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Effect of blast wave on lightweight structure performance

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Review Article

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Key words:

Aluminum Foam, blast loadings, composite structure, - 3-D numerical model, structural behavior.

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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. The armored vehicles should be protected from explosives attacks using lightweight sandwich structure.

In this study, the protection system against blast effect is highlighted using composite structures to protect vehicles. The response of the light composite structure is studied using 3-D finite element analysis (FEA). The blast field test is conducted and 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 tests 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 tests 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 a mitigation system to protect the bottom of the armored vehicles against blast hazard.

I. INTRODUCTION

Over the last years, the terrorist attacks have 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[1- 5]. The sudden release of energy from an explosion in the air produces an instantaneous high-temperature and high-pressure detonation wave in the surrounding atmosphere. The energy carried by the blast pressure wave decreases as propagation distance and time increase. The pressure behind the shock wave front can instantly reduce to below the air pressure of the surrounding atmosphere[2, 24]. A typical explosion pressure time history curve is 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 applications because of their ability to mitigate shock blast wave hitting structures[6,-10, 22].

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 [11, 12]. However, a reliable numerical model validated against measured field data is an effective tool to analyze the structure performance under blast effect[11, 12].

Mukherjee[14] carried out a number of blast experiments on sacrificial layered cladding to investigate the performance of sandwich structure under blast loading. Boyd[15] 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 and Brendan[16] 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[17] used the rigid polyurethane foam (RPF) to strengthen sandwich steel structure under blast load. 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[18] used the pyramid cover system (PCS) to strengthen sandwich steel structure under blast load. 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 field blast test and 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. 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-thickness Armox-500 plate. Numerical results obtained by the FEA are compared with the data obtained from the field test. They show that the numerical model can well predict the performance of steel structures under blast impact.

This study also presents a comparison between the performances of 7-mm-thickness Armox plate and composite structure composed of 7-mm-thick Armox strengthened by ALF under impact of the blast wave effect. The ALF is used as an internal core structure between two Armox steel plates. The face steel plate is 3 mm thick and the rear steel is 4 mm thick with 34-mm-thickness ALF as a filling material between the two plates. The 3-D numerical model is proposed using the FEA to investigate the behavior of the composite sandwich structure under the blast wave obtained from detonating 150-kg TNT located at three-meter stand-off distance. The composite structure performance is compared with the Armox plate behavior. The results show that the ALF could be used as a core material to absorb the blast wave energy.

The ALF is used as internal core for different types of steel plates to study blast mitigation based on constant sheet thickness of the ALF. The behavior of the lightweight sandwich structures is investigated under the blast waves obtained from detonating 6-kg 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 displacement-time histories of the lightweight sandwich structures.

II. MODEL VALIDATION

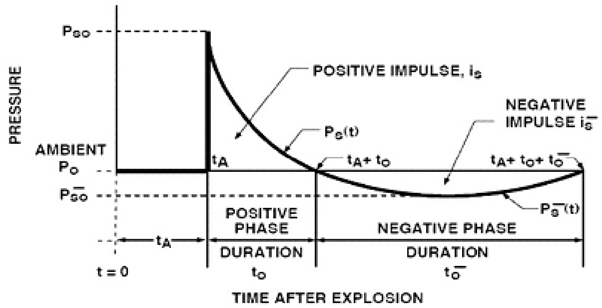

Fig. 1: A typical explosion pressure-time history in open air[2].

The current validation is conducted based on the field blast test. The field blast test is conducted by detonating 150-kg TNT charge located at the three-meter standoff distance from 7-mm-thickness Armox steel plate, as shown in Fig. 2. The dimension of the Armox steel plate is 60 cm width and 90 cm length. The maximum displacement at center point of Armox plate is recorded to compare with numerical results. The steel plate is fixed with four channel steel beams using continuous welding, as shown in Fig. 2. The maximum displacement is measured at the centre of the Armox plate. The maximum deformation is 53 mm, as shown in Figs. 3 and 4.

The hydro-code program (AUTODYN)[19] supported by the finite element program (ANSYS) is used in the numerical modeling. In numerical modeling, air and equivalent TNT explosive are simulated by Euler processor. The air and the equivalent TNT explosive are

III. PARAMETRIC STUDY

To satisfy the equation of state (EOS) of ideal gas[12]. The standard constants of air and TNT are obtained from the Autodyn-3D material library. These include air initial internal energy En =2.068×105 kJ/kg; air mass density ρ=1.225 kg/m3; and ideal air constant γ=1.4. The data that defines the steel plates (Steel 1006) material are chosen from the library and modified. The linear equation of state and strength model is applied[20]. The yield stress of steel is assumed 3.5×105 kPa and its shear modulus was 8.18×107 kPa. The mechanical properties of Armox-500 steel are mass density =7.85×103 kg/m3; Shear modulus G =8.22×107 kPa; yield stress = 1.615×106 kPa and its shear modulus was 8.22×107 kPa.

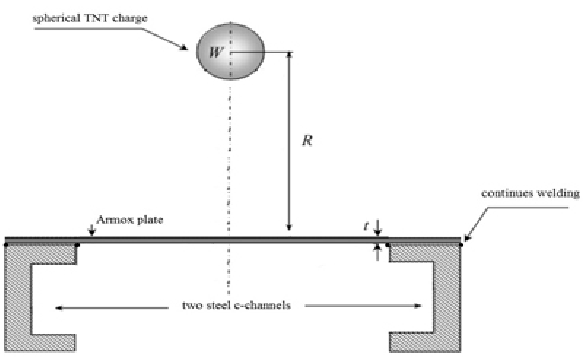

Fig. 2: Cross section for test specimen.

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 Fig. 5. The model is conducted in AUTODYN, as shown in Fig. 7. The blast wave from detonation of 150 kg TNT is striking the steel plate. The displacement-time history is obtained and shown in Fig. 8. The maximum displacement is 50 mm. The numerical model can well predict the blasting-induced pressure on steel structures.

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

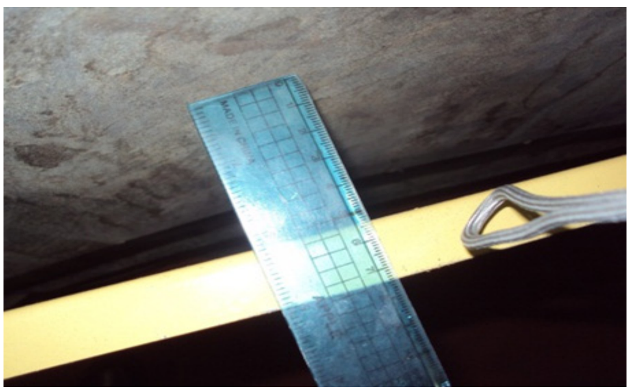

Fig. 4: The max deflection of Armox plate.

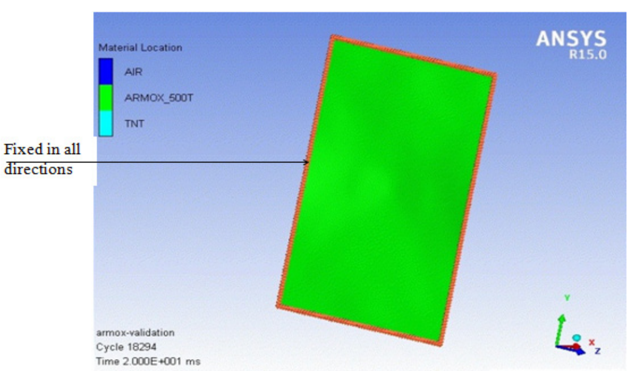

Fig. 5: Model of steel plate.

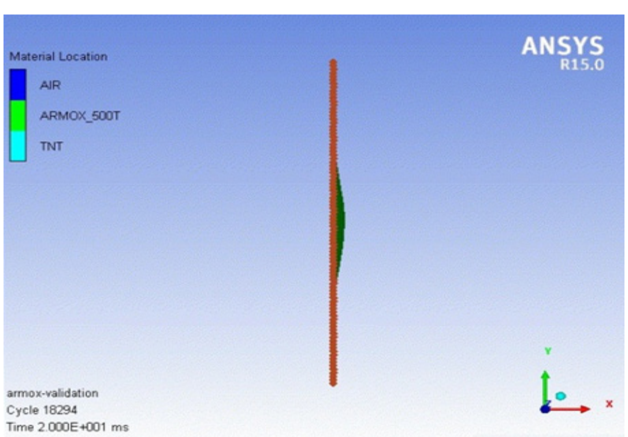

Fig. 6: Deflection of armox plate.

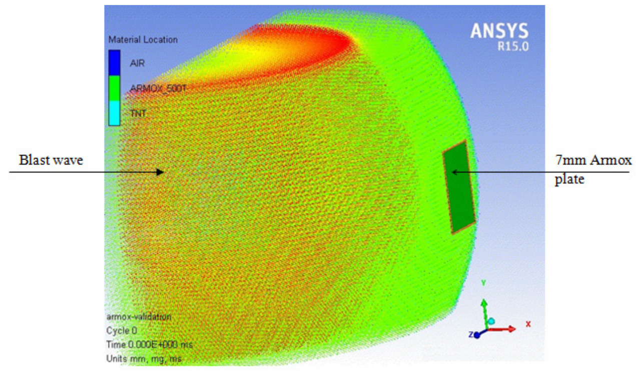

Fig. 7: Blast wave propagation hitting Armox plate.

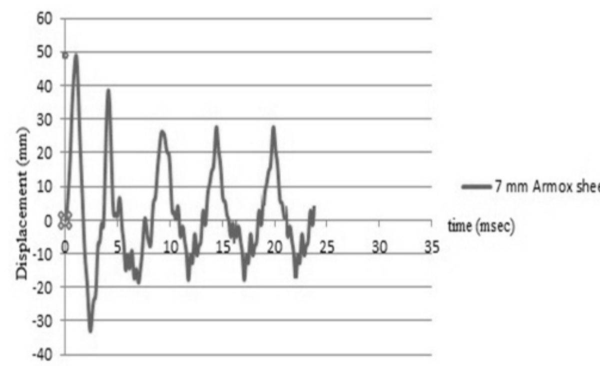

Fig. 8: Displacement time history for Armox plate.

Numerical model is conducted to investigate the effect of ALF on Armox plate performance to resist blast wave. The ALF is used as an internal core material between two Armox steel plates with total thickness 7 mm. The face steel plate is 3 mm thick and the rear steel plate is 4 mm thick with the 34-mm-thickness ALF as a filling material between the two steel plates, as shown in Fig. 9. The dynamic behavior of the ALF as a porous material is described by the von Mises model. 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 the ALF is defined as porous density equals 500 kg/m^3; initial compaction pressure set 7×10^3 kPa; solid compaction pressure is 1.33×10^5 kPa; compaction exponent is considered 1.4; Shear Modulus is 1.88 GPa; Yield Stress is proposed 7×10^3 kPa; and the Hydro Tensile limit is -2 GPa.

The composite structure consists of two outer steel plates. The dimensions of steel plate are 90 cm length (l) and 60 cm width (b), as shown in Fig. 9. The face steel plate is 3 mm thick (t_f) and the rear steel plate (t_b) is 4 mm thick. The ALF is used to fill the space between the two outer steel plates. The thickness (t_c) of the ALF is 34 mm, as shown in Fig. 9.

The composite structure is totally fixed at the four edges, as shown in Fig. 10. The composite structure is subjected to blast wave obtained from detonating 6-kg TNT explosive charge at a stand-off distance of 1 m which is equivalent 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- 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 the finite element model is used to link adjacent nodes characterized by stiffness components.

The displacement-time history is calculated at the center of the composite structure due to the blast wave using the 3-D numerical model. The displacement-time

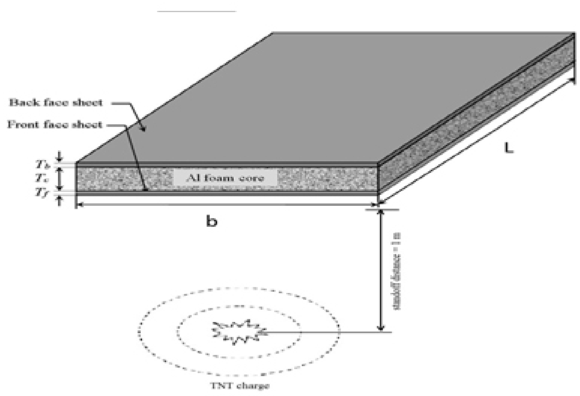

Fig. 9: Construction of aluminum foam-cored panel and loading condition.

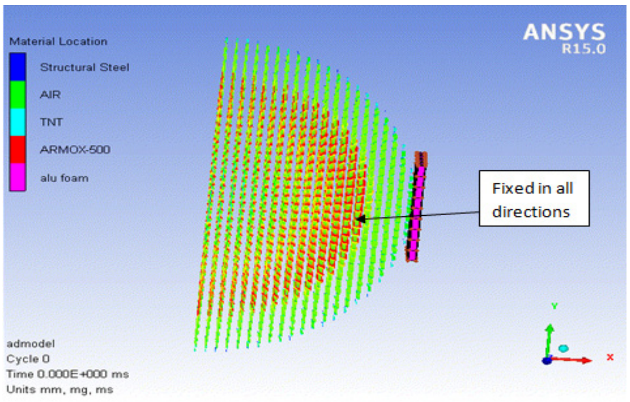

Fig. 10: Blast wave propagation hitting composite structure.

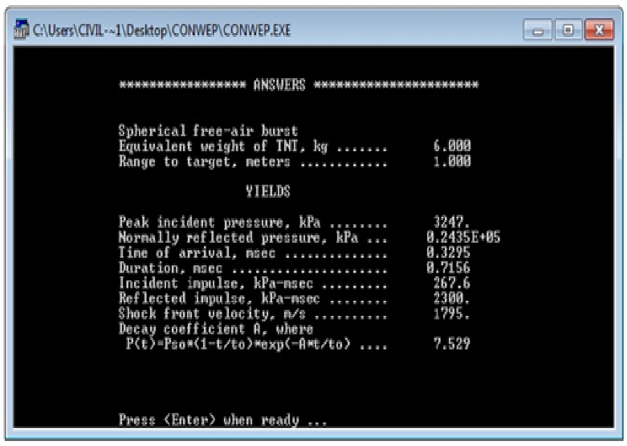

Fig. 11: Pressure resulted from the detonation of 6-kg of TNT at a stand-off distance 1 m using the CONWEP.

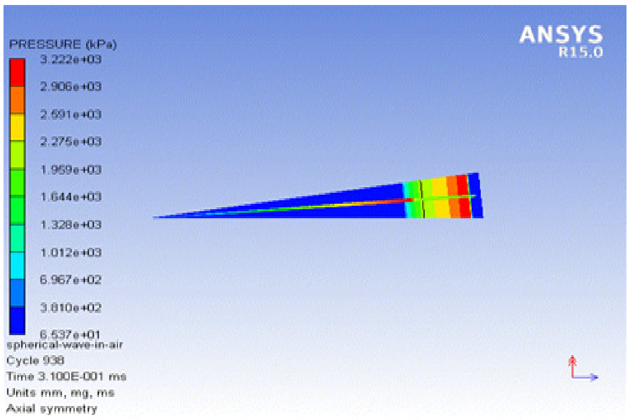

Fig. 12: Pressure resulted from the detonation of 6-kg of TNT at a stand-off distance of 1 m using AUTODYN 2-D.

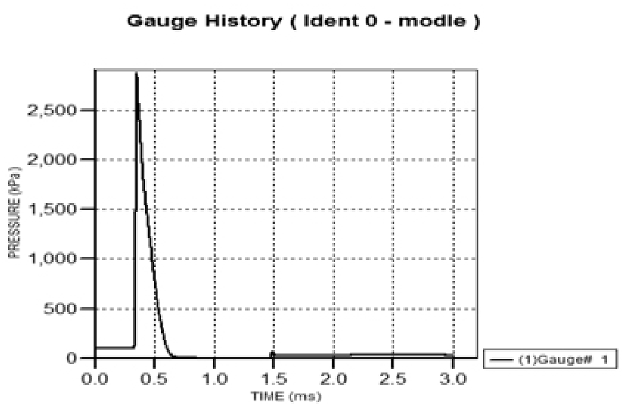

Fig. 13: Pressure time history for a charge of 6-kg TNT at a stand-off distance of 1 m from AUTODYN.

history for Armox plate and Armox plate strengthened by ALF are compared, as shown in Fig. 14. The results show that the performance of composite structure under blast impact is better than the performance of Armox steel plate.

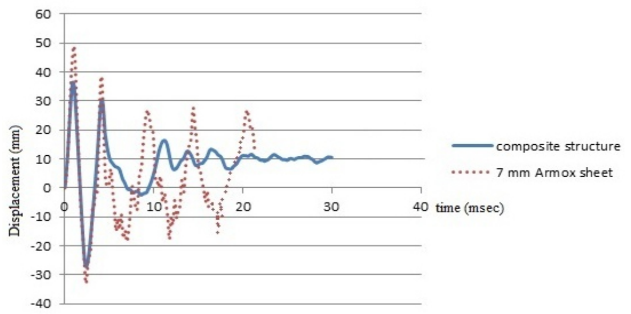

Fig. 14: The displacement-time history profiles at points 1 for the four cases.

IV. BLAST IMPACT ON PERFORMANCE OF LIGHTWEIGHT COMPOSITE STRUCTURE

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

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

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

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

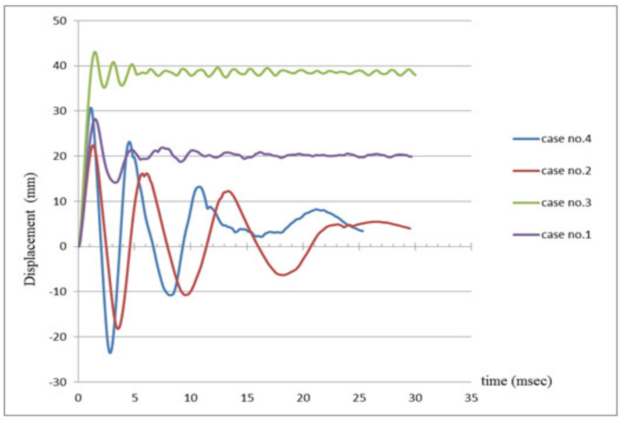

Fig. 15: The displacement-time history profiles at centre for the four cases.

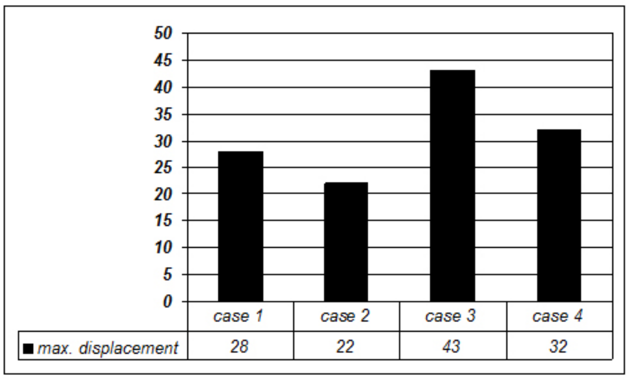

Fig. 16: The maximum displacements at the Centre of composite structure obtained by the FEA.

V. DISCUSSIONS

The ALF as core material encased by the two steel plates is used to discuss the impact of blast hazard on lightweight sandwich structure performance. The field blast test is conducted to study the performance of Armox steel plate. The field blast test is used to validate numerical model of the composite structure under blast effect. The FEA gives a good estimation for the response of the lightweight sandwich structures based on different TNT explosive charges. The maximum displacements of the composite structures are recorded at the centre of the rear steel plate.

In general, the sandwich steel structures play an important role to resist the blast load. AS the Armox-500 steel plate is used as a face plate the small maximum displacement is obtained. Using ALF with Armox-500 steel sheets reduces the maximum displacement more than Armox-500 steel plate. The use of lightweight 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. Lightweight sandwich structures are used to protect bottom of armored vehicles from blast hazard.

V. CONCLUSIONS

A 3-D nonlinear finite element analysis has been used to predict the performance of sandwich.

Steel structures with ALF core under 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 are in reasonable agreement with those obtained by the field blast test.
- 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) can be used in light weight composite structures as a core to absorb the energy of the blast wave propagation hitting the sandwich steel structures. Light weight composite structures can be used to protect the bottoms of armoured vehicles from blast hazard.

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