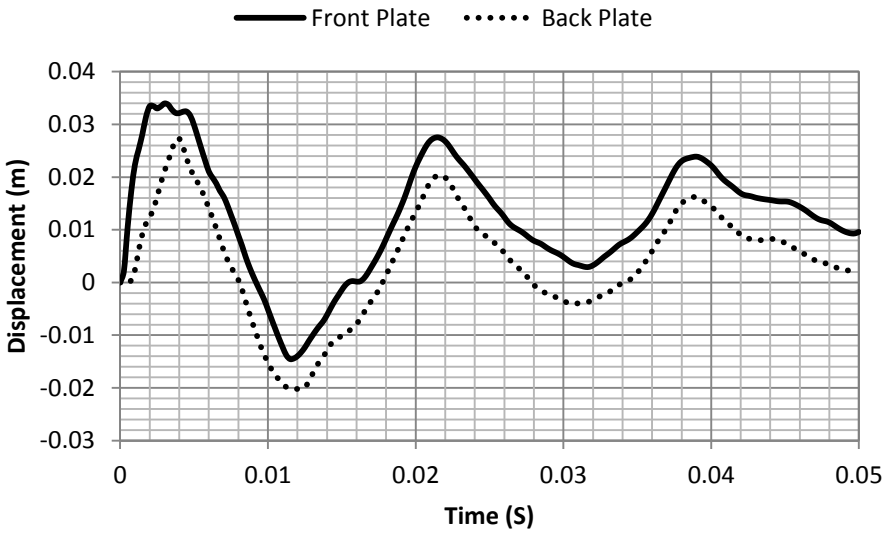

Fig. 12. Time history of midpoint displacement (Model 1, 1.5 Kg TNT)

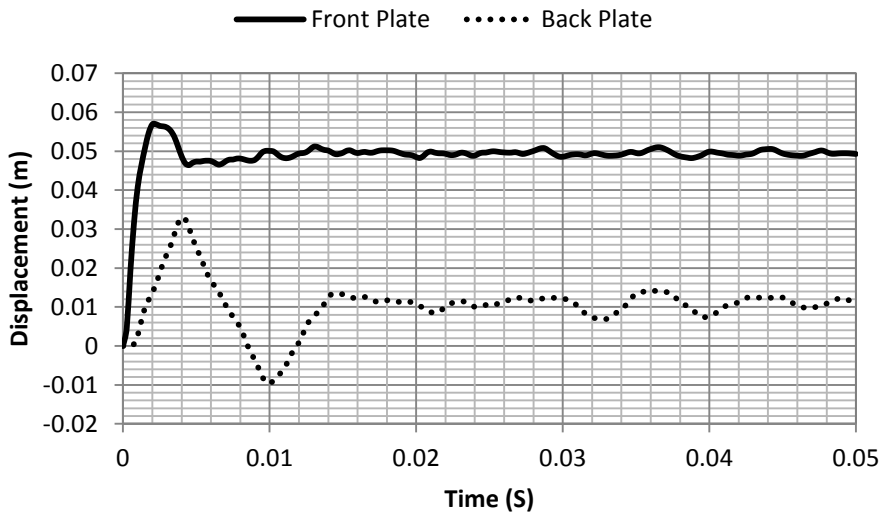

Fig. 13. Time history of midpoint displacement (Model 1, 3 Kg TNT)

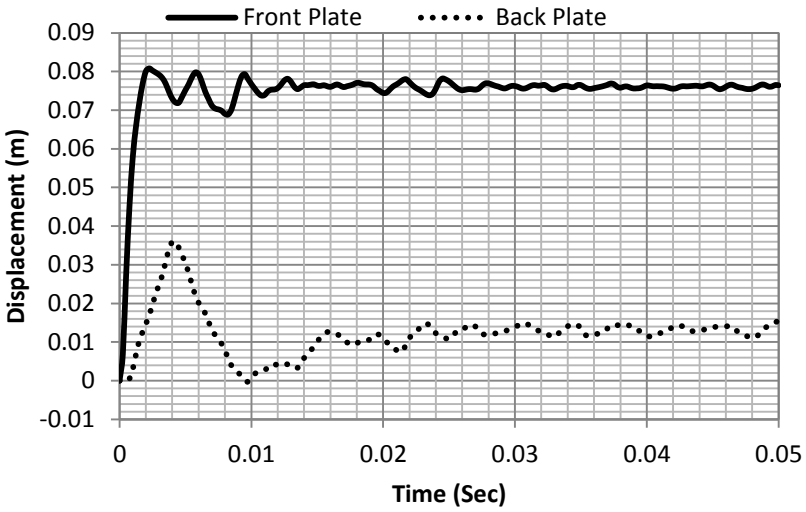

Fig. 14. Time history of midpoint displacement (Model 1, 4.5 Kg TNT)

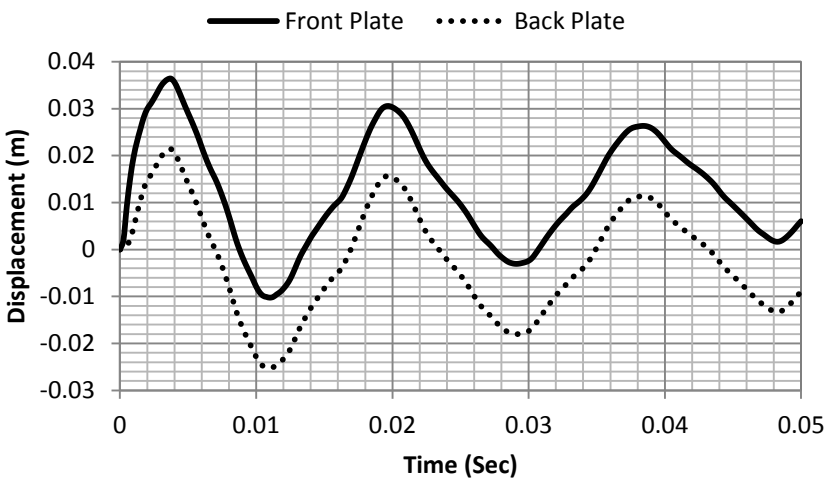

Fig. 15. Time history of midpoint displacement (Model 2, 1.5 Kg TNT)

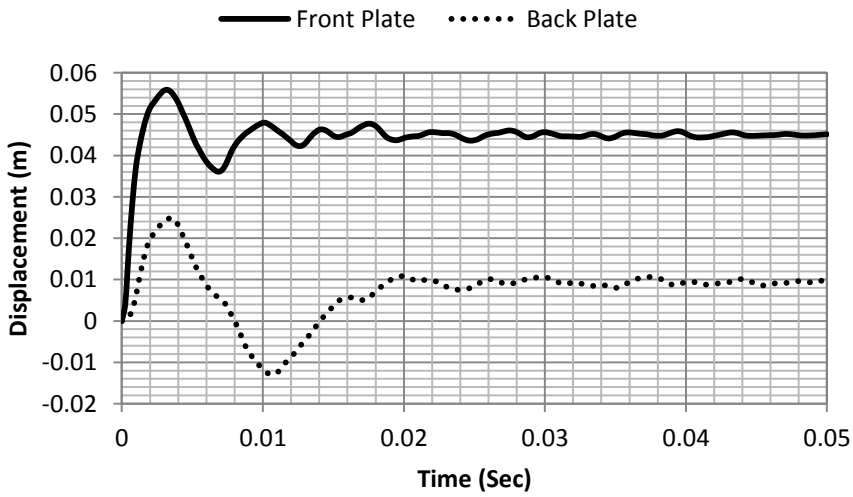

Fig. 16. Time history of midpoint displacement (Model 2, 3 Kg TNT)

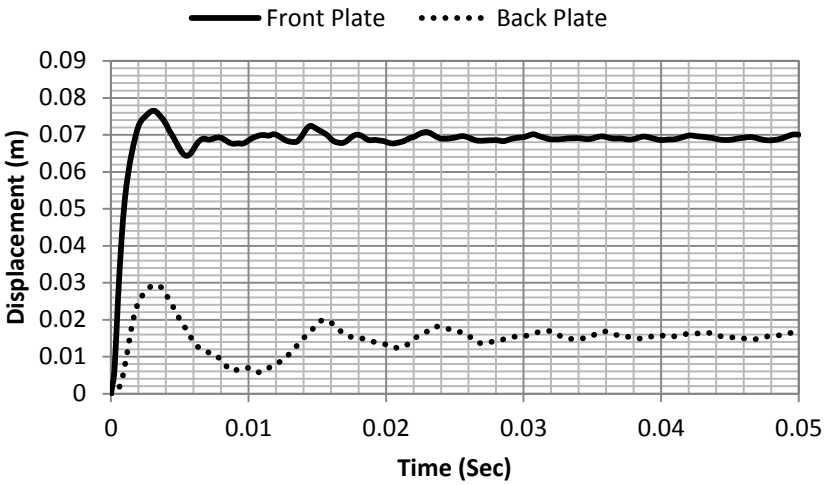

Fig. 17. Time history of midpoint displacement (Model 2, 4.5 Kg TNT)

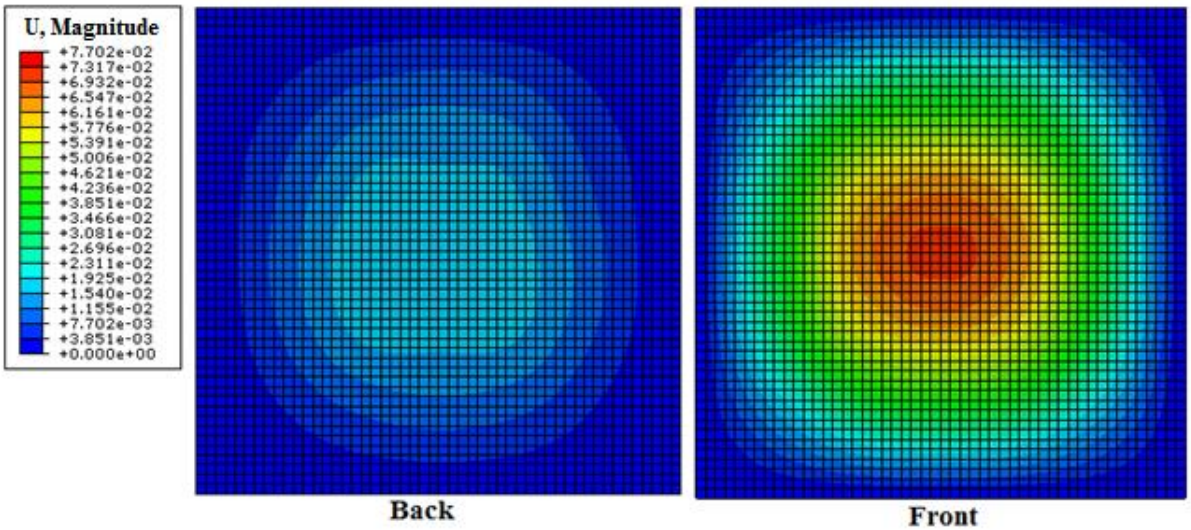

Fig. 18. Displacement counters (meter) for Model 2 under 4.5 Kg TNT

Comparison with Equivalent Structures

To evaluate the influence of this novel structural arrangement, a solid plate with same weight and material was modeled and analyzed under blast load and the results obtained were used for comparison (Figure 19a). In addition, a sandwich panel without holes in the core elements (conventional I-core sandwich panel, Figure 19b) was considered and the results compared with the new configuration. Two panels were quite similar (geometry, material and loading) but the only difference was in the web's opening.

Figure 20 shows the midpoint displacement of the equivalent solid plate under different explosive charges. The benefits of a sandwich panel over a solid plate to withstand blast loads are clearly evident by the lower back plate deflections, when compared with the equivalent weight solid plates subjected to the same blast loads. The benefits of such structure are especially important at high blast loads (4.5 Kg TNT), wherein the midpoint displacement of the back faces was only about 50-60% of those for the solid plate.

At low impulse levels (1.5 Kg TNT), the benefits decreased and displacements of the sandwich panels was about 70-90% of the solid plate. Therefore, the panels should be designed according to the possible blast loads to achieve its maximum benefits due to plastic dissipation. In Table 2, maximum midpoint displacement of these numerical specimens is presented.

According to the results, sandwich panels with hollow I-core allow more plastic deformation and energy dissipation than conventional I-core sandwich panel under blast loads. The performance of hollow I-core increased as blast loads increased, because more plastic dissipation is expected in high explosive charge. As shown in Figure 21, the midpoint displacements of two panels, with or without hole, are almost identical in 1.5 Kg TNT, but in higher blast loads (3 and 4.5 Kg TNT) the maximum response of the hollow I-core sandwich panel decreased significantly.

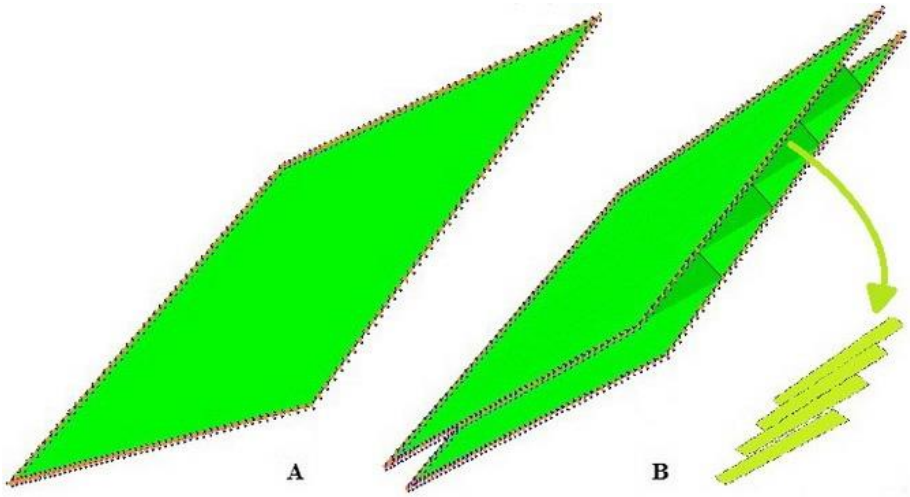

Fig. 19. Equivalent solid plate (A) and sandwich panel without hole in core (B)

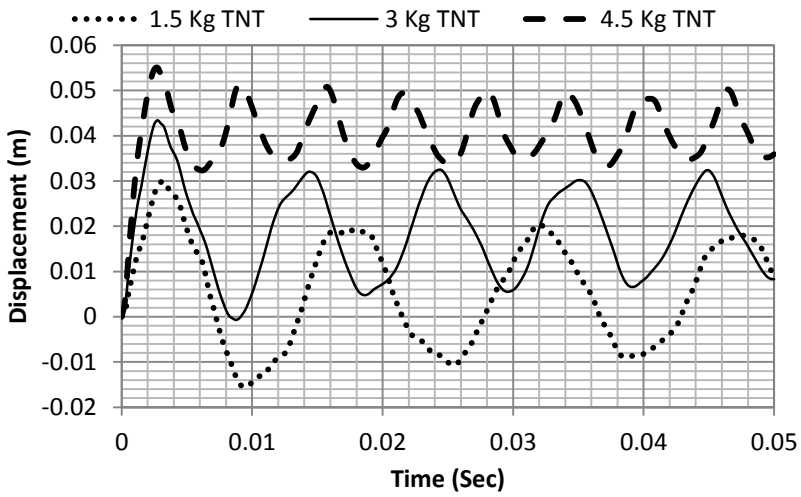

Fig. 20. Time history of midpoint displacement of equivalent solid plate

Table 2. Maximum midpoint displacement (meter) under blast loading

Displacements (in meter)	Model 1		Model 2		Solid Plate
	Front Plate	Back Plate	Front Plate	Back Plate	
1.5 Kg TNT	0.0339	0.0272	0.0364	0.0213	0.0299
3 Kg TNT	0.0569	0.0329	0.0558	0.0248	0.0434
4.5 Kg TNT	0.0808	0.0359	0.0764	0.0293	0.0550

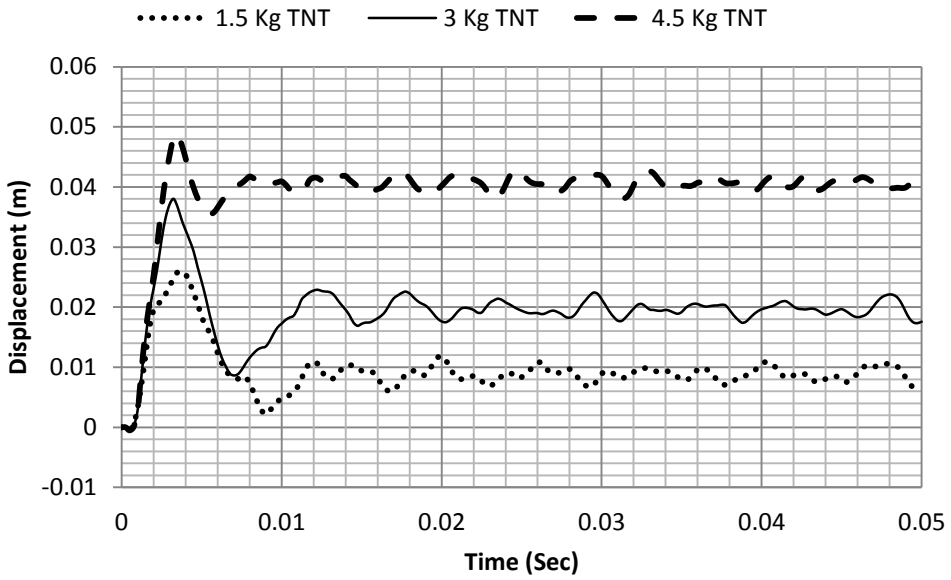

Fig. 21. Time history of midpoint displacement of equivalent sandwich panel without hole in core (Model 1, back plate displacement)

Energy of Models

Comparison of the history of total work done and the history of total plastic dissipation, shows that most of the work done by the blast loads was dissipated by plastic deformation. As charge weight increased, this effect intensified. Figures 22 and 23 show comparison of total work and plastic energy history for two different charges in Model 1.

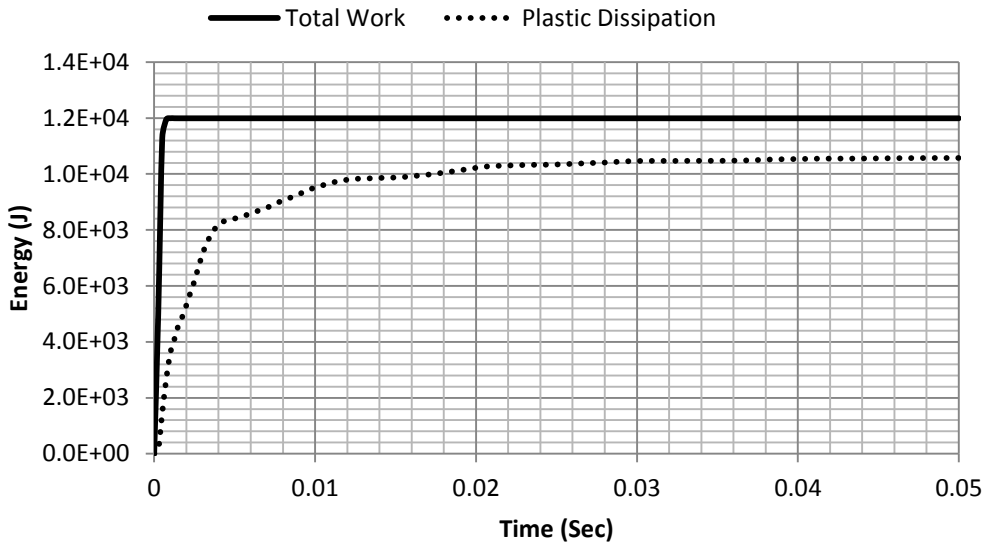

Fig. 22. Comparison of total work and plastic dissipation energy (Model 1, 1.5 Kg TNT)

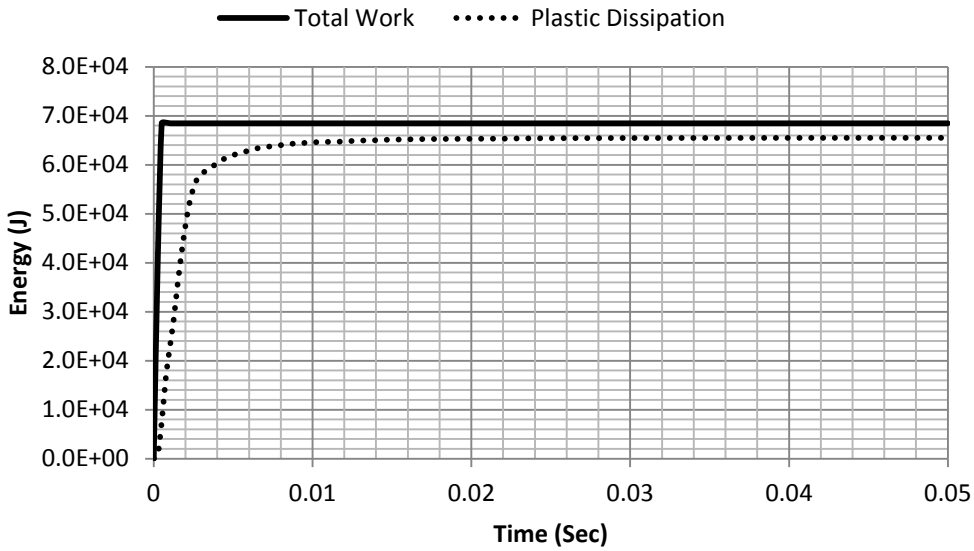

Fig. 23. Comparison of total work and plastic dissipation energy (Model 1, 4.5 Kg TNT)

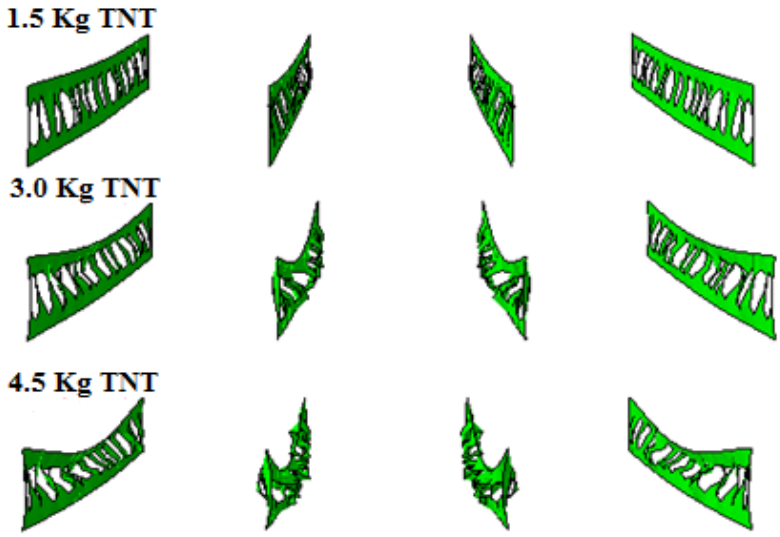

Fig. 24. Core's deformation under different loads (Model 1)

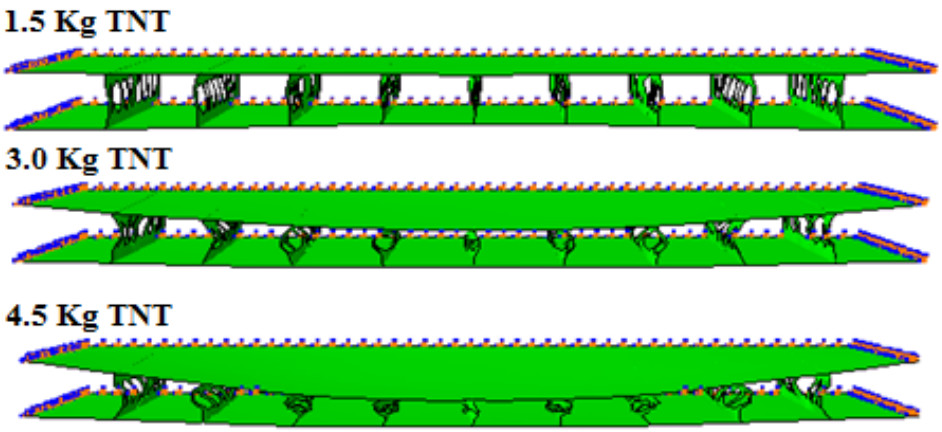

Fig. 25. Cross-section of deformed shape under different loads (Model 2)

It was evident that the displacements of the midpoint of the back plates do not change considerably for all applied blast loads. Almost complete densification of the mid-area of the core elements occurred in the largest load (4.5 Kg TNT) (Figures 24 and 25). Most of the applied blast loads were dissipated in the core's elements by plastic deformation. During explosion, the kinetic energy can partially be absorbed by the bending and tensioning of the structure, that is, a global response of the whole structure. On the other hand, a large amount of the kinetic energy was dissipated by the plastic deformation, especially in cores elements, which deform locally (Zhu, 2008). Comparison of plastic energy dissipation for Models 1 and 2 are presented in Figures 26 and 27, respectively.

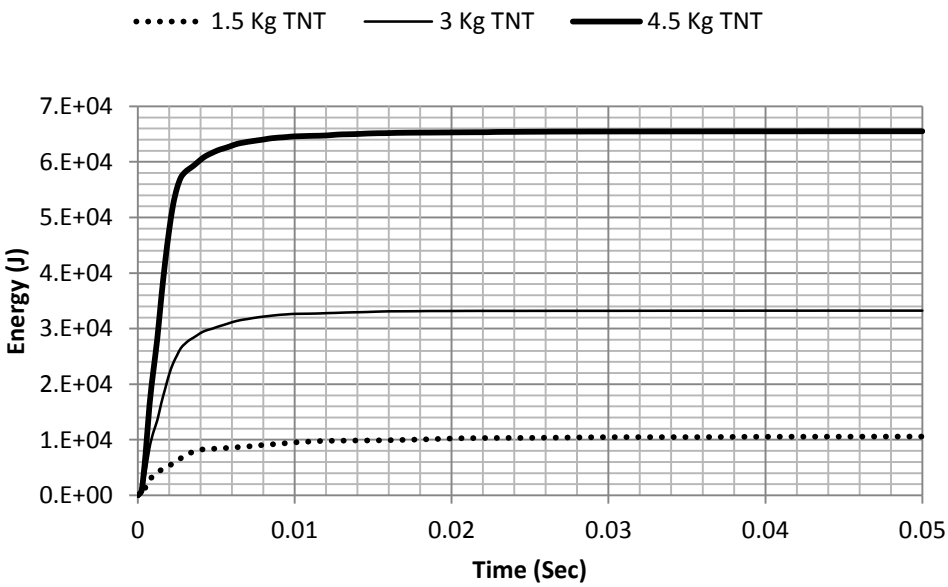

Fig. 26. Comparison of plastic energy dissipation for Model 1

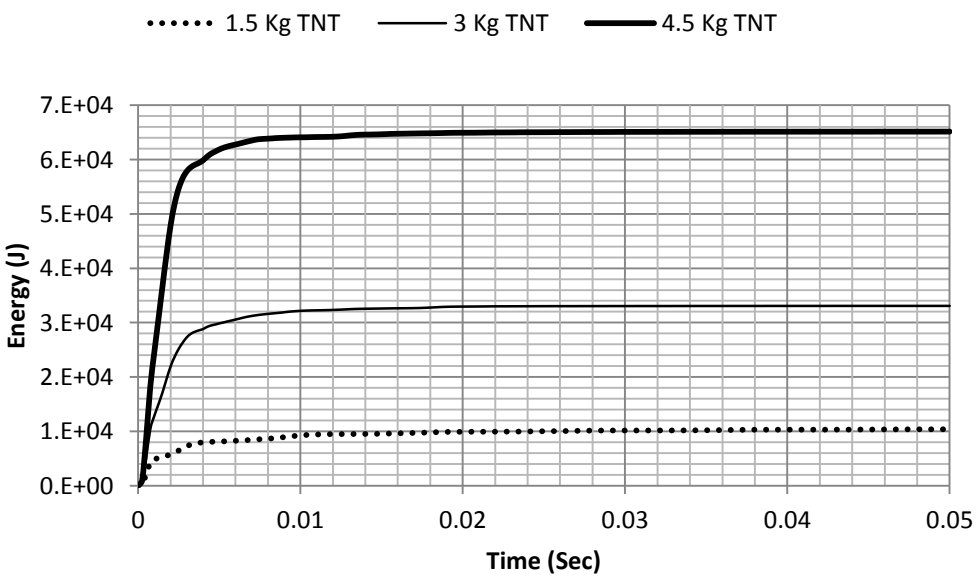

Fig. 27. Comparison of plastic energy dissipation for Model 2

Influence of Strain Rate

Blast loads produce very high strain rates (10^2 - 10^4 s^{-1}). This high loading rate would alter the dynamic mechanical properties of target structures. When strain rate dependency was included in the numerical analysis of blast loaded structures, the yield stress increased as the strain rate increased and because the elastic modulus was higher than the plastic modulus, a stiffer response was achieved in the analysis and less deflection was obtained. Norris et al. (1959) investigated steel with different static yield strength under tension at different strain rates. According to their results, strength increase of 9-23% was observed for the different steel types. This fact was further confirmed by the observation of results obtained by the current numerical study. However, the rate of decrease in midpoint displacements depends on the charge weight and results are sensitive to the values of adopted material data, D and n. Therefore, more precise data would be required for analyses and design purposes. Time history of the midpoint displacements of the Model 1 for 1.5 Kg and 4.5 Kg charge are shown in Figures 28 and 29, respectively.

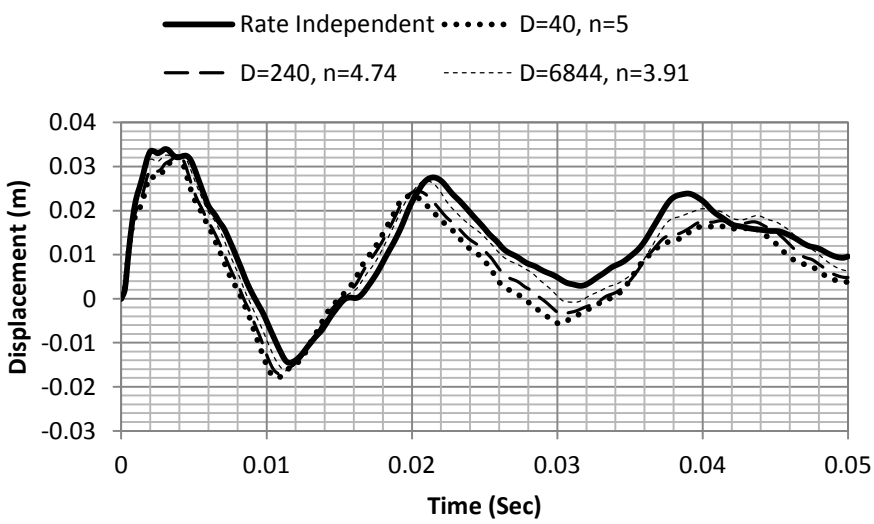

Fig. 28. Strain rate effect on displacement of front plate (Model 1, 1.5 kg TNT)

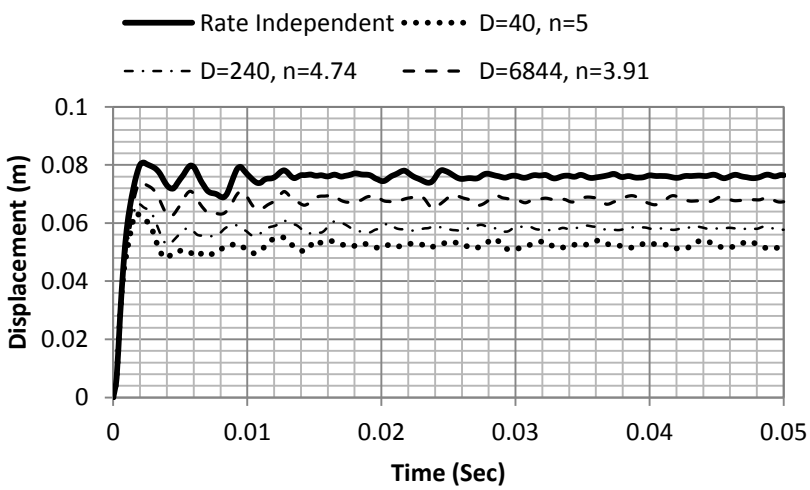

Fig. 29. Strain rate effect on displacement of front plate (Model 1, 4.5 kg TNT)

Asymmetrical Blast Loading

To study the effects of asymmetrical blast loads, Model 1 was analyzed under different charges with the 50 cm stand-off distance directly above a point with 50 cm distance from edges of the panel and displacement time history of center of the panel and the point directly under the blast center in the panel were observed. Figures 30 to 32 show the displacement time-history for 1.5-4.5 Kg explosive charges, respectively. According to the results for all front plates, maximum displacements in the hypocenter exceeded the displacement in the center of the plate due to the localized nature of blast loads and subsequently more pressure was applied to hypocenter. On the other hand, for the back plates, the displacement in the center was more than the hypocenter because plastic deformation in core elements dissipated most of the blast energy and therefore, the response of back plates was smoother. This phenomenon is a function of the distance from the boundary conditions. The center of the plate has more distance from the clamp boundary conditions and therefore its response is less stiff. Asymmetrical blast loads did not only change the overall response of panels as discussed earlier, but also affected the stress distribution pattern. Figure 33 shows the deformed shape and stress distribution in Model 1 subjected to 4.5 Kg asymmetrical blast loads, as presented in this figure, stress concentrated in the hypocenter of blast loads and nearby core elements.

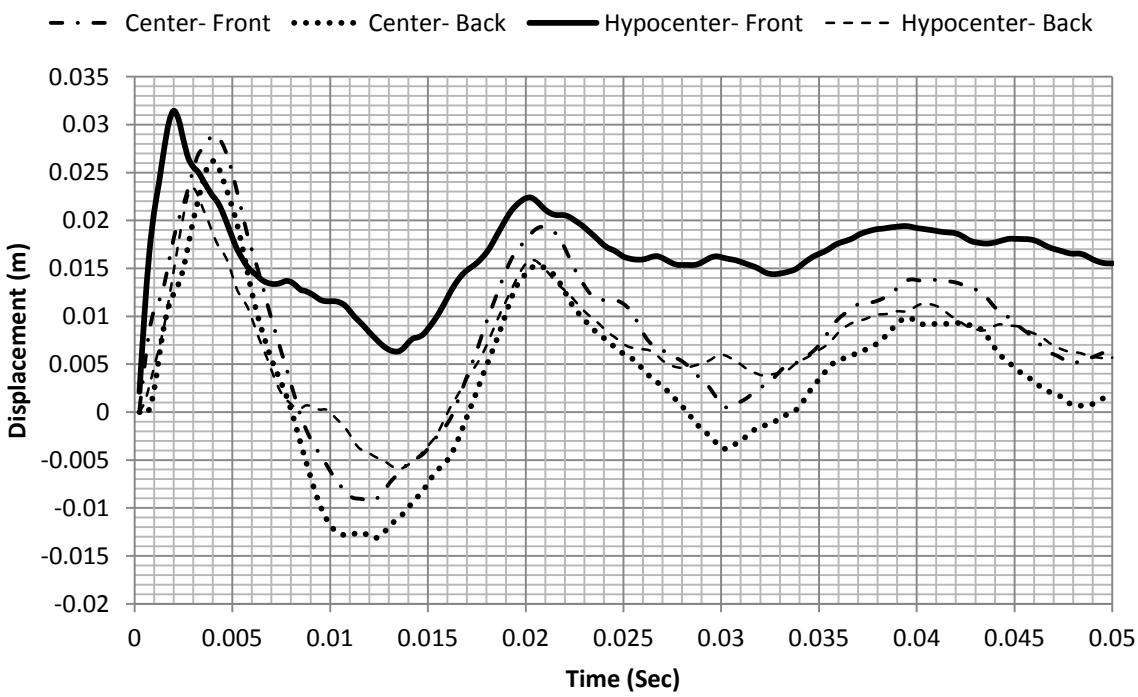

Fig. 30. Displacement time-history under asymmetrical blast load (Model 1, 1.5 Kg TNT)

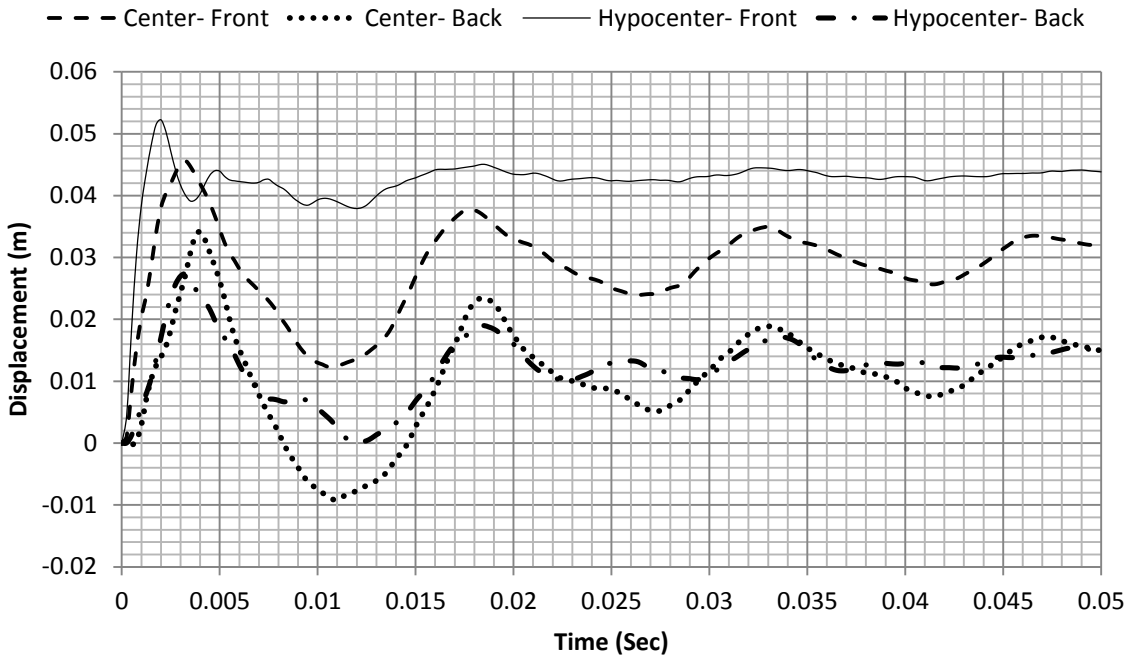

Fig. 31. Displacement time-history under asymmetrical blast load (Model 1, 3 Kg TNT)

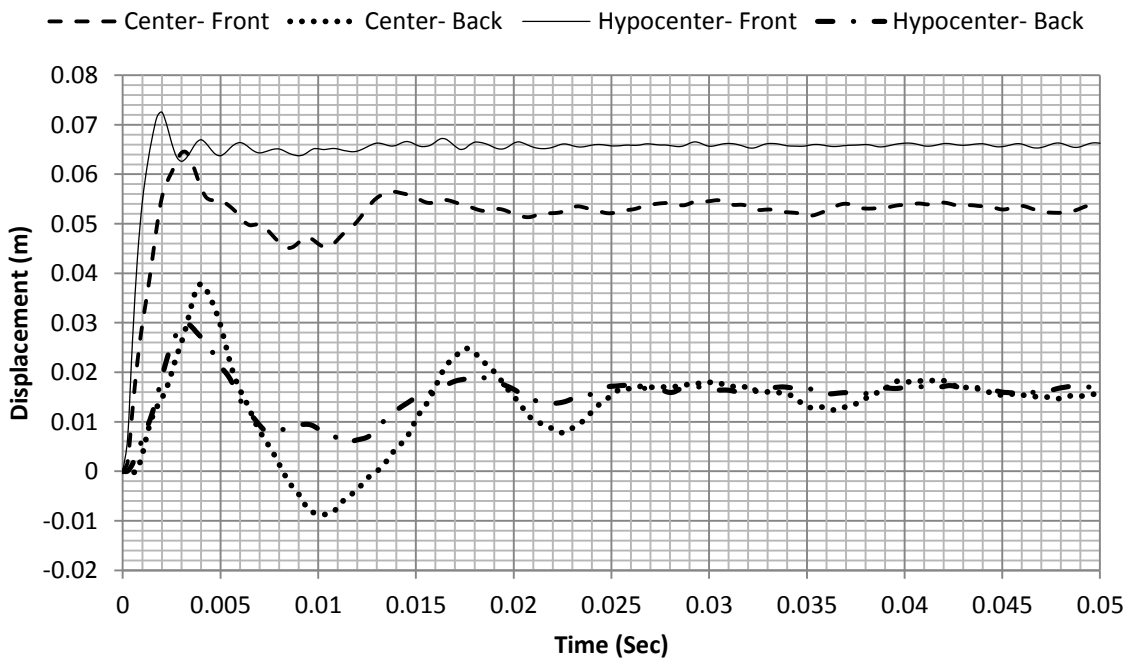

Fig. 32. Displacement time-history under asymmetrical blast load (Model 1, 4.5 Kg TNT)

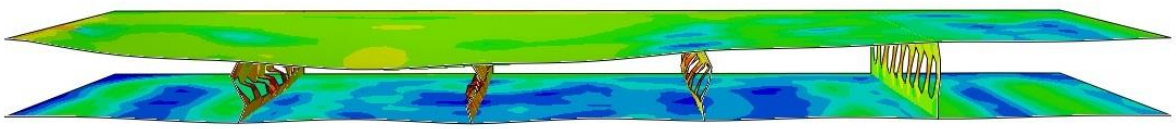

Fig. 33. Cross section of deformed shape of Model 1 subjected to asymmetrical blast loads

Influence of Boundary Condition

As mentioned in Section 2.3, in this study, three states of boundary conditions were adopted for panels. These boundary conditions were applied to both cover plates. The main conclusions of this study are that the boundary conditions of plates have a significant influence on the dynamic response under blast loading. Freedom of edges increased the midpoint displacement especially in the free vibration phase, as shown in Figure 34.

Figures 35 and 36 show the displacement time history of the center of the panel and also middle of the free edges for BC2 and BC3. As presented in these figures, for front plates, the displacement history of the center was always bigger than the middle of the free edges, while the back plate displacement of free edges exceeded the center due to boundary effects. Therefore, in the design and construction of sandwich panels with free edges, such a phenomenon should be considered.

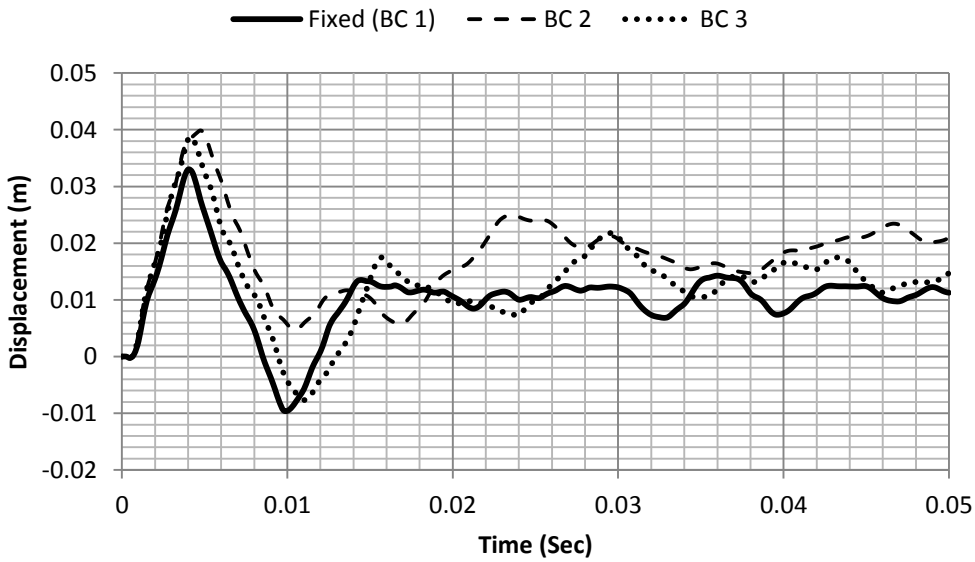

Fig. 34. Influences of boundary conditions (Model 1, 3Kg TNT)

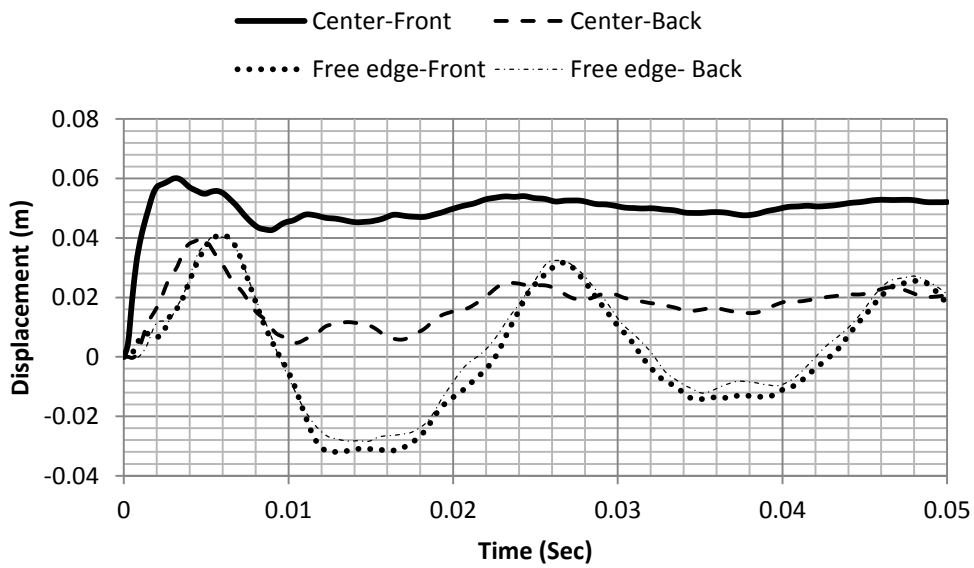

Fig. 35. Displacement time history for Model 1 (BC2, 3 Kg TNT)

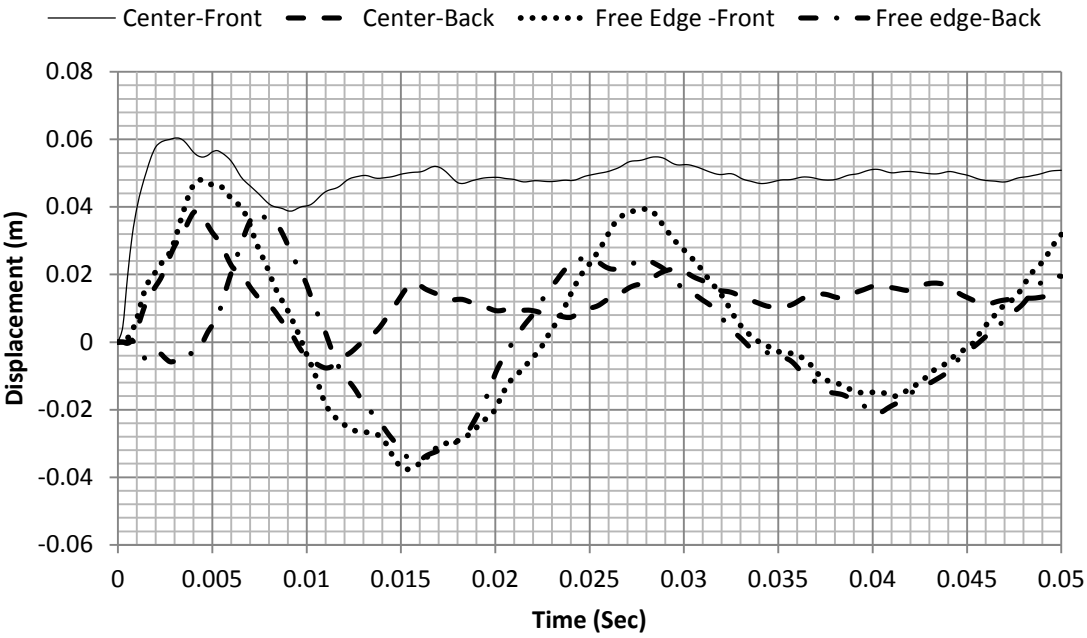

Fig. 36. Displacement time history for Model 1 (BC3, 3 Kg TNT)

CONCLUSIONS

In this paper, the dynamic response of a novel steel I-core sandwich panel with hollow web under blast loading was numerically investigated. The numerical results were compared with the available experimental data and good agreement was observed. Different parameters such as I-core configuration, mesh dependency, boundary conditions, explosive charge weight, asymmetrical loading and strain rate were considered in this study and effects of changing the earlier mentioned parameters were quantified.

According to numerical results, the dynamic response of the panel, as expected, are drastically dependent on explosive weight and with the increase of the charge weight, the effectiveness of numerous thin web elements versus fewer and thicker web elements was enhanced. Boundary conditions of plates have a significant influence on the dynamic response under blast loading. Freedom of edges increased the midpoint displacement, especially in the free vibration phase. While for front plates, the displacement history of the center is always bigger than the middle of the free edges, back plate displacement of free edges may exceed the center. Therefore, in the design and construction of sandwich panels with free edges, such a phenomenon should be considered. Results also show that when rate dependence was included, the midpoint displacement decreased, therefore the effects of strain rate should be incorporated in the FE analysis of blast loaded panels. However, the rate of decrease depends on the charge weight and results are sensitive to the values of the adopted material data.

The proposed structural model was also compared with equivalent structures and according to the results, sandwich panels with hollow I-core allow more plastic deformation, energy dissipation and less midpoint displacement than the conventional I-core sandwich panel and equivalent solid plate. In comparison with the equivalent solid plate, the benefits of the novel structure are particularly important at high impulse loads, and at low impulse levels the benefits decrease. Therefore, the panels should be designed according to possible specific blast loads to achieve its maximum benefits.

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