Australian Journal of Basic and Applied Sciences, 11(5) April 2017, Pages: 143-156

AUSTRALIAN JOURNAL OF BASIC AND APPLIED SCIENCES

ISSN:1991-8178 EISSN: 2309-8414
Journal home page: www.ajbasweb.com

Protective Panels Design against Blast Loads

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ARTICLE INFO

Article history:
Received 18 January 2017
Accepted 28 March 2017
Available online 1 May 2017

Keywords:
Blast Load, Standoff distance, Charge weight, AUTODYN, Deformation, Protective Panels, Front plate, Rear plate.

ABSTRACT

As a result of repeated terrorist incidents around the world causing huge loss of property and human lives. While the threat of a conventional explosion charge is defined by two equally important elements, the charge quantity (weight), the standoff distance between the blast source and the target. Furthermore, most casualties and injuries sustained during explosions are not only caused by the pressure or heat resulting from a charge detonation. But also, by fragmentation of walls, shattering of windows, and non-secured objects that are propelled at high velocities by the blast. Thus, protection of critical structures against blast load has become a critical issue. The research objectives were to increase the building impulsive capacity against a blast load that is applied on their facade without any modification in the building structure; these objectives were achieved using a protective panel as a barrier between the blast load and the building. Herein the research considered a study to achieve a panel design that could prevent a blast wave from reaching the building structure and minimizing the pressure behind the panel, besides a withstanding panel against consecutive explosions after the main blast. Furthermore the research investigate the alternation of design parameters to achieve the desired panel design including the filling material, thickness of panel's plates and separation distance between the front and rear plates. This paper includes six different models to be tested against a breaching charge of 50 kg of TNT at 1m standoff distance. The design of Protective panels consists of two steel plates with 350 mm gap. The structural design of the panel includes plate thickness, distance between front and back plate and filling material. Various panel designs were examined with and/or without different filling materials. Moreover, strengthen mechanism is implemented for plates using shear connectors and horizontal stiffeners. Panel design approach is accomplished using the finite element analysis through ANSYS AUTODYN. Eventually, the first three models have a large deformation, while the fourth and fifth model resulted in a medium deformation, finally, the sixth model resulted in a significant small deformation recorded 64mm; this model is committed as the most suitable panel design for protecting building against blast load. In conclusion the deformation decrease through the increase of plate thickness and the usage of concrete as filling material, as well as the strengthen mechanism using horizontal plates.

INTRODUCTION

With the rising threat of terrorism, protecting critical structures such as embassies, governmental buildings, and airports against explosion threats has become a critical issue. Therefore, there is a need for the development of techniques that can protect such structures against the blast load. The threat of a conventional explosion charge is defined by two equally important elements, the charge quantity (weight), the standoff distance between

To Cite This Article: Mohamed Fekry, Gamal Mahmoud, Mohamed El Shafey., Protective Panels Design against Blast Loads. ***Aust. J. Basic & Appl. Sci.***, *11(5): 143-156, 2017*

the blast source and the target. Most casualties and injuries sustained during explosions are not only caused by the pressure or heat resulting from a charge detonation. But also, by fragmentation of walls, shattering of windows, and non-secured objects that are propelled at high velocities by the blast. Ensuring that the exterior walls of a structure capable to withstand a blast without producing deadly fragments is a critical part of minimizing injuries to building inhabitants.

Penchant scientific and research works introduced several techniques for protection against explosion. Mana conducted an extensive study comparing the effect of blast load on building with and without a soil barrier (Maňas, 2017); in addition to Zhou and Hou research which was steel plate barrier (Hou, 2008). Moreover researchers reduced the effect of blast load on the building foundation by reinforcing the building columns by advanced material cast; in addition to ultra-high performance concrete material (Jun Li, 2017)and (Hongwei Wang, 2017). Furthermore the protection of container was conducted by Elshafey.M. introducing a container protection against hazards material vessels in transportation, (Elshafey M., 2012) and (Braimah, 2012). On the other hand, deploying CFRP (carbon fiber reinforced polymers composite) in masonry wall design for protecting against bombing, the design was verified experimentally. Ehasni et al, introduced a method of protection by using composite material succeeded in protection against blast of approximately 100 kg TNT; however, the cost of using CFRP is expensive and not applicable for all buildings, found in(Peña, 2009).

Changing material used in building walls is not enough for protection due to the fragments that will results from other features in the façade, such as the glasses and fabrics. Otherwise, Shimaa et al studied the effect of reinforced concrete barrier in protecting a building form 1000 kg TNT, the building was severely damaged after the blast load and the barrier was completely destroyed(Osman Shallan, 2014). Consequently, walls alone cannot protect building form explosion, the need of another method of protection arises. Researchers directed to designing protective panels to support blast load without any damage in constructions behind. Blast barriers were introduced known as CMI barriers (corrugated metals Inc.), Crawford and Lan designed from corrugated sheet metal filled with sand; the barriers aims to protect premises against ballistics including projectiles weapon and air blast (Lan, 2006). Mustafa introduced a barrier made from steels with angles orientation as an orthogonal meshed fence; another observation for the research that pressure was the governing parameter in the study; however other researchers preferred to use deformation. The bomb used in Mustafa model was 50 kg TNT and standoff distance one meter (Mustafa Sami Elsayed, 2009). Carbon fiber was used as exterior protecting layer on masonry wall, where explosion could be handled without wall failure. Although the enhanced wall succeeded to support the explosion, the author stated that it is very expensive to enhance all the building walls, in addition to windows and glasses that cannot be enhanced(Peña, 2009).

When the detonation source is located close to the ground, then the wave will be reflected and amplified by the ground producing reflection waves (U.S. ARMY CORPS OF ENGINEERS , 2008). The definition of blast wave is air wave in motion due to explosion (Bjerketvedt, 1997); depending on two equally important elements, the charge weight, and the standoff distance between source and target. Usually the blast wave alters the ambient atmospheric pressure with a significant range; referred to side-on overpressure decaying as the shock wave expands outward from the detonation source. After period of time, the pressure is dropped under the ambient pressure; which leads to suction or negative pressure phase. Also, this will lead to suction winds that carry debris away from the explosion source (T. Ngo, 2007). Finally the amount of explosives will determine the value of peak and negative pressure which are determined from over pressure and pressure after decay (Baker, 1973).

Previous studies conducted clarify the performance of steel barrier filled with concrete against blast load. Otherwise, the barrier reached the plastic deformation near failure state. Consequently, the panel design should be improved to support a blast load of 50 kg TNT while reducing the regions of plastic deformation to ensure the panel survival without failure after the blast; this stage is critical for building protection, because bomb explosion may leads to consequence explosions on smaller scale afterward. This paper introduces improved protective panel design against breaching charge of 50 Kg at standoff distance of 1 meter. Various designs were numerically modeled at which 6 designs only are presented in this paper. The protective panels are evaluated based on the maximum allowable deformation of the front and rear plates as well as the filler material in between. The results presented in this paper showed great performance against 50 Kg charge with minimum plastic strain.

1. *AUTODYN modeling:*

2.1 Explosion Remap:

Remapping allows for detonating the amount of explosives that is of interest in 1-D and then transform it into 3-D model. The remap is prepared by knowing the shortest distance between the center of the explosion and the nearest point of interest. In this study the point of interest is one meter from the center of explosion. This distance is used while building the 2-D mesh to set out the length of the portion representing the air. The part used to simulate a 2-D explosion is called the “Wedge”. This can be meshed in the local coordinate system I and J. The meshing is accomplished using the I direction keeping it constant in the J direction; and should be equal to one cell, two “J” lines. Similarly, the remapping is done using mesh size one-quarter millimetres. The equivalent number of cells is 4000 cells (Elshafey, 2008).

After creating the wedge, it was filled completely with air. Subsequently, the radius of the spherical charge, determined using Equation 1. Fig. 1 represents the material location for air and TNT and the velocity vectors after detonation within the wedge. After filling the air with the explosive charge, a detonation point was defined at X=0 and Y=0. Then, the program was initiated and ran to the point at which the shock front was almost at the end of the wedge. At this point the program was terminated, a remap file was created and the wrap-up time was recorded. The recorded wrap-up time is used in the 3-D models as the initial time for the models. The EOS in the material model for the TNT is automatically updated from JWL to Ideal Gas when the compression is close to -1.

$$r = \sqrt[3]{\frac{3*W*1000}{1.63*4*\pi}} \qquad (1)$$

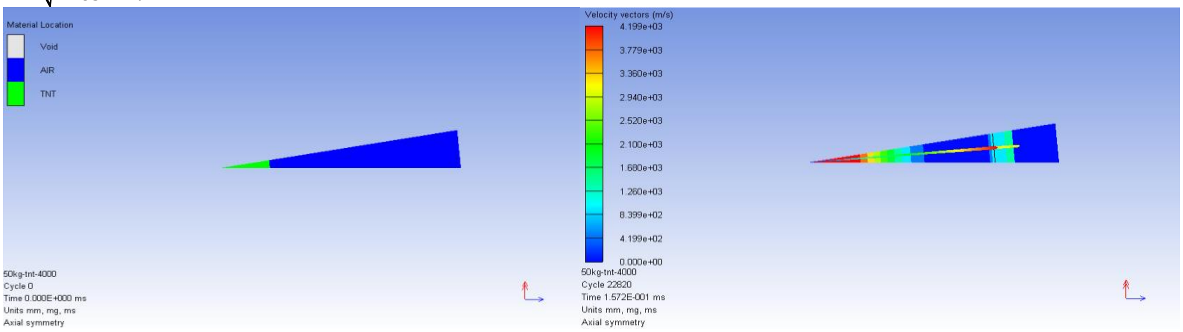

Fig. 1: The Wedge part used to simulate air for remapping.

2.2 Verification Model:

The model validation for accuracy is based on the previous work found in (Mustafa Sami Elsayed, 2009).

Thus, the media actual dimensions on X, Y and Z coordinates are 6m, 3m and 1m respectively. The model is axisymmetric on X axis. In addition to, the boundary conditions of the system’s elements are set as Fixed-Fixed in the Z-direction. The charge weight is 50 Kg TNT, which is located at coordinate (0, 0, 0). Also the stand of distance is 1m. The material of the structural elements used to build the mitigation systems is steel of I-Beam, Plate, Angle and Tube with thicknesses of 5, 15, 10.61 and 4.773mm respectively. The cross-sectional area of the individual system elements is preserved at 4500mm2, with the same projected area of 300X1000mm. The lateral spacing between the elements is selected to a value of 100mm. The verification model includes only the plate model; however the base model presented several models rather than the plate one. Movable measuring points are located on the plates at the middle. Fig. **2** shows the model setup.

By comparing the results monitored by gauges number 10 and 11 in both the verification and base model it was found that results are very near to each other. Firstly reading of gauge 10 the peak value in the base model recorded 82mm and the verification model recorded 79mm as shown Fig. **3** respectively. Secondly the 11th gauge recorded a peak value for base model equal to 65mm as the same of verification model as shown in Fig. **4**.

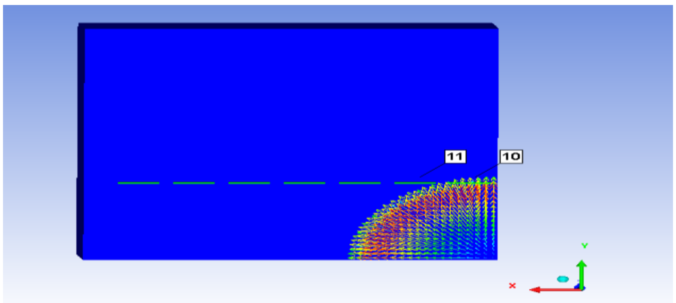

Fig. 2: AUTODYN model setup

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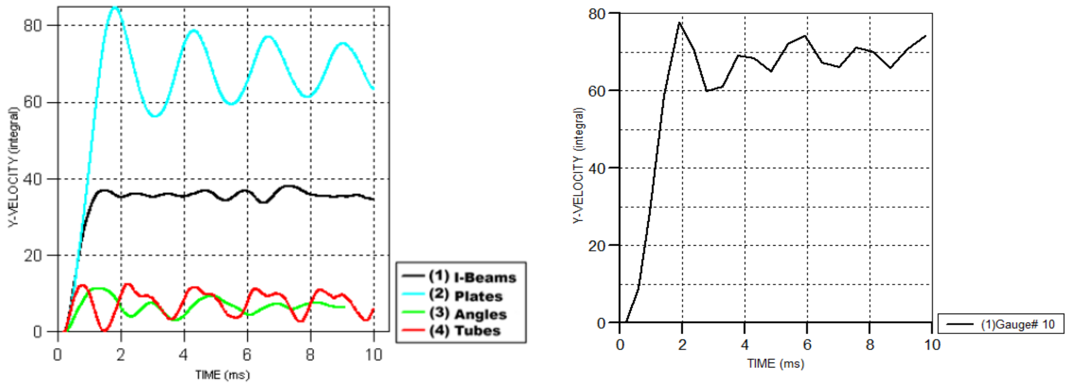

Fig. 3: Deformation time history at gauge no.10

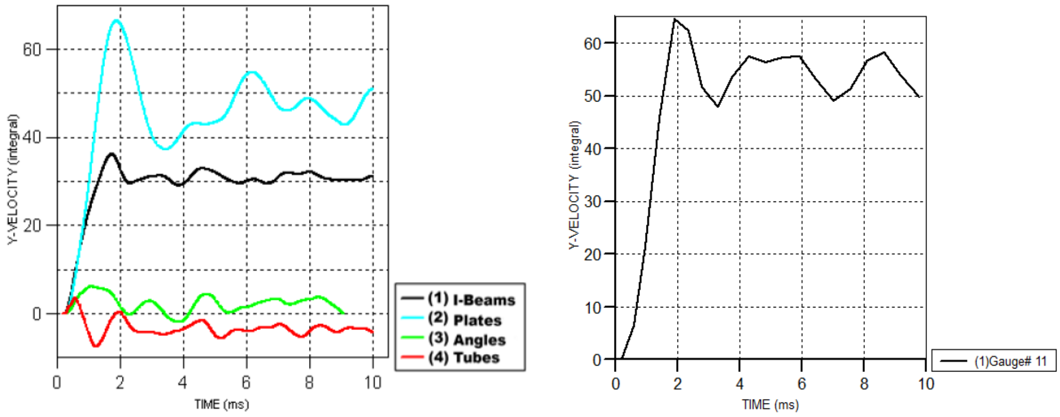

Fig. 4: Deformation time history at gauge no.11

Models Hypothesis:

The design of Protective panels consists of two steel plates (rear and front) with 350 mm gap. Two configuration methods were used to fill the gap between the plates. The first configuration method uses air and concrete to fill the gap. While the second configuration method uses shear connectors and horizontal plates to connect the two plates. Both configurations maintained the standoff distance between the charge and the panel. Table 1 shows the various configurations description.

Table 1: Models description.

Method	Model name	Areal density t/m^2	Model description		
			Plate thickness	Separated distance between plates	Separated distance condition
I	S5A_350	374.722	5 mm	350 mm	Filled with air
	S20A_350	2409.23	20 mm	350 mm	Filled with air
	S5C_350	8395.55	5 mm	350 mm	Filled with normal concrete
	S20C_350	9813.076	20 mm	350 mm	Filled with normal concrete
II	CPS 1	2422.213	20 mm	350 mm	Plates are connected together with 12 mm shear connectors (distributed horizontally and vertically with 500mm).
	CPS 2	2999.492	20 mm	350 mm	Plates are connected together with 12 mm horizontal plates (distributed vertically with 500mm).

Numerical Analysis:

Physical model define the panel design parameters and explosion parameter; those parameters include panel dimensions and supports, in addition to explosion charge weight and stand of distance. Firstly, the panel design consists of two steel plates with yield stress 4.0E+05 (kPa). The model dimensions are 3 meters length, 3 meters width and 350 mm thickness; which considered standard dimension of fence's partition; moreover, the panel is supported from the bottom. The reason behind supporter selection is limitation of deformation in the middle; hence in the case of side fixed supporter the panel will be free to deform at the middle, otherwise bottom fixed support will constraint the middle from deformation.

Secondly, the effective charge weight was selected to the 50 kilogram TNT. Another crucial and effective parameter that effects the panel deformation is the stand of distance between charge and panel. The standoff distance between the charge and the panel is 1m; value depends on angle of inclination for the reflected blast wave. The following points brief the stand of distance issue:

1. Standoff distance less than one meter, then inclination angle of blast wave is near to perpendicular on the panel, which results in scattering of the wave without any intersection between them. This will reduce the effect of the blast wave on the panel. Hence, distance less than one meter is excluded.
2. Standoff distance greater than one meter will require extensive computation capabilities, in addition to, there will be insignificant effect.

3.1 Finite Element Model:

The Analysis of blast propagation is accomplished using ANSYS AUTODYN finite elements package. AUTODYN proposes several mathematical solvers for analyzing blast propagation in structures. Steel plate is considered a shell and solved using shell model. The air surrounding the bomb during the simulation is modeled with dimensions of 4 meters length, 3 meters width, and 3 meters height.

Moreover, gauges measure the pressure and deformation; the process of gauges selection and placement is critical for the accuracy of the model. Two categories of gauges presence, fixed and movable gauges, the fixed gauge is suitable for measuring the pressure which is mounted behind the panel at distance 1m, 2m and 3m respectively. Otherwise the movable gauge is suitable for measuring the deformation by integrating the Z axis velocity, which is mounted on the height of the panel at height 0.5m, 1.5m and 3m respectively from the ground.

Fig. 5 shows the mounting configuration for fixed and movable gauges in the model.

Finally, the boundary condition is set as fixed free from the lower cross-section to satisfy the proposed physical model. The following points brief the model hypothesis:

- Panel dimension 3 X 3 X 0.35 m.
- Boundary condition is fixed-free from the ground.
- Charge weight is 50 Kg.
- Standoff distance one meter.

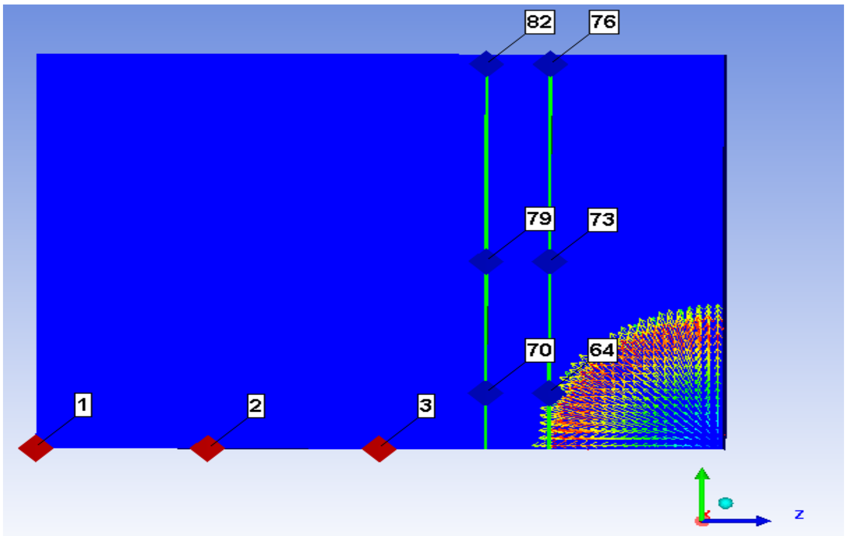

Fig. 5: Fixed and movable gauges.

RESULTS AND DISCUSSION

4.1 Pressure without panel:

Gauges have a great effect on determining the value of pressure that will reach the building. Fig. 6 shows a comparison between three gauges setup and the peak pressure observed by them. The third gauge is the close to the bomb hence it recorded a peak pressure value equal to 2000 kPa; however the far gauge from the bomb which is gauge number one recorded the least peak pressure equal to 500 kPa.

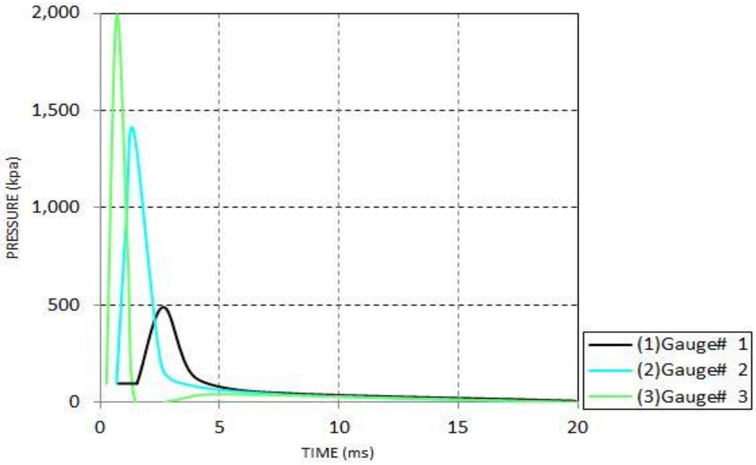

Fig. 6: Pressure time history.

4.2 Method I:

The first method consists of four models, the designation of the models are S5A-350, S20A-350, S5C-350 and S20C-350.

- ***S5A_350:***

The maximum pressure observed at the third gauge with a value of 118 kPa recorded at 4 milliseconds; however the peak pressure observed in the other two gauges recorded only 106 kpa and 107 kpa at 9 and 7 milliseconds for the first and second gauges respectively. The values of pressures recorded by the three gauges are shown in Fig. 7.

The front plate in S5A-350 design failed after applying the blast load; then continues in deformation until contacted with the rear plate; hence, the blast wave was transmitted to the rear plate. Furthermore, the rear plate deformed without failure. Fig. 8 contains a graph showing the deformation of front and rear plate respectively against time for the three gauges. The graphs show that the rear plate starts deformation at 2.2 milliseconds recording a maximum deformation of 270 mm at the end of the analysis, as observed by the gauge 70. In addition to, the maximum deformation of the front plate was observed to be 518 mm at the end of the analysis, as observed by the gauge 73.

In Conclusion, the separation distance has affected the deformation of the front plate due to the allowance to deform more until contacting the rear plate and transmitting the load. Fig. 9 shows comparison between different deformation plots at time interval during the run.

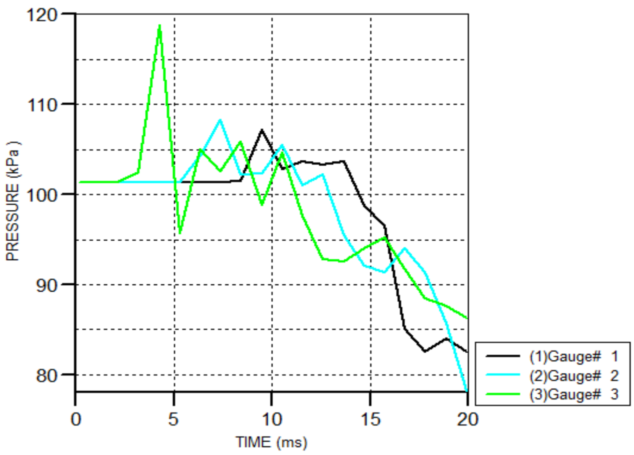

Fig. 7: pressure time history

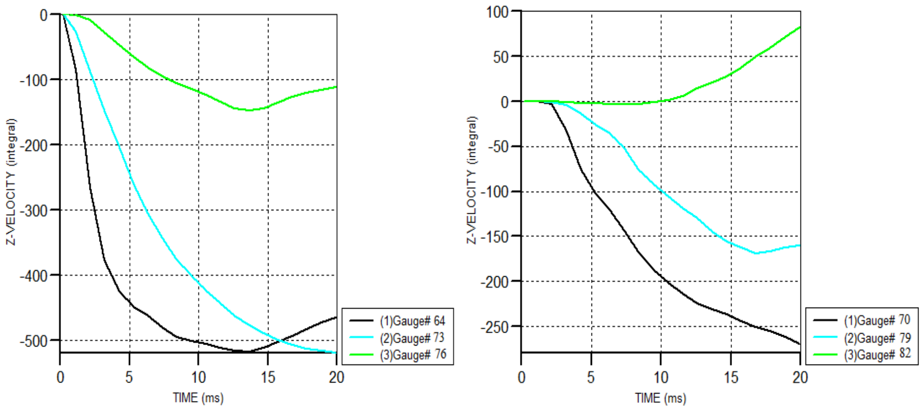

Fig. 8: deformation time history for front and rear plate

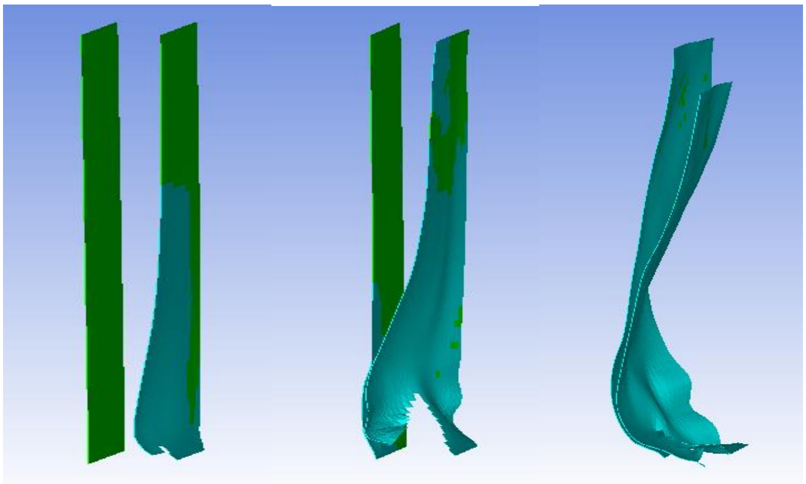

Fig. 9: deformation plot at different time step

- ***S20A_350:***

Pressure distribution is uniform compared to the previous model, due to the increase of the thickness which leads to damping more amount of the wave and reducing the fluctuation behind the panel. The peak pressure of the three gauges is very near in value, approximately around the 101 kPa which is equal to the ambient pressure as shown in Fig. 10. Concluding from pressure observation the effect of pressure is not critical in assessment of panel design, because the panel caused the pressure to be approximately equal to ambient pressure. Consequently, the deformation will be the main assessment criterion for evaluating each panel design.

S20A_350 has a thickness of 20 mm, hence, the deformation of rear plate was near zero, recording a deformation of negligible value caused by vibration resulted from the blast wave; due to no contact between the front and rear plate. On the other hand, the front plate recorded a maximum deformation of 175 mm at the end for the gauge 73 reading. Fig. 11 shows the deformation of front and rear plate respectively, both deformation graphs are against time and for the three gauges. Fig. 12 shows the deformation during the analysis run.

The filling medium is changed to normal concrete instead of air. The group consists of two models with designation as the following S5C-350 and S20C-350. Normal concrete will affect the transmission of load from the front plate to rear plate.

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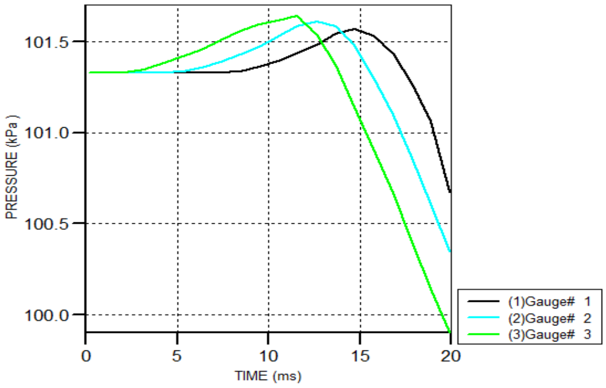

Fig. 10: pressure time history

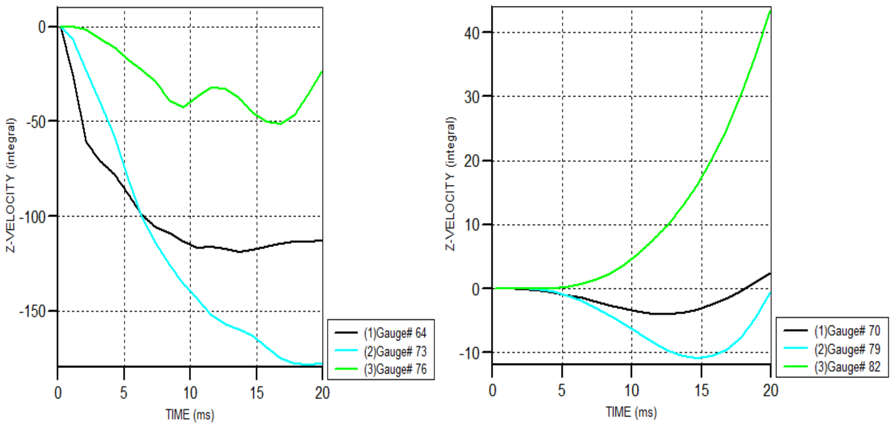

Fig. 11: deformation time history for front and rear plate

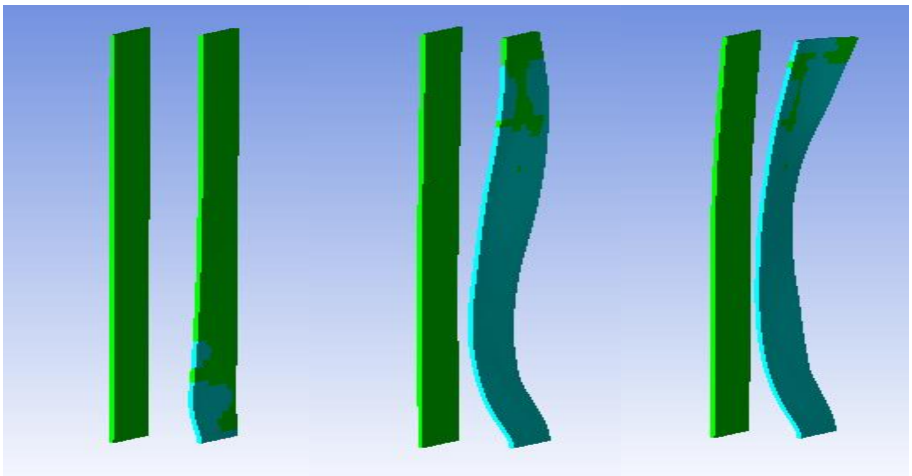

Fig. 12: deformation plot at different time step

- ***S5C-350:***

S5C-350 model, the front plate deformed without failure until reached maximum value equal 33 mm at 3 millisecond for the gauge 64, then the plate transmitted the load to the concrete; after that the plate return back. The gauge 73 recorded 65 mm. The concrete crushed instantaneously after the blast; reducing the transmitted load to the rear plate. On account of this, rear plate starts deformation after the blast recording maximum deformation equal 207 mm for the gauge 70 at the run's end.

Conclusion observed from 350 separate distance filled with concrete models that the inertia effect of the concrete decays energy, which will leave a lower amount of energy transmitted to the rear plate. The graph in Fig. **13**: deformation time history for shows the deformation of the three gauges on front and rear plate against

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time; and Fig. 14: deformation plot at different time step shows the deformation plots along time interval during the analysis run.

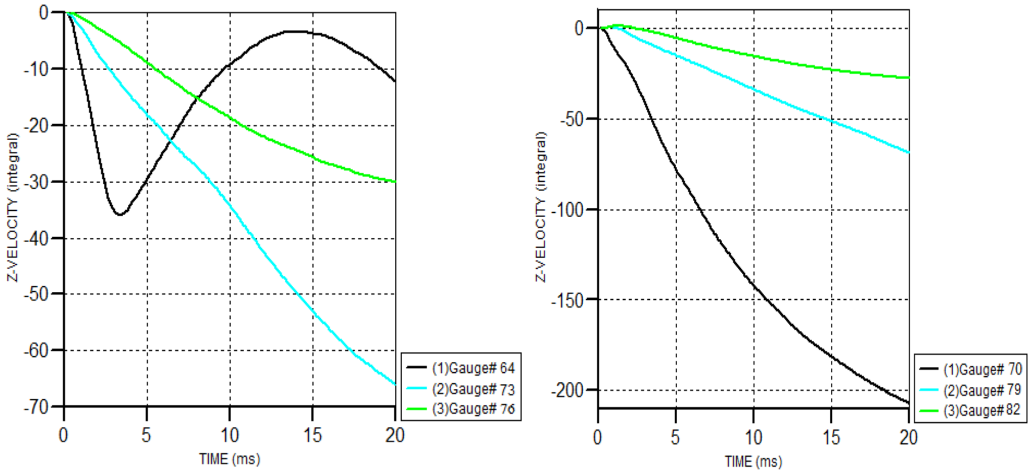

Fig. 13: deformation time history for front and rear plate

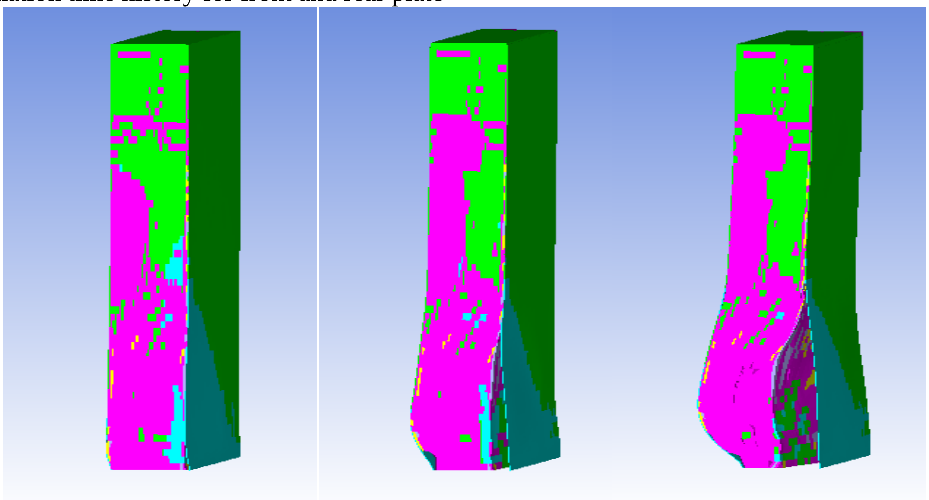

Fig. 14: deformation plot at different time step

- ***S20C_350:***

Likewise the previous model, the S20C-350 exhibits deformation behaviour very near in value for the front plate. Deformation in front plate reached maximum values of 25 mm at 2.5 milliseconds and 39 mm at the run's end for gauge 64 and gauge 73 respectively. Rear plate's deformation recorded maximum deformation equal 47 mm for the gauge70 and 73 mm for the gauge 79. Consequently, the thickness altered in this model improving the behaviour of rear plate with significant improvement in the front plate. Fig. 15 shows deformation of front and rear plate for the three gauges against time; and Fig. 16 shows the deformation plot along several time intervals during the run of the S20C-350 model.

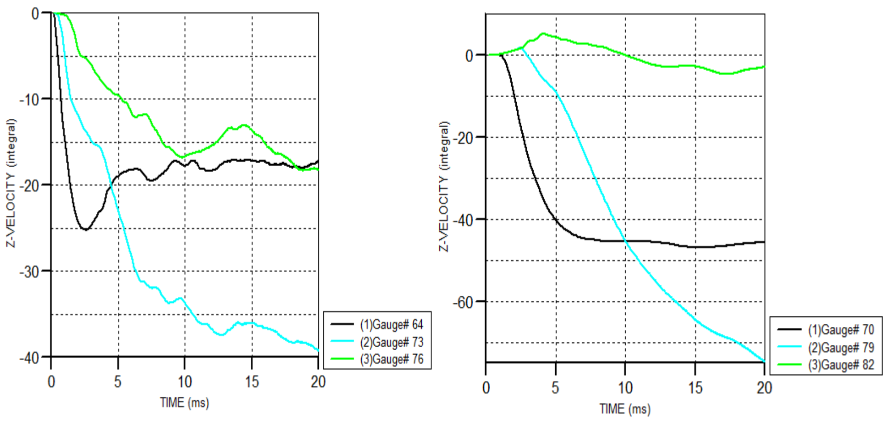

Fig. 15: deformation time history for front and rear plate

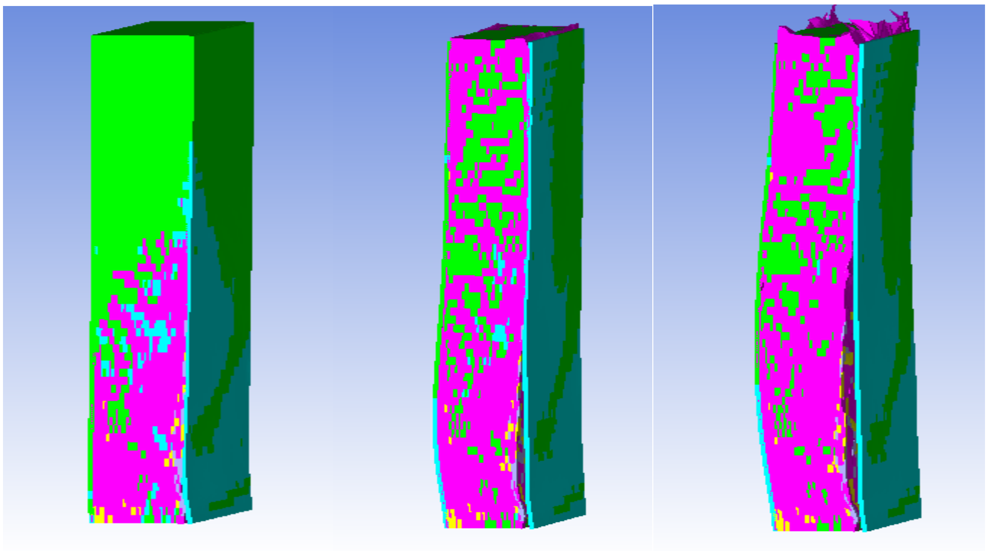

Fig. 16: deformation plot at different time step

4.3 Method II:

The second method consists of two models, the designation of the models are CPS1 and CPS 2.

- ***CPS1:***

The model introduced in this part called combined protection system (CPS); two models are introduced in this part. First model is plates joined with shear connectors CPS1. Second model shows the analysis of plates joined with plates at offset distance of 500 mm horizontal direction only CPS2.

CPS1 model consists of two plates with rectangular array of shear connector with vertical and horizontal offset equal to 500 mm. The shear connectors have diameter of 12 mm, the other design parameters are concluded in the previous section. Fig. 17 shows the orientation of shear connectors. Concluding form added connector, the panel will be deformed as single rigid body; which will enhance the deformation behaviour of the panel. The panel recorded maximum deformation of 86 mm for the whole panel; deformation graph is shown in Fig. **18** the maximum is recorded at the gauge 79. Moreover the maximum deformation occurred at 17 milliseconds; after that the panel relived the deformation. Another crucial point observed is the location of the maximum deformation which is located at the midpoint of the panel. Fig. 19 shows the location of the maximum deformation; located at the panel middle. The plastic deformation is observed at the shear connector joint location, in addition to the increase of plastic deformation percentage along the plates. Fig. 20 introduce the plastic deformation at joint location with distribution along the front and rear plates.

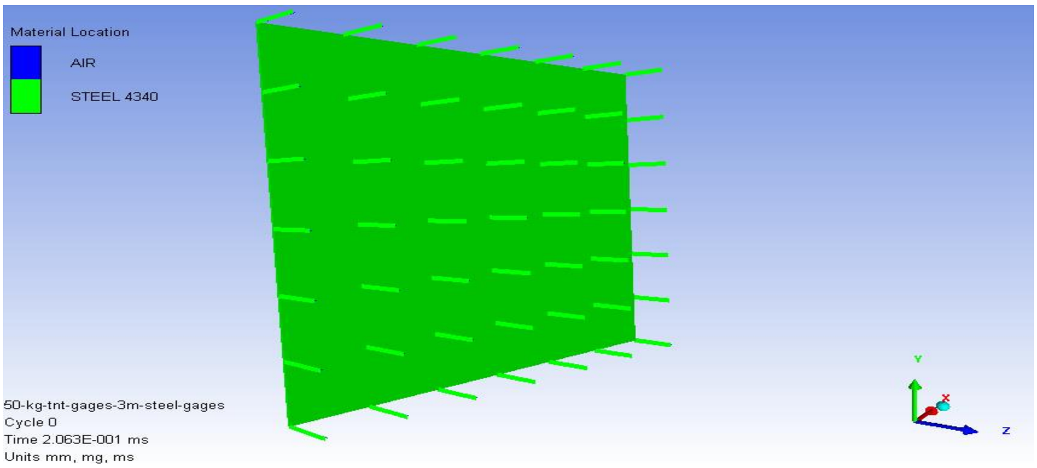

Fig. 17: Orientation of shear connectors inside the panel.

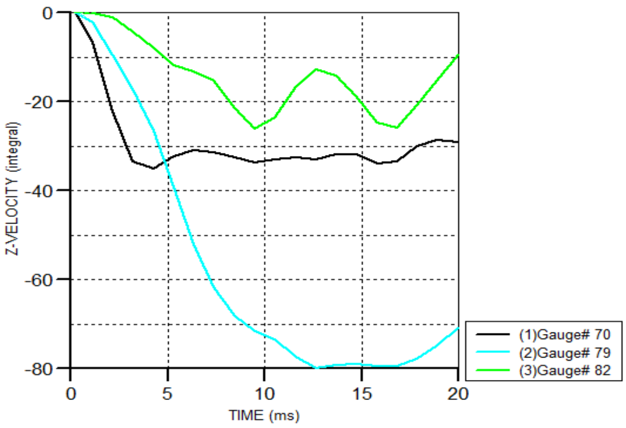

Fig. 18: Time displacement curve

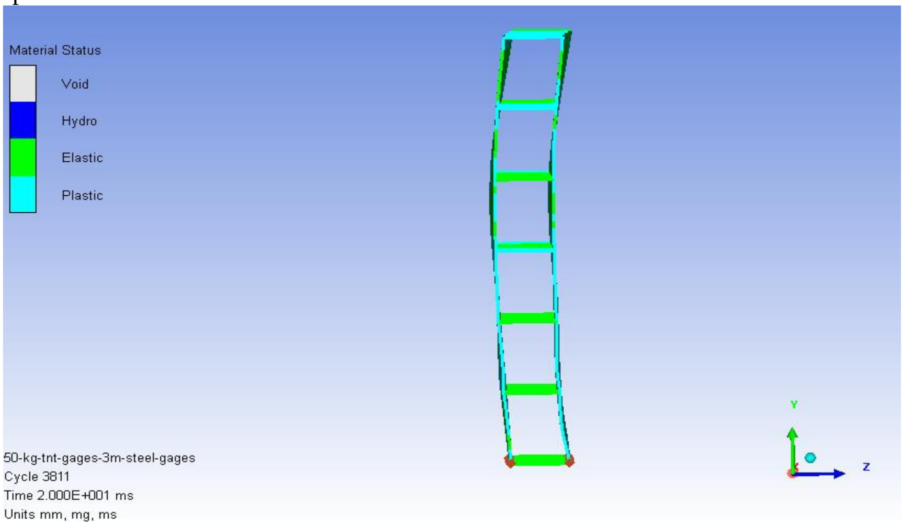

Fig. 19: Location of the maximum deformation located at the panel middle.

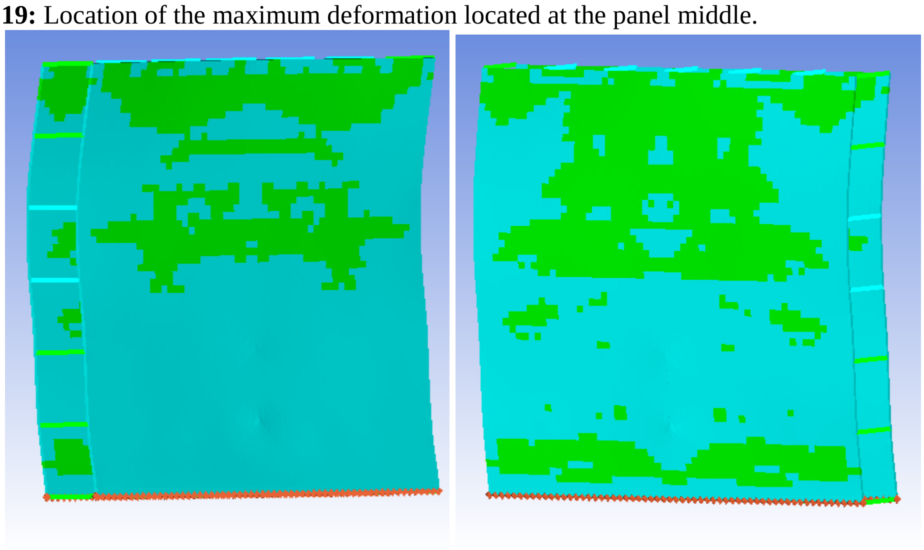

Fig. 20: Plastic deformation region in front and rear plate.

- ***CPS2:***

Shear connector is replaced in the second model with horizontal plate; where the plate is distributed along the height at 500 mm. The horizontal plates have thickness of 12 mm. Plate orientation inside the panel is described in Fig. 21. The plate concept increased the connected area between the plate and the connector. Hence, the deformation is reduced recording 64 mm at the gauge 79, due to the distributing of the load on both plates. Fig. 22 shows the location of the maximum deformation; located at the panel middle. Moreover the deformation graph is introduced in Fig. 23. Fig. 24 shows the distribution of plastic deformation along front, rear and horizontal plates. Concluded from the second model, the increase of the contact area between plates and connector distributed the deformation along plates, adding to that the contribution of connector cross-section area in deformation reduction. The lower horizontal connecting plates achieved a larger plastic deformation region compared to the upper plates; this is because of the lower plates are near to the bomb.

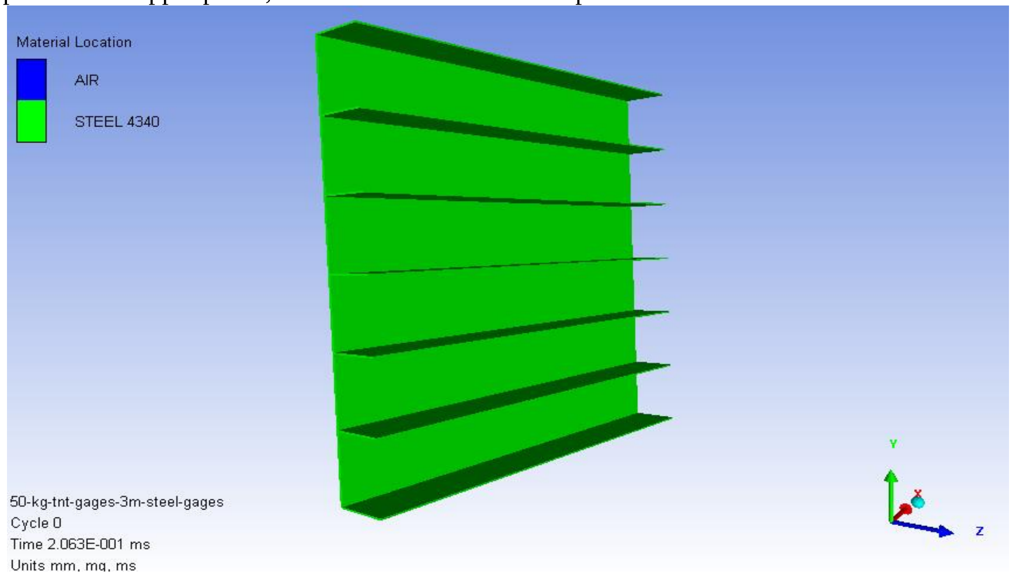

Fig. 21: Orientation of horizontal plates inside the panel.

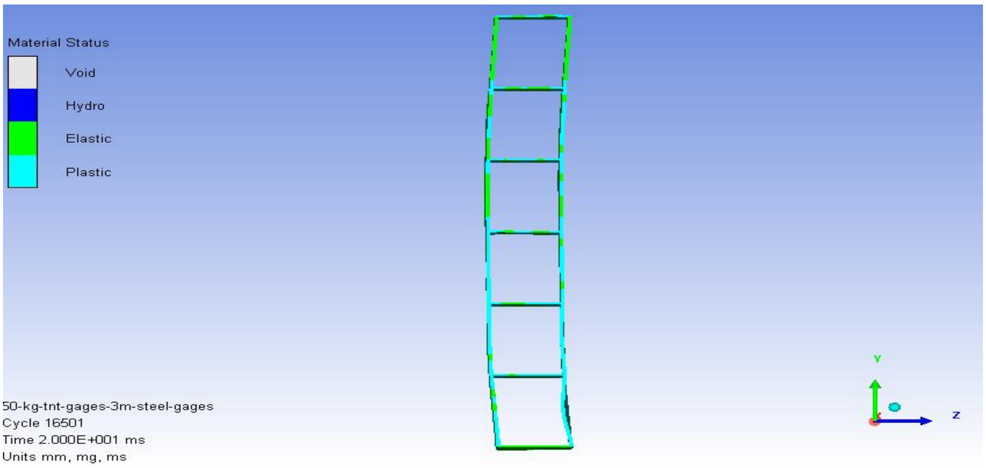

Fig. 22: Location of the maximum deformation located at the panel middle.

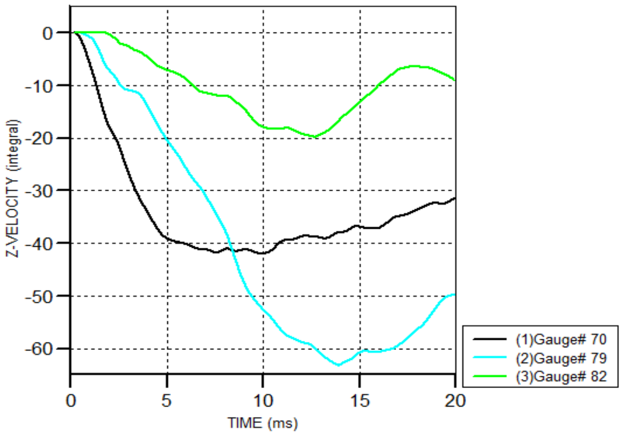

Fig. 23: Time displacement curve

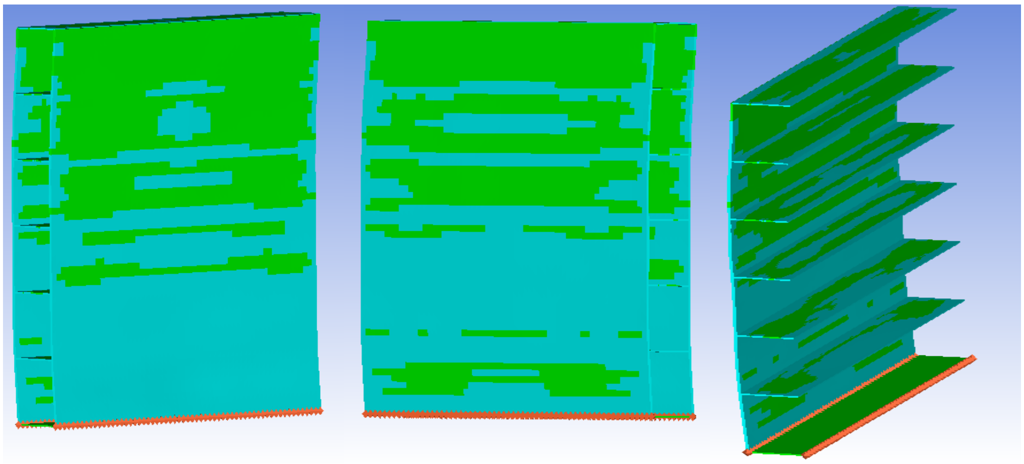

Fig. 24: Plastic deformation region in front, rear and horizontal plate.

Conclusion:

Six protective panels against blast load were investigated in this paper. Panels design consists of front and rear steel plates with several mounting configuration. The investigation was accomplished using finite element package AUTODYN; analysis parameters were consistence with other research parameters and it reflected the real cases. Results presented before ensured that all the panels supported the blast load of 50 kg TNT with minor failure. The concept of placing a solid barrier to oppose the blast load showed promising results; which will be concluded through the following bullets:

- The concept of designing the protective panel having a solid face could prevent around 94 % of the blast load.
- Boundary condition used in the research is fixed free, has modified the strengthen technique for the panel.
- As long the plate thickness is increased the panel deformation will decrease, however the deformation of the front and rear plates have direct relation with the separation distance in the case of air filling model, consequently the rear plate will be a backup plate till the front one is totally failed or deformed until contacting the rear one.
- Several filling materials were investigated including the air and concrete; in addition to the investigation along the alternation of filling distance which is the separation distance between the plates.
- There are two load transmission techniques, in the case of air filling the two plates will act as a backup mechanism, however in the case of concrete filling the two plates share the load.
- By increasing the separation distance in the case of air filling model the deformation of the rear plate decreases significantly, otherwise the front panel deformation increases.
- The increase of separation distance in the case of concrete filling model has more significant improvement in decreasing the deformation on the front and rear plates compared to the air filling model.
- Another strengthen mechanism introduced in the research is the shear connectors instead of filling material in the separation distance between. This mechanism improved the deformation of both panels to reduce the plastic region without any failure in the panel.
- Another significant strengthen mechanics is the horizontal plates configuration instead of shear connectors; which increase the cross sectional area and result in deformation reduction. This mechanism introduced the panel design which could support consecutive blast load.

Eventually, the panel design was satisfying for protecting premises against a blast load up to 50 kg TNT, which could be handled by a pedestrian beside the fence. Although such threat was resolved, however the panel design will require more modification to support higher blast load.

Future work and recommendation in the result of the research conclusion include the following: validating the achieved design model experimentally, variety of filling material to be used in the separation distance to improve the behavior of the panel such as advanced composite material, investigate the proposed design to be used in protecting underwater structure, investigate the panel against ballistic load and Adding the effect of soil structure interaction and the panel fixation in an extensive study.

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