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## Impact of blast hazard on lightweight sandwich structure performance

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### Abstract

The use of explosives to attack vehicles has been increased during the last few years. The terror attacks lead to death of innocent people (civilian and military). The armored vehicles should be protected from explosives attacks using light weight sandwich structure.

In this study, the protection system against blast effect is highlighted using composite structures to protect vehicles. Blast field test is expensive to conduct. The response of the light composite structure is studied using 3-D finite element analysis (FEA). The reviewed blast field test is used to verify the 3-D numerical model. The composite structure strengthened by aluminum foam (ALF) is used to protect the bottom of the armored vehicle against the blast wave propagation. The ALF is used to fill the space at the sandwich structure as a light weight material.

This study presents a comparison between the results obtained by both the reviewed field blast test and the FEA to validate the accuracy of the 3-D finite element model. The effects are expressed in terms of displacement-time history effect on the sandwich steel panels as the explosive wave propagates. The results obtained by the reviewed field blast test have a good agreement with those obtained by 3-D numerical model. The ALF improves the performance of the sandwich structure under the impact of blast loading. The light weight sandwich structure could be used as mitigation system to protect the bottom of the armored vehicles against blast hazard.

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## 1. Introduction

Over the last years, the terrorist attacks have been increased. One of these is the use of explosives to attack vehicles. The explosive charge causes a blast wave that strikes structures causing different damages depending on the explosive weight and the distance between the charge and the target (Fiserova 2006; Smith and Hetherington 1994; Henrych 1979; Grujicic et al. 2007; Bergeron et al. 1998), The sudden release of energy from an explosion in the air produces an instantaneous high-temperature and high-pressure detonation wave in the atmosphere. The energy carried by the blast pressure wave decreases as the propagation distance and time increase. The pressure behind the shock wave front can instantly reduce to below the air pressure of the surrounding atmosphere (Smith and Hetherington 1994). A typical explosion pressure time history curve was shown in Fig.1.

Protection of vehicles from blast load remains the main concern of the researchers. The vehicle's hull was protected from blast wave by using energy-absorbing structures fixed on it. Lightweight materials such as aluminum foam (ALF) and honeycomb are effective materials for blast protection application because of their ability to mitigate shock blast wave transferred to structures due to explosions (Liu and Katsabanis 1997; Gustafsson 1973; Hanssen 2001; Vaidya 2004; Zhen-Hua Lu 2013; Juho Park and Hae-Jin Choi 2015).

It is very expensive to conduct field blast tests in every site and sometimes it is impossible to carry out such field tests due to safety and environmental constraints (Dharmasena et al. 2008; Hao et al. 1998). However, a reliable numerical model validated against measured field data is an effective tool to analyze the structure performance under blast effect (Dharmasena et al. 2008; Hao et al. 1998; Ming 2008).

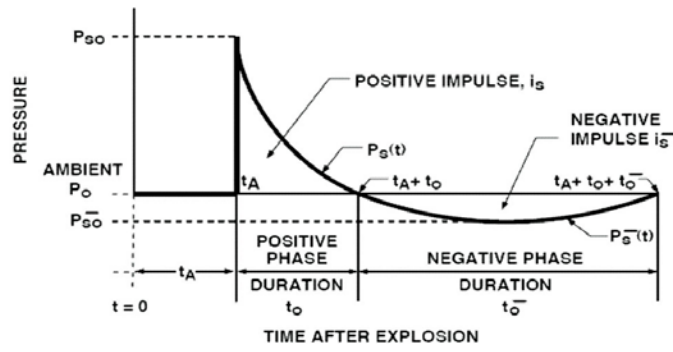
Mukherjee et al. (1999) carried out a number of blast experiments on sacrificial layered cladding to investigate the performance of sandwich structure under blast loading. Boyd et al. (2000) carried out blast experiments on a fixed steel plate subjected to blast loading. He investigated the acceleration, pressure-time, and displacement-time histories based on experimental and numerical studies. Lee et al. (2004) numerically investigated the response of the honeycomb core sandwich structures subjected to blast loading and optimized the structure in terms of energy absorption. Mazek and Mostafa (2013) used the rigid polyurethane foam (RPF) to strengthen

sandwich steel structure under blast load. The field blast test was conducted. They used the finite element analysis (FEA) to model the sandwich steel structure strengthened by the rigid polyurethane foam under shock wave. Mazek (2014) used the pyramid cover system (PCS) to strengthen sandwich steel structure under blast load. The field blast test was conducted. The finite element analysis (FEA) was used to model the sandwich steel structure strengthened by the PCS under shock wave.

The present study is conducted to discuss a comparison between the results obtained by both the field blast test and the numerical model to validate the accuracy of the 3-D finite element analysis (FEA). The field blast test is conducted to record the maximum displacement at the center point of Armox plate as shown in Figs.2 and 3. The 3-D FEA is used to analyze the effect of blast wave of 150-kg TNT located at three-meter stand-off distance from 7-mm Armox-500 plate as shown in Figs.4, 5 and 6. Numerical results obtained by the FEA (Fig. 8) are compared with the data obtained from the field data. It shows that the numerical model can well predict the blasting-induced pressure on steel structures.

This study also presents a comparison between the performances of 7 mm Armox plate and composite structure composed of 7 mm Armox strengthened by ALF under impact of the blast wave effect. The ALF is used as an internal core structure for two Armox steel plates with total thickness 7 mm; the face sheet is 3 mm thickness and the backing sheet is 4 mm thickness with 34 mm ALF as a filling material between the two sheets. The 3-D numerical model is proposed using FEA to investigate the behavior of the composite sandwich structure under the blast wave obtained from detonating 150-kg TNT located at the three-meter stand-off distance. Numerical results obtained by the FEA of the composite structure are compared with the numerical results of the Armox plate. It shows that the aluminum foam (ALF) could be used in light weight composite structures as a core to absorb the energy of the blast wave pressure.

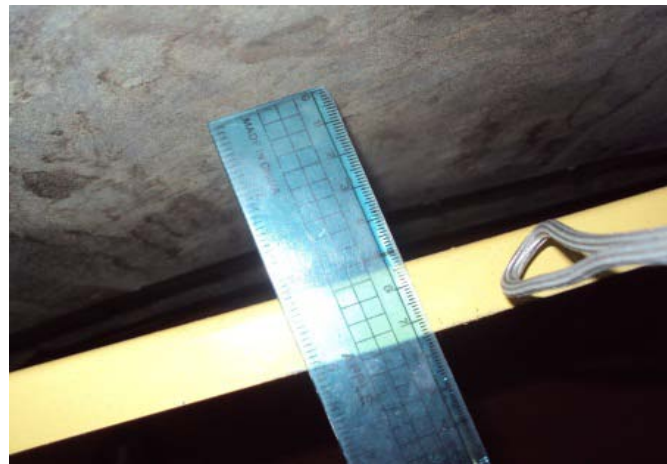
The ALF is used as internal core for different types of steel plates to study blast mitigation based on constant sheet thicknesses of the ALF. The behavior of the light weight sandwich structures is investigated under the blast waves obtained from detonating 6 and 10-kg TNT explosive charges at a stand-off distance (R) of 1 m. Numerical results obtained by the FEA are expressed in terms of the maximum displacement-time histories of the light weight sandwich structures to study the lightweight sandwich structures used to protect vehicles' bottom.



**Fig. 1:** A typical explosion pressure-time history in open air (after Smith and Hetherington 1994)



**Fig. 2:** Effect of 150 kg of TNT at a distance of 3m on 7mm ArmoX-500 plate



**Fig. 3:** The max deflection of ArmoX plate.

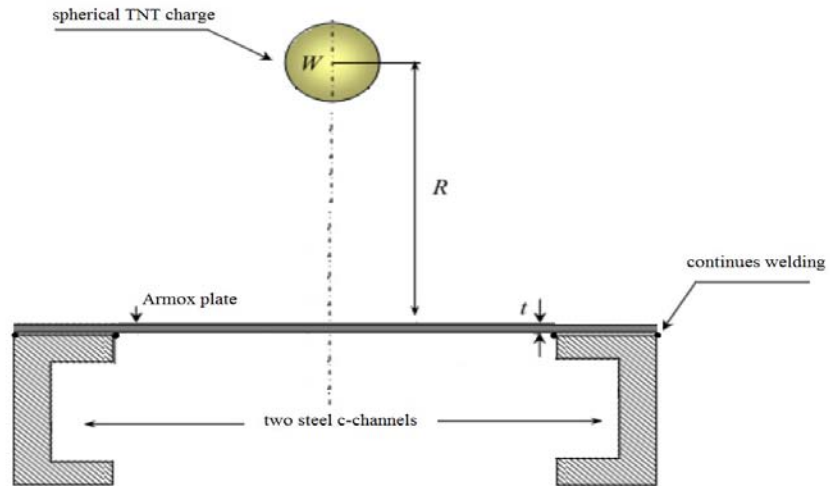


Fig. 4: Cross section for test specimen.

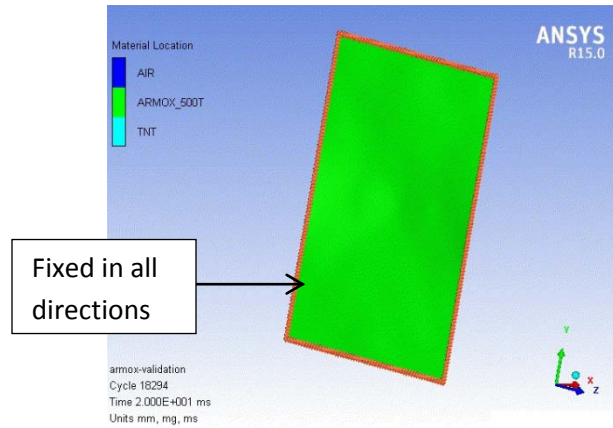


Fig. 5: Model of the plates (shell model).

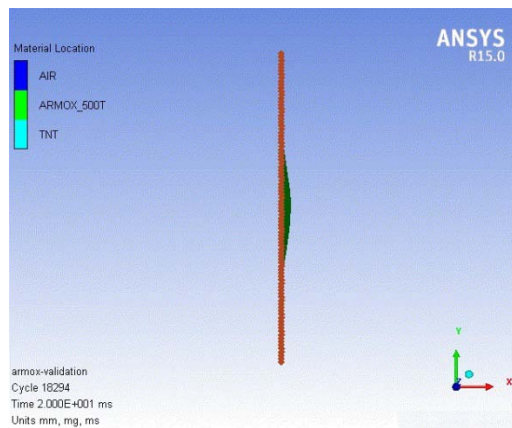


Fig. 6: Deflection of ArmoX plate.

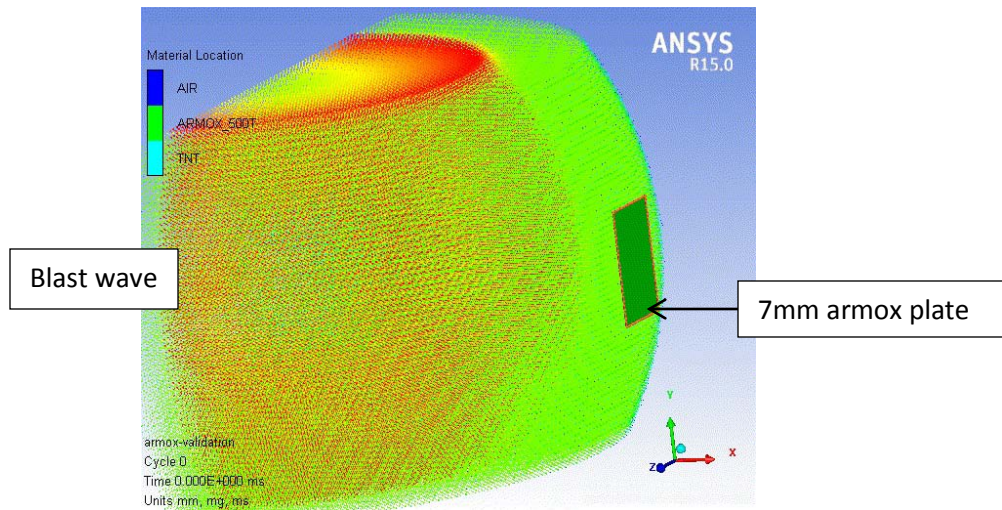


Fig. 7: Blast wave propagation hitting ArmoX plate.

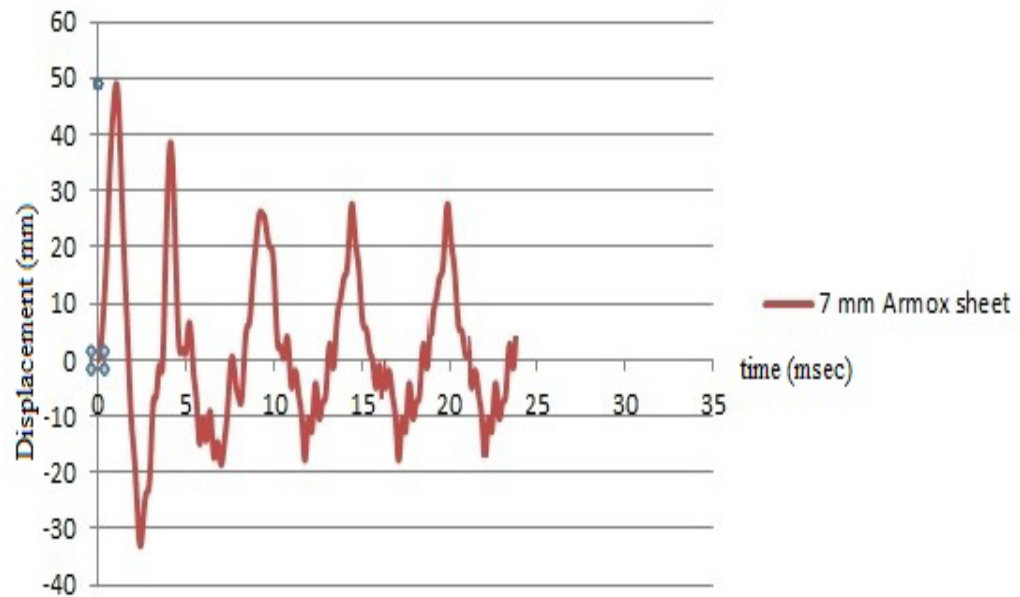


Fig. 8: Displacement time history for ArmoX plate.

## 2. Numerical model of Armox-sheet

The hydro code program (AUTODTN) supported by the finite element program (ANSYS) is used in the present study. In numerical modeling, air and equivalent TNT explosive are simulated by Euler processor. The air and the equivalent TNT explosive are assumed to satisfy the equation of state (EOS) of ideal gas (Hao et al. 1998). The standard constants of air and TNT are obtained from the Autodyn-3D material library. These include air initial internal energy  $E_n = 2.068 \times 10^5$  kJ/kg; air mass density  $\rho = 1.225$  kg/m<sup>3</sup>; and ideal air constant  $\gamma = 1.4$ . The data that defines the steel plates (Steel 1006) material was chosen from the library and modified. The linear equation of state and strength model (Johnson and Cook 1983) was applied. The yield stress of steel was assumed  $3.5 \times 10^5$  kPa and its shear modulus was  $8.18 \times 10^7$  kPa. The mechanical properties of armox-500 steel are mass density  $= 7.85 \times 10^3$  kg/m<sup>3</sup>; Shear modulus  $G = 8.22 \times 10^7$  kPa; yield  $= 1.615 \times 10^6$  kPa and its shear modulus was  $8.22 \times 10^7$  kPa (M Nilson 2003).

Shell element is used to model the Armox plate. The boundary condition applied to the steel plates is fixed in all direction as shown in Figs. 5. The fixation of steel plate is represented for continues welding from four sides. The steel plate is supported by steel channels (Fig. 4).

### 2.1 Modeling of Armox plates strengthen by ALF

The dynamic behavior of aluminum foam material as a porous material is described using the approach proposed by Kipp (1999) where the equation of state P- $\alpha$  compaction model together with the Von Mises yield strength are used. The Von Mises yield criterion describes the material elastic limit and its inability to support large shear stresses. Material failure occurred when the material is not able to withstand tensile stresses exceeding the material's local tensile strength. The hydrodynamic tensile model is used for simulation, and the model requires a specified constant hydrodynamic tensile limit to determine failure occurrence. The physical data of aluminum foam is defined as porous density equals 500 kg/m<sup>3</sup>; initial compaction pressure set  $7 \times 10^3$  kPa; solid compaction pressure is  $1.33 \times 10^5$  kPa; compaction exponent considered 1.4; Shear Modulus is 1.88 GPa; Yield Stress proposed  $7 \times 10^3$  kPa; and the Hydro Tensile limit is -2 GPa.

The composite structure consists of two outer steel plates. The dimensions of steel plate are 900 mm length and 600 mm width. The face sheet is 3 mm thickness and the backing sheet is 4 mm thickness. The ALF is used to fill the space between the two outer steel plates. The thickness of the ALF is 34 mm as shown in Fig. 9. There are two panels one of them the steel plates are normal mild steel and the other are armox-500 steel.

The composite structure is totally fixed at four edges as shown in Fig. 10. The composite structure is subjected to blast wave obtained from detonating 10-kg TNT explosive charges at a stand-off distance of 1 m which is equal to blast wave obtained from detonating 150-kg TNT located at the three-meter stand-off distance (scaling law). The pressure-time history hitting the composite structure is calculated by both CONWEP and AUTODTN as shown in Figs.11, 12 and 13.

Shell element is used to model both the membrane (in-plane) and the bending (out-of-plane) behavior of the sandwich steel structure. Shell element consists of 4-node rectangular shape each node having 6 degrees of freedom (three translations and three rotations).

The solid element is also used to model the behavior of the ALF core. The solid element is chosen since it possesses in-plane and out-of-plane stiffnesses. The solid element allows for both in-plane and out-of-plane loads. The solid element is cubic in shape and has 8 nodes each node having 3 degrees of freedom (three translations).

The cubic solid element and the rectangular shell element interface are used between the ALF core and steel plates to ensure the compatibility conditions at the interface surface between them as well as the associated stresses and strains along the interface surface. This type of finite element is used to link adjacent nodes characterized by stiffness components.



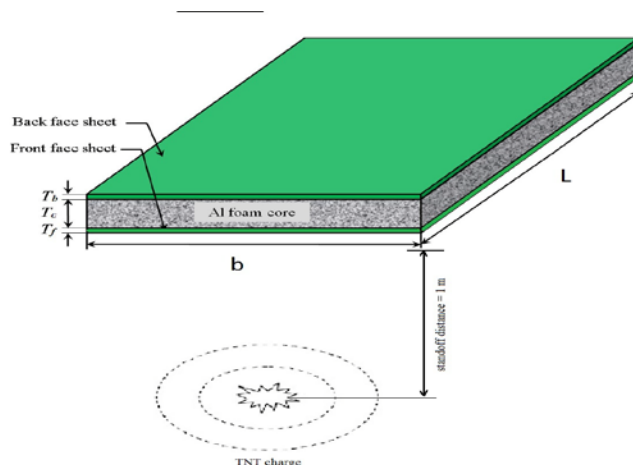


Fig. 9: Construction of aluminum foam-cored panel and loading condition.

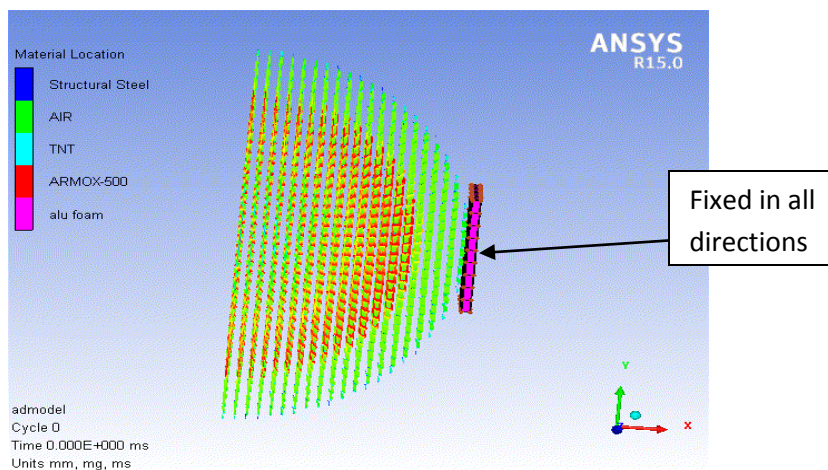


Fig. 10: Blast wave propagation hitting composite structure.

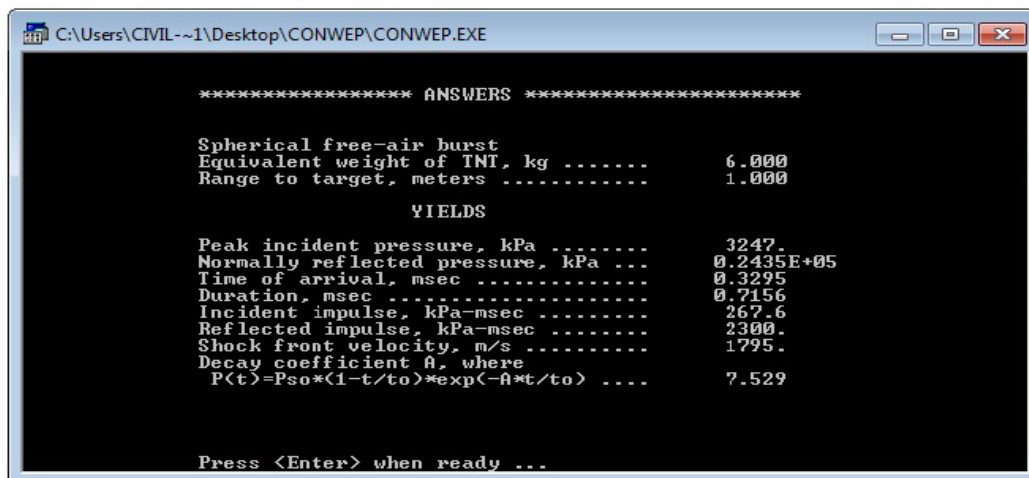


Fig. 11: Pressure resulted from the detonation of 6-kg of TNT at a stand-off distance of m using the CONWEP.

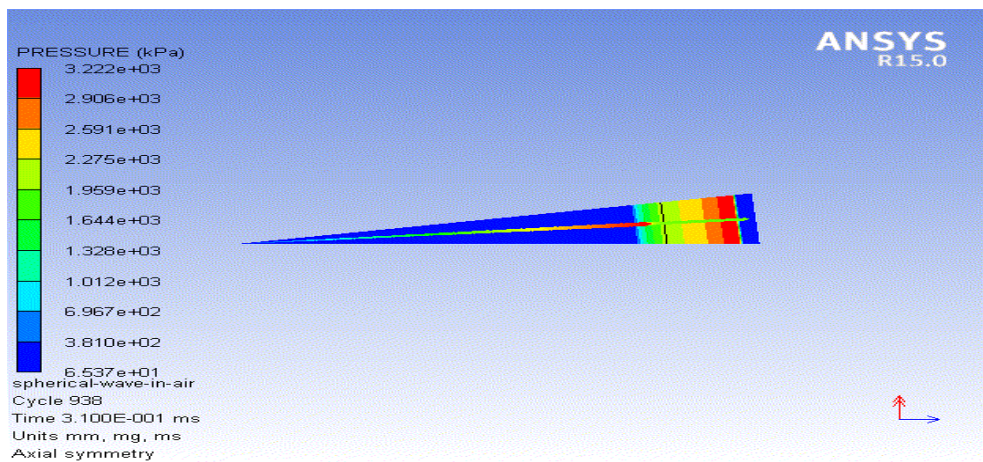


Fig. 12: Pressure resulted from the detonation of 6-kg of TNT at a stand-off distance of 1 m using AUTODYN 2-D.

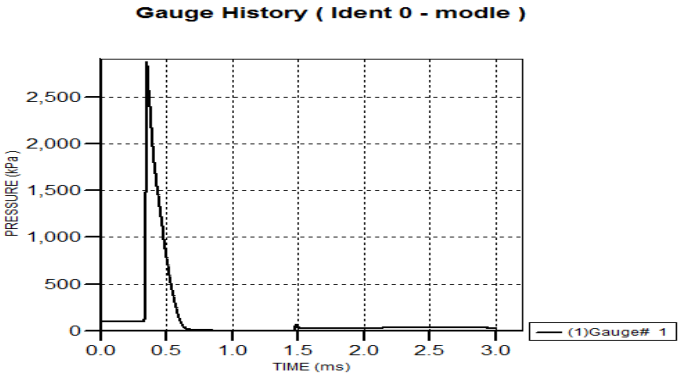


Fig. 13: Pressure time history for a charge of 6-kg TNT at a stand-off distance of 1 m from AUTODYN.

**3. Blast impact on performance of light weight composite structure:**

The displacement-time history is calculated for the center of the composite structure due to the blast wave using the 3-D numerical model. The displacement-time histories for ArmoX plate and ArmoX plate strengthened by ALF are compared as shown in Fig. 14. It shows that the performance of composite structure under blast impact is better than the performance of ArmoX steel plate.

Four cases of the composite structure are studied. At the first case, the composite structure composed of two steel plates from normal mild steel with ALF core under the effect of detonation of 6-kg TNT explosive charges at a stand-off distance of 1 m. At the second case, the composite structure composed of two steel plates from armox-500 steel with ALF core under the effect of detonation of 6-kg TNT explosive charges at a stand-off distance of 1 m.

At the third case, the composite structure composed of two steel plates from normal mild steel with ALF core under the effect of detonation of 10-kg TNT explosive charges at a stand-off distance of 1 m. At the fourth case, the composite structure composed of two steel plates from armox-500 steel with ALF core under the effect of detonation of 10-kg TNT explosive charges at a stand-off distance of 1 m.

The displacement-time history profiles at the centre of the panel for the cases are calculated to discuss the impact of composite structures. Fig. 15 shows the comparison between the displacement-time histories at point 1 for each case. The maximum displacements at the centre of composite structure obtained by the FEA are compared to show their performance under blast wave as shown in Fig. 16.

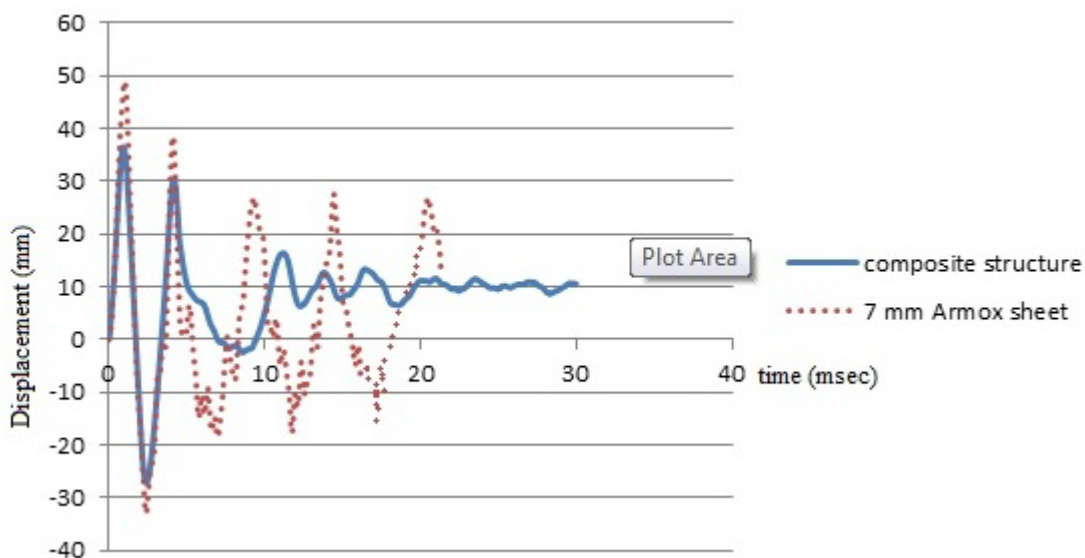


Fig. 14: The displacement-time history for composite structure and Armox.

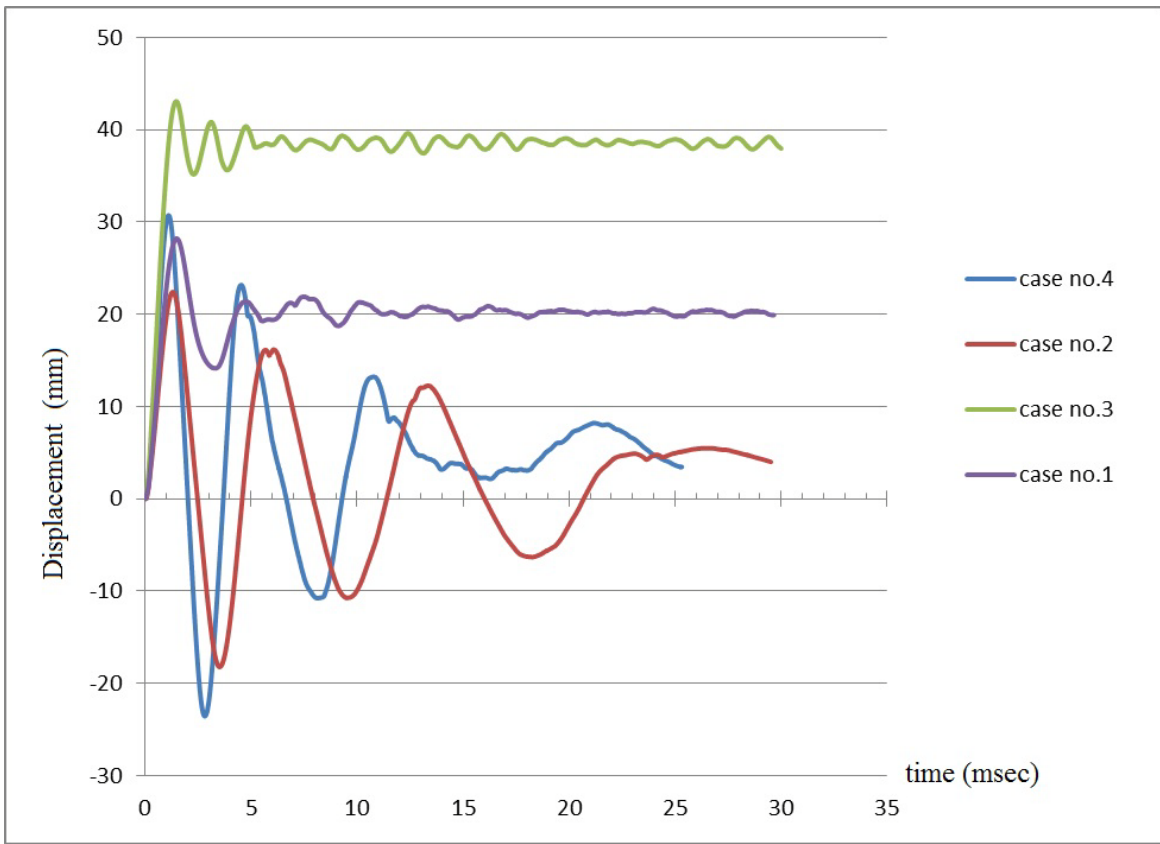


Fig. 15: The displacement-time history profiles at points 1 for the four cases.

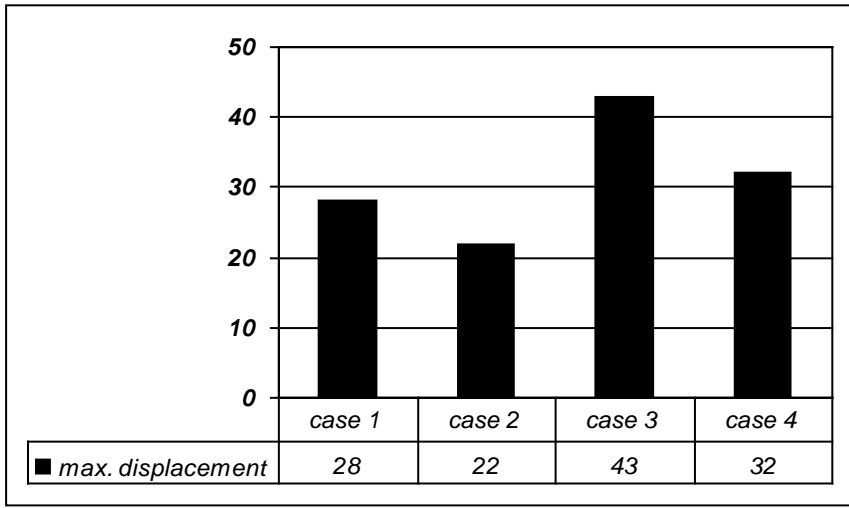


Fig. 16: The maximum displacements at the Centre of composite structure obtained by the FEA.

#### 4. Discussions

The ALF cored sandwich with different face-sheet composed of the same material is used to discuss impact of blast hazard on light weight sandwich structure performance. The field blast test is conducted to study the performance of armox plate and the numerical model for validation purpose. The FEA gives a better estimation of the response of the light weight sandwich structures on different TNT explosive charges. The maximum displacements of the composite structures are recorded at the centre of the backing steel plate.

In general, the sandwich steel structures play an important role to resist the blast load. The cases of using armox-500 steel as a face sheets gives the smallest displacement. Using ALF with armox-500 steel sheets reduce the maximum displacement than armox-500 steel plate. The use of light weight sandwich structure reduces the maximum displacement up to 40%. The ALF has a large amount of strain energy which can absorb the kinetic energy of the blast wave propagation. Light weight sandwich structure used to protect bottom of armored vehicles from blast hazard.

#### 5. Conclusions

A 3-D nonlinear finite element analysis has been used to predict the performance of sandwich steel structures with ALF core under the blast effect. In this study, the performance of the composite is modelled and analyzed using nonlinear finite element computer program AUTODYN 2D and 3D. The field blast test is also conducted for validation purpose. The following conclusion can be drawn regarding the performance of composite structure under impact of shock wave propagation.

- The pressure-time histories calculated by the 3-D numerical model is in reasonable agreement with those obtained by both the field blast test the empirical method developed by (Beshara 1994).
- Based on the field blast test and the empirical method developed by Boyd et al. (2000) the 3-D numerical model gives a better estimate for displacement-time histories.
- The 3-D finite element model can be successfully used to analyze and estimate the performance of composite sandwich using ALF core based on the field blast test.
- The response of the armox-500 steel plates with ALF is reduced up to 40%.

The aluminium foam (ALF) could be used in light weight composite structures as a core to absorb the energy of the blast wave propagation hitting the sandwich steel structures. That can be used to protect bottom of armoured vehicles from blast hazard.

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