



## Blast hazard impact on V-shape composite panel performance

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### Abstract

The terrorist attacks have been increased during the last few years. Blast wave propagation is a great engineering challenge to protect structures such as vehicles and buildings. Mitigation systems used to protect the structures remain a sophisticated engineering problem.

In this study, the V-shape composite structure is studied as a mitigation system to protect the bottom of vehicles against blast impact. The reviewed field blast test is used from another research conducted by Mazek *et al.*<sup>[1]</sup> to verify the proposed numerical model of the V-shape composite structures under blast effect. The numerical model is proposed by 3-D nonlinear finite element model (FEM).

The displacement-time history of the V-shape composite (VSC) structure is presented as the blast wave propagates. The impact of the V-shape panel inclination on the V-shape composite structure performance is analyzed and presented under the blast effect. There is a good agreement between the results obtained by both the field blast test and the numerical model. The VCS structure improves the armored panel performance under the vehicles based on the impact of detonating different TNT explosive charges.

## I. INTRODUCTION

The mitigation system under vehicle body can be used to survive the vehicle from the explosives<sup>[2]</sup>. The mitigation system performance had considerable interest for many years<sup>[2, 3 and 4]</sup>.

The composite structure performance is better than metal structure performance. The composite structures give high strength to weight ratio to provide added armor to be installed on military vehicles<sup>[2, 3 and 4]</sup>. Several studies have discussed sandwich composite structure performance under the impact of blast load<sup>[3, 4, 5 and 6]</sup>.

Xue and Hutchinson<sup>[3]</sup> discussed the behavior of both the composite structure and the steel plates under the blast effect. The composite structure performance shows higher shock resistance than the steel plate performance at the case of equal mass criteria. Nonlinear finite element analysis (FEA) was conducted to study the composite structure and the steel plate. Mori *et al.*<sup>[4]</sup> investigated the performance of the honeycomb core composite structures subjected to blast loading. The composite structure was optimized in terms of energy absorption. Sriram and Vaidya<sup>[5]</sup> studied the performance of aluminum foam composite structures exposed to blast loading. Mazek and Mostafa<sup>[6]</sup> used the rigid polyurethane foam (RPF) to improve composite steel

structure performance under blast effect. Field blast tests were conducted. They used the 3-D FEA to study the performance of the composite steel structure strengthened by the RPF under blast shock wave. Abdel Wahab *et al.*<sup>[7]</sup> discussed the effect of blast wave on lightweight structures performance experimentally and numerically.

The VSC structure assists to mitigate the blast energy delivered to the vehicle's bottom by deflecting the blast wave away from the body of the vehicle<sup>[8]</sup>. A flat surface causes a significant pressure concentration beneath the surface<sup>[8]</sup>. The pressure is trapped between the bottom of the vehicle and the ground. A significant load transfers to the vehicle so the vehicle is thrown upwards into the air. The passengers inside the vehicle could be severely injured and killed by the downwards acceleration of the vehicle. The blast wave propagation is affected by the geometry of the target, as shown in Fig. 1.

Genson<sup>[9]</sup> carried out very small scale experiments to investigate mitigation effects of V-shape hulls exposed to buried charges. Ma<sup>[10]</sup> conducted experimental tests on welded V-shape plates with inclination angles of 90° and 120°. The V-shape plates were subjected to buried explosives to simulate landmine blast effects. Mazek *et al.*<sup>[1]</sup> carried out blast field tests for V-shape composite structures to protect vehicles from mining.

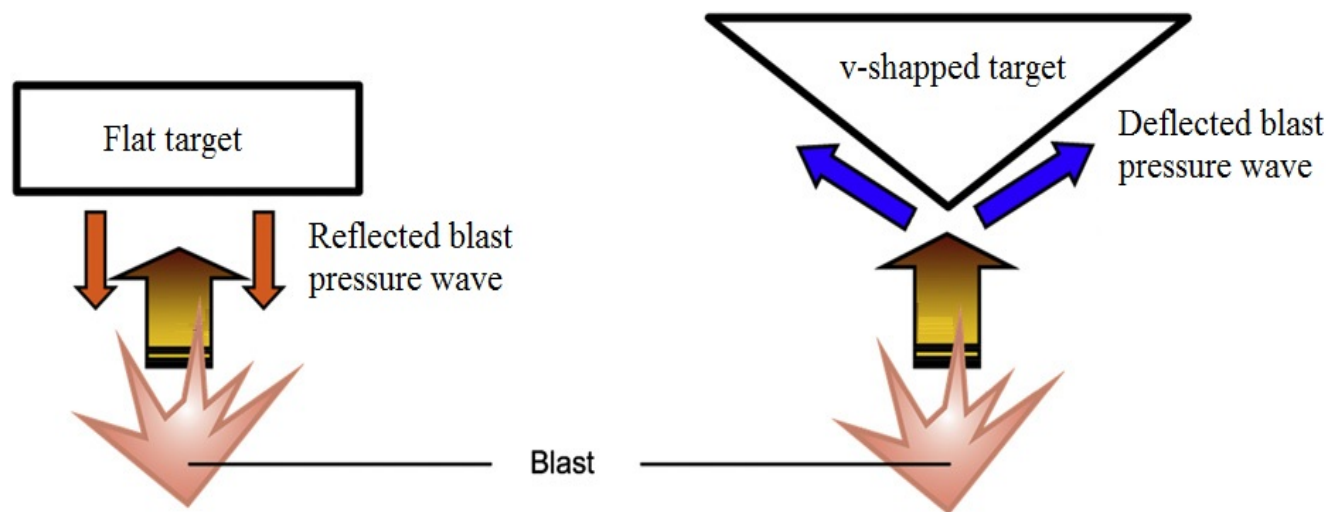


Fig.1: Flow of blast wave hitting flat and V-shape targets

This paper aims to study the VSC structure performance so as to protect the bottom of the vehicles from underground explosive. The 3-D FEA is used to study the performance of the VSC steel panels to protect the bottom of the vehicles, as shown in Fig. 1. The VSC structure with aluminum foam (ALF) cores strengthened by steel cross ribs is used to study blast mitigation based on constant sheet thicknesses of the ALF. The reviewed field blast test is also used to record maximum displacement at the centre point of the VSC steel panel. The VSC structure is subjected to a blast wave propagation obtained from detonating of ten-kg TNT explosive charge at one-meter stand-off distance<sup>[1]</sup>. The plastic displacements of the specimen are measured after explosion<sup>[1]</sup>. The comparison is presented between the results obtained by both the field blast test and the 3-D FEM to validate the accuracy of the 3-D FEA. The constitutive model for this analysis contains elasto-plastic materials. An elasto-plastic model is employed to represent the performance of the VSC structure and the ALF layer. The proposed model is programmed using the computer program Autodyn-3D<sup>[13]</sup>. The VSC structure model strengthened by the ALF is also implemented in a finite element code Autodyn3D.

The 3-D FEM considers the effects of the blast effect, the VSC structure, and the ALF. The displacement-time history of the VSC structure is calculated as the explosive wave propagates. Numerical results obtained by the FEA are compared with the data obtained from the reviewed field blast test. Maximum displacements of the VSC structures are recorded and computed by the authors.

The study included a parametric study on the performance of the VSC structure panels with different inclination angles w.r.t the horizontal axis under blast wave propagation. The inclination angles are varied from 0°, 12°, 16°, 20°, up to 22°. The V-shape sandwich structure panels

are also subjected to blast wave obtained from detonating of 10-kg and 15-kg TNT explosive charges at a stand-off distance (R) of 1m. The 3-D FEA is used to understand the effect of inclination angles on the performance of the V-shape sandwich structures. The performance of the VSC structures with various inclination angles is presented in terms of displacement-time history. The V-shape angles of the composite structure are the most efficient parameter to mitigate the blast wave propagation. However, the V-angle of the composite structure is governed by vehicle ground clearance.

## II. MODEL VALIDATION

Field blast tests are often difficult to perform due to safety and environmental constraints<sup>[11]</sup>. Blast tests conducted in the field face many challenges such as test setup, cost, people injury, environmental risks, and measurements accuracy<sup>[11]</sup>. The current validation is conducted based on the field blast test carried out by Mazek *et al.*<sup>[1]</sup>. This field blast test was conducted using ten-kg TNT explosive located at one-meter away from the top of the V-shape structure. The field blast test was conducted in free air to measure the deformations of the V-shape composite structure.

The VSC structure is a composite sandwich structure filled with ALF cores strengthened by steel cross ribs, as shown in Fig. 2. However, the VSC structure was used as a mitigation system to protect the bottom of vehicle from blast impact. The test specimen consists of double sheets made of normal mild steel with inclination angles (22° and 16°), as shown in Fig. 2.

The VSC structure was strengthened by steel cross ribs between the outer steel plates, as shown in Fig. 2. The thicknesses of the outer steel plates are 5 mm. The VSC structure was also filled with the ALF, as shown in Fig. 3. The thickness of the steel cross ribs is 4 mm and the

height of the steel cross ribs is 34 mm. Steel ribs were welded on the lower steel sheet with 300 mm internal spaces, as shown in Fig. 3. These internal spaces were filled with ALF sheets, as shown in Fig. 3. The specimen

was welded onto test rig (vehicle's chassis), as shown in Fig. 3. The previous specimen was prepared and assembled with special requirements to be tested against TNT explosive<sup>[1]</sup>.

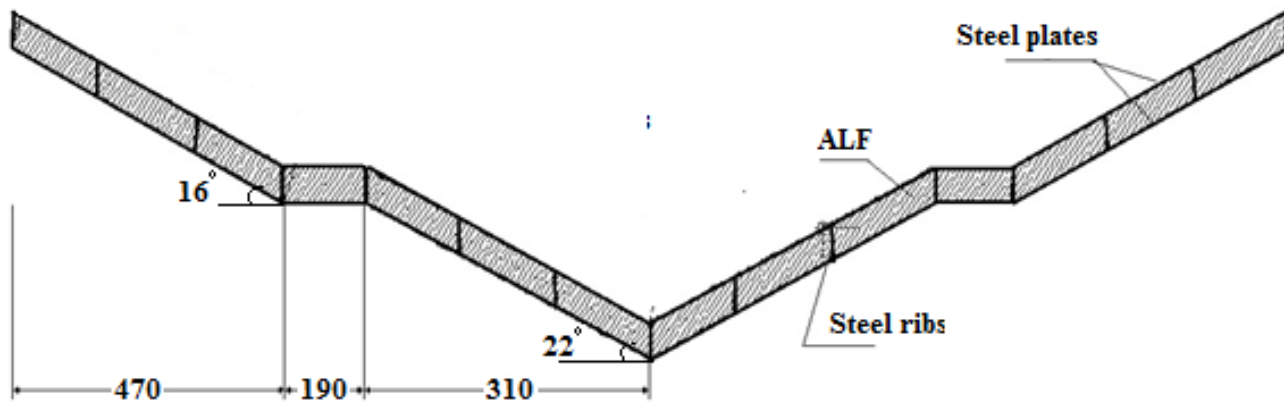


Fig. 2: The geometry of the V-shape composite structure (after Mazek et al.<sup>[1]</sup>)



Fig. 3: The use of ALF as a filling material for the V-shape composite structure (after Mazek et al.<sup>[1]</sup>)

Ten-kg TNT explosive was installed at the middle of the test rig frame. The explosive charge was hanged with wire rounded on steel pipe of the charge holder frame, as

shown in Fig. 4. The vertical distance between the TNT charge and the crown of the specimen was one meter, as shown in Fig. 4.

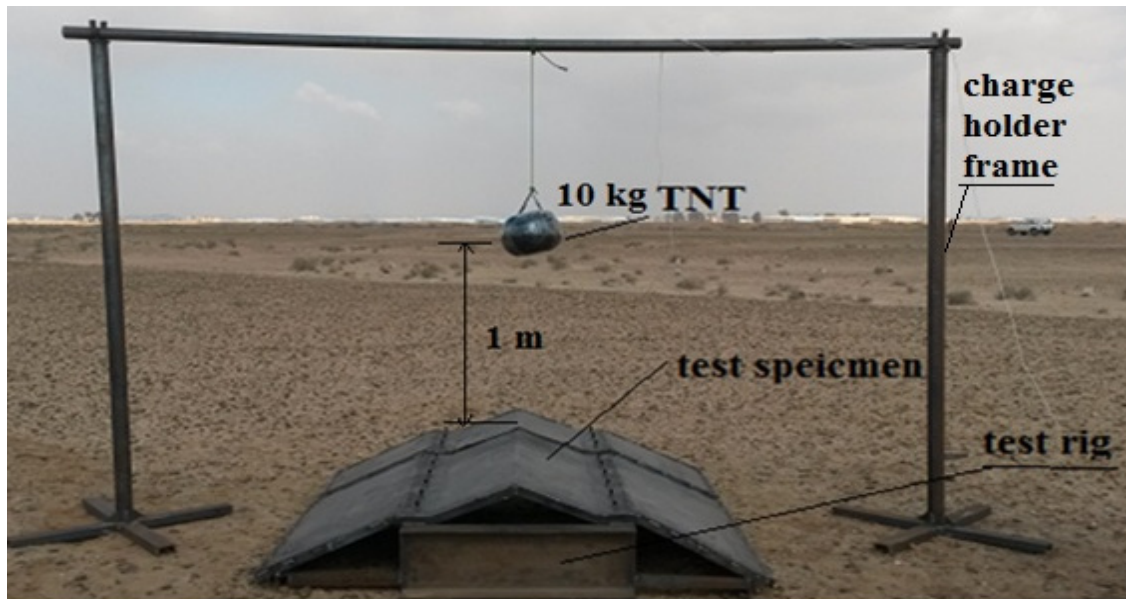


Fig. 4: 10-kg TNT explosive charge was hanged on charge holder (after Mazek *et al.*<sup>[1]</sup>)

The test specimen was placed in the setup frame configuration and the TNT explosive was also set, as shown in Fig. 4. High speed camera was used to capture the blast wave propagation, as shown in Fig. 5. The fireball and blast wave generated in free air are shown in Fig. 6. The VSC structure strengthened by both the steel cross ribs and ALF was deformed, as shown in Fig. 7.



Fig. 5: High speed camera used in the field blast test (after Mazek *et al.*<sup>[1]</sup>)

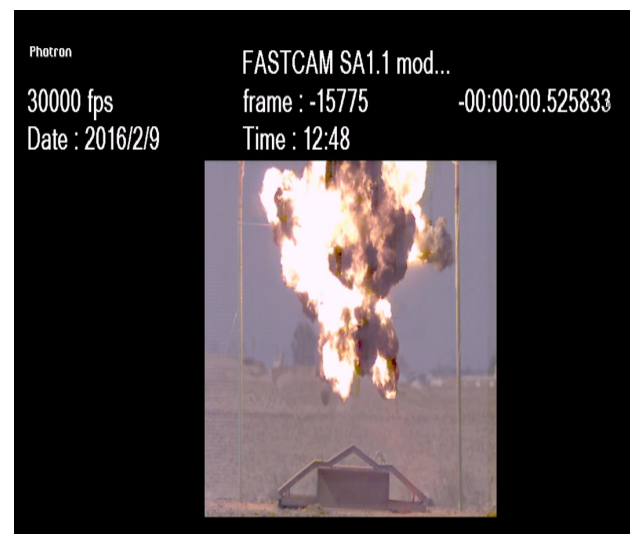


Fig. 6: Explosive scene by 10-kg TNT explosive (after Mazek *et al.*<sup>[1]</sup>).



Fig. 7: Test specimen strengthened by the steel cross ribs and ALF after explosion (after Mazek *et al.*<sup>[1]</sup>).

The plastic deformations of the specimen were measured after the impact of the explosion, as tabulated in Table 1. The 3-D FEM is used to simulate the performance of the VSC structure under the blast wave propagation. The 3-D FEA is carried out using ANSYS/AUTODYN which is specifically used to compute dynamic response and widely used to simulate blast loading<sup>[12]</sup>. In 3-D FEM, air and TNT explosive are computed by Euler processor. The air and the TNT explosive are considered to satisfy the equation of state (EOS) of ideal gas<sup>[12]</sup>. 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  $\gamma = 1.4$ .

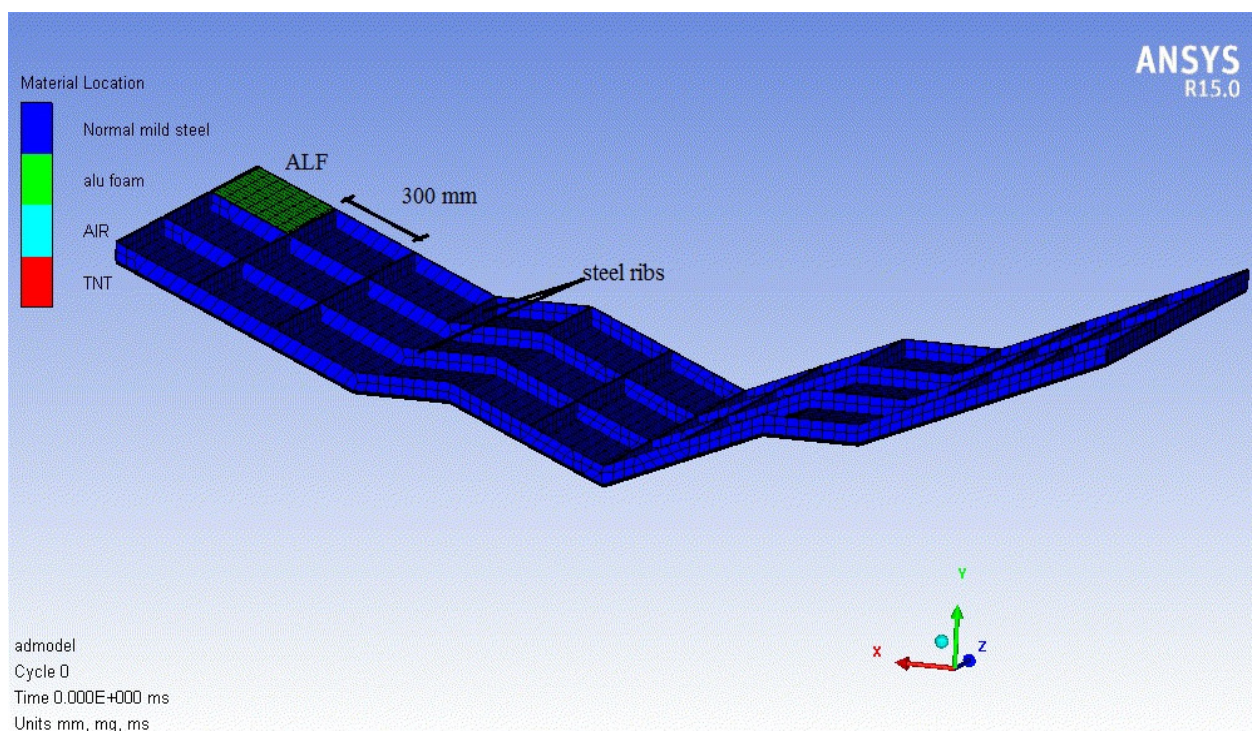
The steel plate material is chosen from the library. The linear equation of state and strength model is applied.

The yield stress of steel is assumed  $3.5 \times 10^4$  t/m<sup>2</sup> and its shear modulus is  $8.18 \times 10^6$  t/m<sup>2</sup>. Ribs and face sheets are simulated by shell elements, and the ALF is simulated by solid elements, as shown in Fig. 8. The V-shape structure is welded onto the chassis, as shown in Fig. 4. The V-shape structure is fixed at welding places, as shown in Fig. 9. The blast wave from detonation of 10-kg TNT explosive hit the V-shape structure is used in the analysis.

The displacement-time history is calculated and shown in Fig. 10. The maximum measured displacement is 50 mm, as tabulated in Table 1. The deformed shape of the V-shape composite structure is computed and compared with the deformed shape of the V-shape structure in the blast field test, as shown in Fig. 11. The results obtained by both the FEA and the field test are in good agreement.

**Table 1:** Plastic deformations obtained by the numerical analysis and the field blast test

location	Plastic deformations computed by the 3-D FEM (mm)	Plastic deformations measured by the field test (mm)	Discrepancy (%)
Gauge 2	44.54	50	10.9
Gauge 4	28.62	30	4.6
Gauge 8	10.01	10	0.1
Gauge 9	3	0	-



**Fig. 8:** 3-D finite element model of V-shape composite structure.

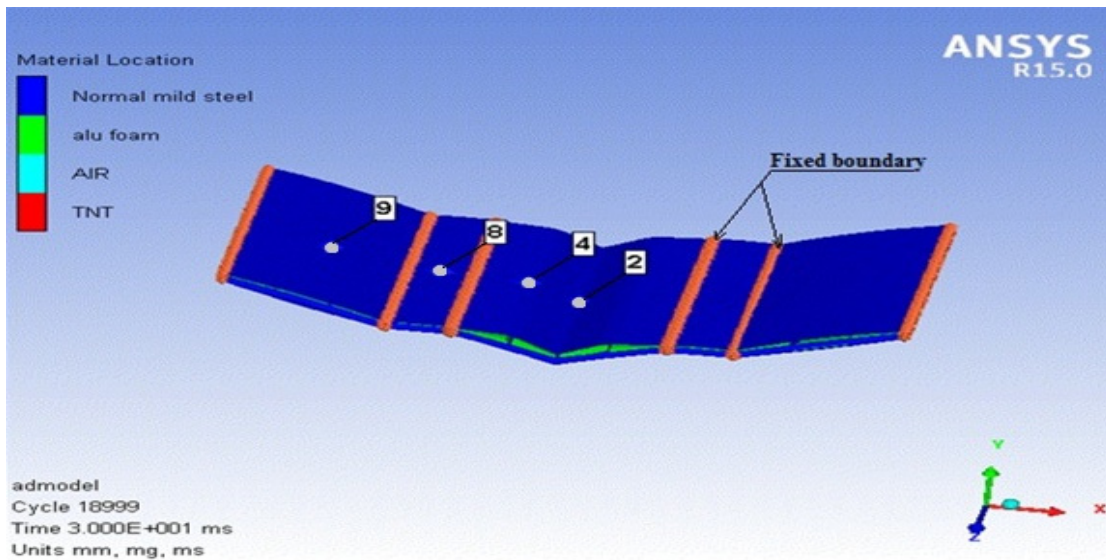


Fig. 9: Gauge locations and boundary conditions.

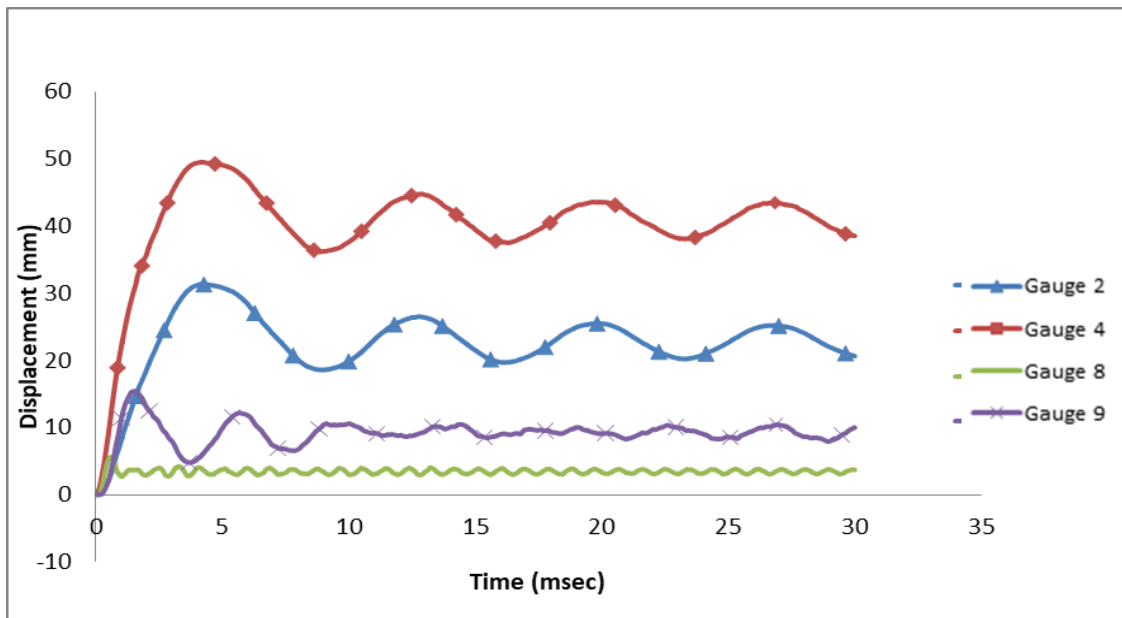


Fig. 10: Computed displacement-time history profile at different gauges of the V-shape structure subjected to detonation of 10-kg TNT

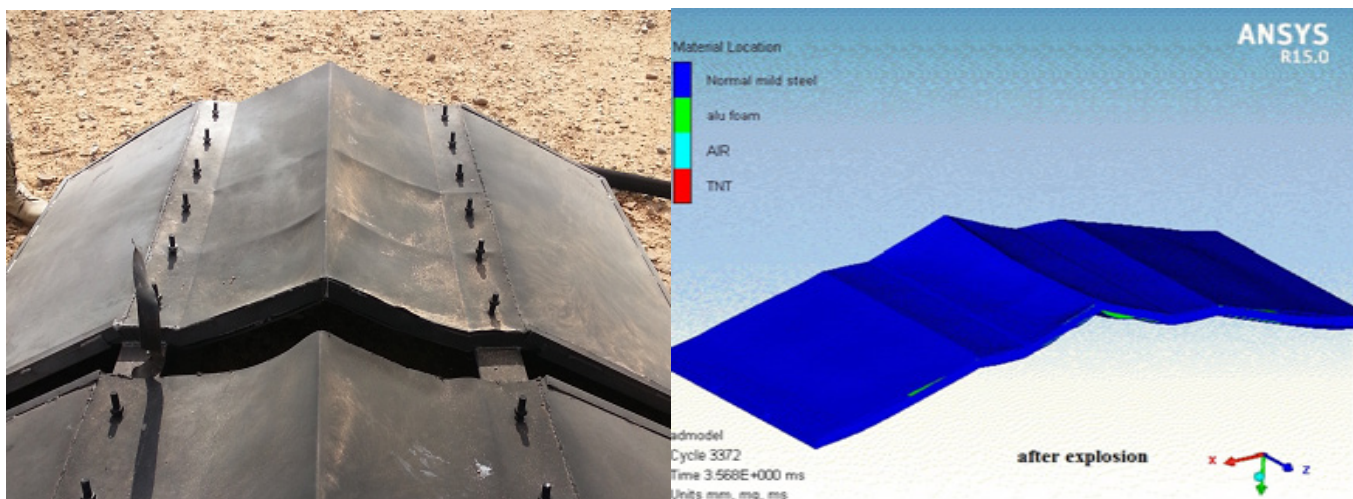


Fig. 11: Field blast test specimen and the 3-D FEM after the detonation of 10 kg TNT

### III. PERFORMANCE OF V-SHAPE STRUCTURE UNDER BLAST EFFECT

This study discusses the effect of inclination angle on the performance of the VSC structure. The behavior of the VSC structures with various inclination angles is investigated using the 3-D FEA. The inclination angle ( $\phi$ ) of the VSC structures is varied from  $0^\circ$ ,  $12^\circ$ ,  $16^\circ$ ,  $20^\circ$ , up to  $22^\circ$ , as shown in Fig. 12. The  $\phi$  angle is varied to discuss the effect of blast wave propagation on the flat and V-shape composite structures. The VSC structures are subjected to blast wave obtained from detonating of 10-kg and 15-kg TNT explosive charges at a one-meter stand-off distance of 1m.

The VSC structure is composed of ALF as core material and outer mild steel plates strengthened by the inner steel cross ribs. The interior space between the cross ribs in two directions is 30 cm, as shown in Fig. 13. The steel of the outer plates and the cross ribs is normal mild steel. The thickness of the steel plate facing the TNT charge is 3 mm. The thickness of the back steel plate is 4 mm. the interior space between face steel plate and the back steel plate is 34 mm, as shown in Fig. 14.

The dimensions of the VSC structures are 900 mm length and 600 mm width, as shown in Fig. 14. The V-shape structures were fixed from four edges and subjected to a surface detonation of 10-kg and 15-kg TNT explosive charges at a stand-off distance of 1 m from the front face-sheet along the centerline of the panel as shown in Fig. 15.

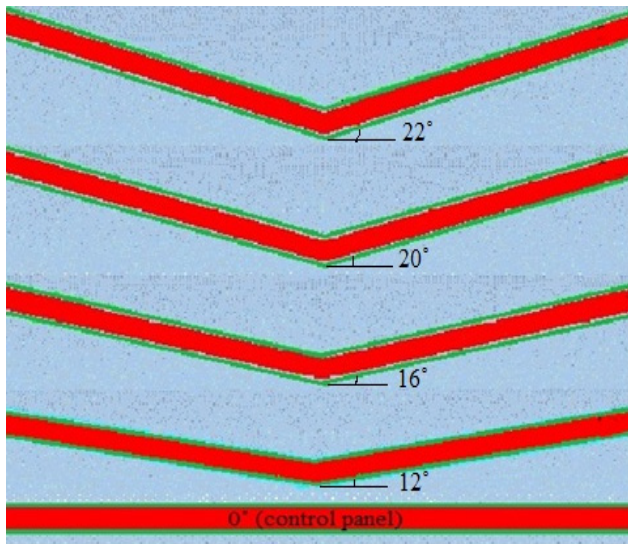


Fig. 12: Variation of inclination angle ( $\phi$ ) of the V-shape composite structures

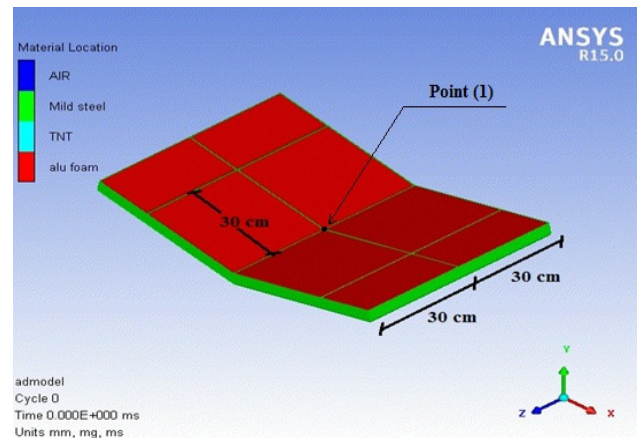


Fig. 13: V-shape composite structure strengthened by steel ribs with interior distance of 30 cm filled with ALF as a core material

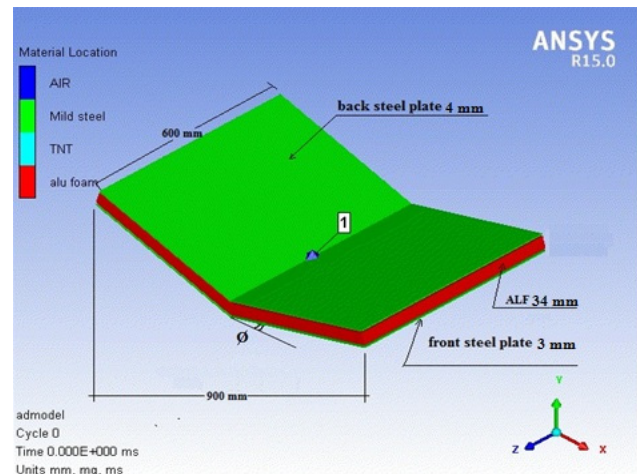


Fig. 14: The V-Shape Sandwich Structure.

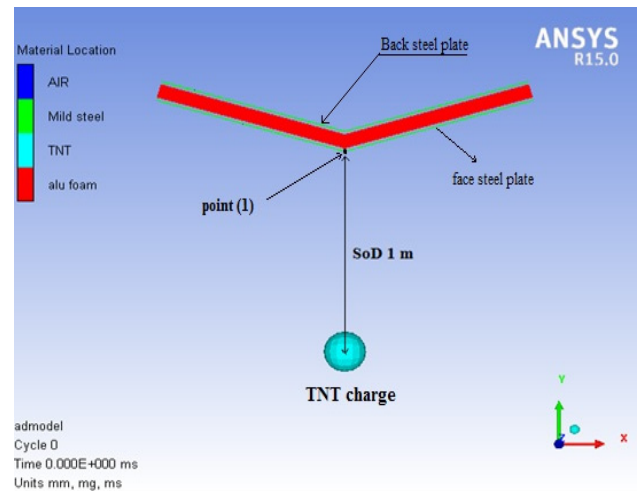


Fig. 15: Loading condition of V-shape composite structures.

#### IV. MODELLING OF V-SHAPE COMPOSITE STRUCTURES

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 [13]. Shell element is used to simulate the behavior of the steel plates and steel ribs. Solid element is used to simulate the behavior of ALF sheets. Flow-out boundary is used to reduce reflection of stress wave from the numerical boundaries. The standard constants of air and TNT explosive are obtained from the AUTODYN-3D material library.

A 4-node rectangular shell element is used to model the steel plates, and the steel ribs. Shell element consists of 4-node rectangular shape each node having 6 degrees of freedom (three translations and three rotations). The shell element allows both the membrane (in-plane) and the bending (out-of-plane).

A solid element is also used to model the ALF core material. 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).

#### V. IMPACT OF INCLINATION ANGLE ON THE PERFORMANCE OF V-SHAPE STRUCTURES

The performance of V-shape composite structures is discussed based on different inclination angles. The displacement-time history of V-shape composite structures due to blast load is calculated using the proposed 3-D FEM.

Ten-kg TNT explosive is used to discuss the performance of the V-shape structures with different inclination angles under impact of blast load. The TNT explosive charge is located at one-meter stand-off distance from the center of the crown of the structure (point 1) shown in Fig. 15. Figure 16 shows the displacement-time history results for each case.

Fifteen-kg TNT explosive is used to discuss the performance of the V-shape composite sandwich structures with different inclination angles under impact of blast load. The TNT explosive charge is located at stand-off distance of one meter from the center of the crown of the structure, at point (1). The displacement-time history profiles at the center of the crown of the panels are calculated for each case, as shown in Fig. 17. The plastic deflections point (1) due to the blast impact are tabulated in Table 2.

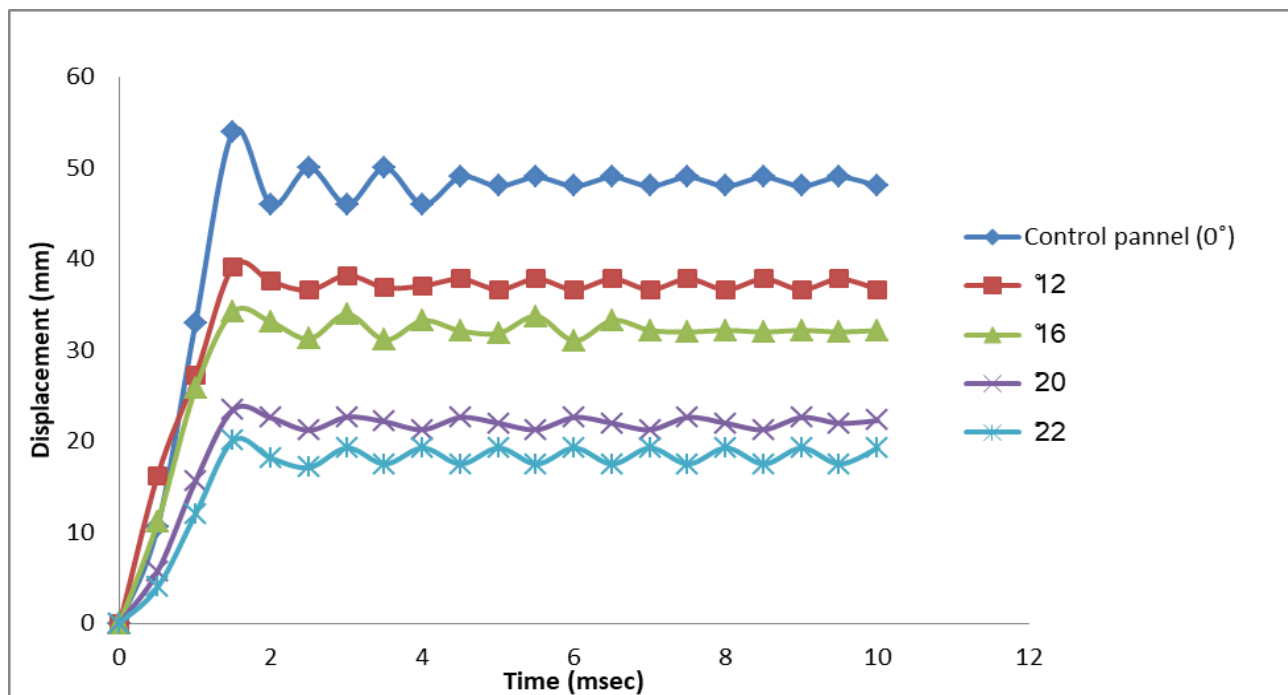


Fig. 16: Displacement-time history of VSC structures with various inclination angles subjected to detonation of ten-kg TNT.



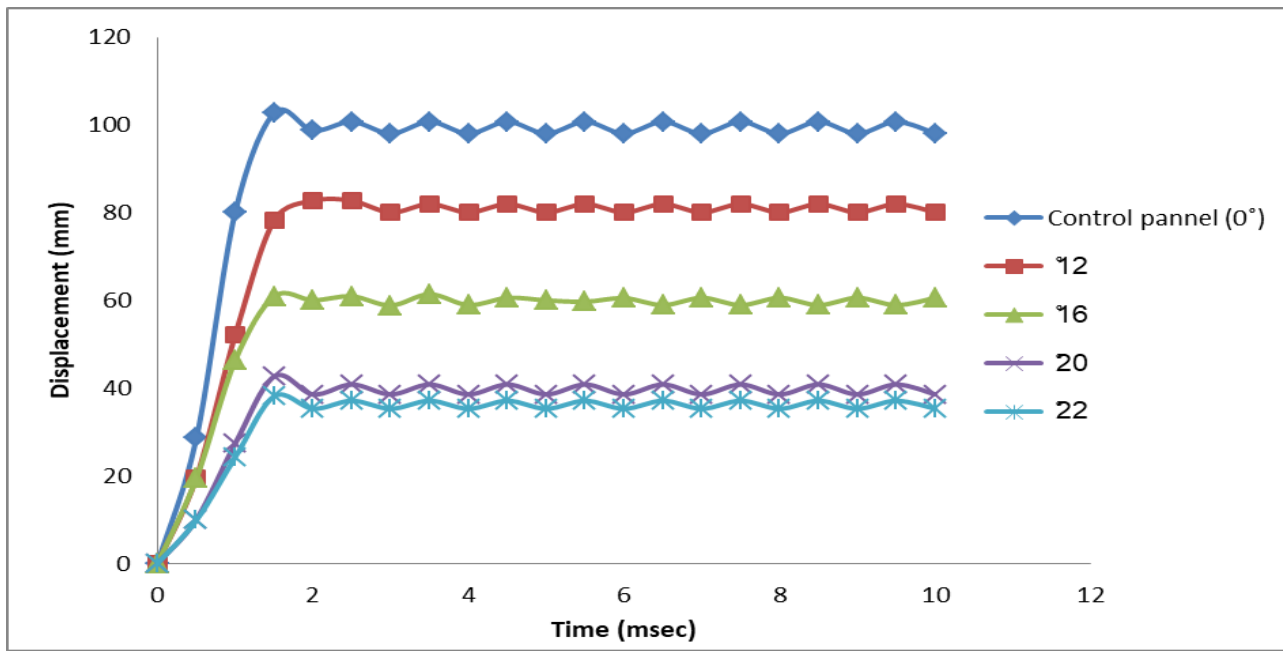


Fig. 17: Displacement-time history of VSC structures with various inclination angles subjected to detonation of 15-kg TNT.

Table. 2: Plastic deformations at point (1) due to the impact of blast load for panels with inclined angles

Core of composite structure	Inclination angle $\phi$ (degree)	Charge Weight (kg)	SoD (m)	Pressure (bar)	Plastic deformation (mm)	Discrepancy (%)
ALF+ ribs 30	0° (control panel)	10	1	44.5	49.72	–
	12°				38.4	22%
	16°				33.22	33%
	20°				23.13	50%
	22°				19.6	60%
ALF+ ribs 30	0° (control panel)	15	1	57.9	100.05	–
	12°				80.3	20%
	16°				60.9	40%
	20°				40.3	60%
	22°				37.7	62%

Results show that the bigger inclination angle ( $\phi$ ) the better blast mitigation. However, the V-shape structure for a vehicle's bottom would ideally be small inclined angle to save a suitable clearance between the bottom and ground surface.

## VI. CONCLUSIONS

- The responses of the V-shape composite structure with inclination angle 12° are reduced by up to 15% with respect to those of flat composite structures.
- The responses of the V-shape composite structure with inclination angle 16° are reduced by up to 25% with respect to those of flat composite structures.

- The results indicate that the response of the V-shape structure decreases with the increase of the inclined angle ( $\phi$ ). So, the V-shape protective shield is superior to a flat- protective shield in resisting loads transfer from an explosive blast.

- The V-shape composite structure is used as a protective layer to protect the bottom of a vehicle from blast load.

- The reviewed field blast tests is used to study the performance of the V-shape composite structures. The 3-D finite element model is used to simulate the field blast test and to predict the performance of the composite structure.

- Extensive parametric study is conducted to adopt the V-shape composite structure to protect the bottom of the armored vehicles under blast load.



- The responses of the V-shape composite structure with inclination angle  $22^\circ$  are reduced by up to 50% with respect to those of flat composite structure.

8 - A 3-D nonlinear finite element analysis has been used to study the effect of inclination angle on the performance of the V-shape composite structures.

- The FEA is used to predict the response of V-shape composite structures with different inclination angles due to the detonation of 10-kg and 15-kg TNT explosive charges placed at 1m SoD from the center of the panel.

- The responses of the V-shape composite structure with inclination angle  $20^\circ$  are reduced by up to 40% with respect to those of flat composite structures.

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