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Numerical Study on the Effect of Horizontally Installed Corrugated Plate Boundary Condition under Blast Load

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ABSTRACT

Blast hazard load on offshore and marine operation resulting very catastrophic failure. Installation of protection devices needs to be applied. There are active and passive protection available. This paper investigates the use of corrugated plate as a passive protection to resist blast loads based on ASCE (American Society of Civil Engineers) - Design of Blast Resistant Building in Petrochemical Facilities. This paper aims to investigate the response in terms of stress, deformation and energy dissipation of corrugated plate with accounting the effect of boundary condition. The horizontally installed corrugated plate is modeled using well known FEA Software, ANSYS. Numerical simulation is validated using meshing sensitivity study. The plate is then loaded by light, medium, and heavy explosions, represented by uniform pressure. Numerical simulation of non-linear structural analysis is performed. Based on the analysis result, it is concluded that the pinned and fixed boundary condition corrugated plate successfully resists the all the blast load variations, but the pinned support gives average better responses.

KEY WORDS: *Blast load, corrugated plate, boundary condition, stress and deformation, energy dissipation.*

NOMENCLATURE

σ	Stress
d	Deformation
θ	Support Rotation
η	Ductility Limit

1.0 INTRODUCTION

The blast hazard is one of the most dangerous accident that could happen on the offshore structure operation. Blast load consists of rapid change of pressure and mostly followed by massive fire that can abrupt the structural integrity of the structure. There were several cases happened that the topside structure could not withstand the blast and fire load, and it leads to total damage and loss of live [1]. The piper alpha explosion was one of the case that the designer did not consider the plan to resist the load from extreme accidental condition, and caused 169 men aboard killed. The rapid change of pressure brought the structure to the total collapse. Several cases happened in Gulf of Mexico. One of the most well-known was on April 10, 2010, when the Deepwater Horizon accident took 11 casualties and caused sea pollution. Again, this accident caused by the structure could not resist the extreme load on potentially harmful location that the explosion could happened.

Several efforts are performed, especially in last decades when the advancing technology of computer simulations made the complex simulations become possible. Rajendran and Lee [2], provide the brief review of analytical solutions of blast loaded plate in both air and underwater conditions. A numerical investigation generated by Kadid [3], Tavakoli [4] and Riyanto [5], by modelling some varied stiffened plates subjected to uniform blast loading. The nonlinear dynamic response of square steel stiffened plates subjected to uniform blast loading was studied. Stiffener configurations and boundary conditions, which affect the dynamic response of the plates subjected to blast loading was considered. Faruqi [6] investigate the response of corrugated plate to resist the time history load.

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2.0 MODELLING AND ANALYSIS SETTING

Corrugated plate consists of 3 (three) parts, namely (a) compression flange, (b) diagonal flange, and (c) tension flange, as stated in [6] and shown in Figure 1. This paper uses dimension of each part of corrugated plate, as shown in Table 1. The corrugated plate geometry is modeled using 3D CAD software. There are 4 (four) panels of corrugated plate with dimension of 2 x 1 m for each panel. The panels are installed horizontally with 2 (two) types variation of boundary condition, fixed and pinned boundary conditions. The contact between panels is assumed bonded connection so the tearing between panels is prohibited.

Table 1: Dimension of Corrugated Plate

Parameter	Value	Unit
a	200	mm
b	200	mm
c	200	mm
h	200	mm
t	10	mm
s	282	mm
w	1000	mm
L	2000	mm
θ	45	degree

Parameter (a) at corrugated plate is the length of compression flange, whilst parameter (b) is the length of diagonal flange. Parameter (c) denotes the length of tension flange. Parameter (h), denotes the height of the corrugated section.

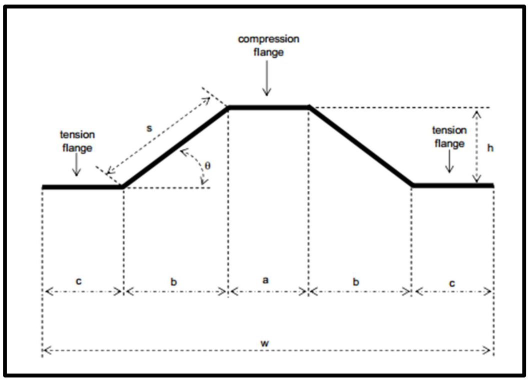

Figure 1: Corrugated Plate Nomenclature [6].

Numerical Finite Element Analysis (FEA) is performed with regarding the material nonlinearity. Structural steel resistance curve is an elastic-perfectly plastic curve with strain hardening. High-strength steel is selected. The material properties are presented in Table 2, whilst the resistance curve is shown in Figure 2.

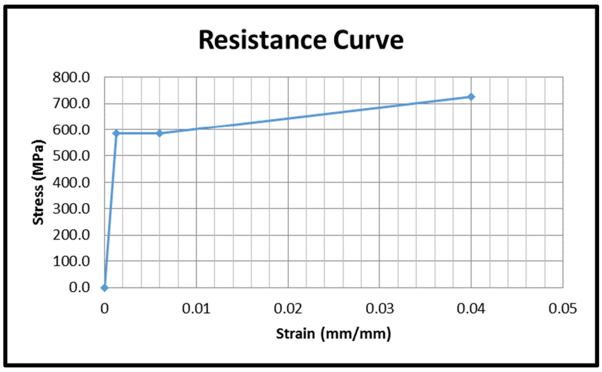

Figure 2: Material Resistance Curve.

Table 2: Material Properties.

No.	Properties	Value
1.	Elastic Modulus (MPa)	2.1×10^5
2.	Poisson's Ratio	0.3
3.	Density (kg/m^3)	7850
4.	Yield Strength (MPa)	585
5.	Ultimate Tensile Strength (MPa)	725
6.	Max Strain	0.04

2.1 Meshing Sensitivity Analysis

Pinned support corrugated plate is selected for numerical validation. Natural period is the parameter used for numerical model validation using meshing sensitivity analysis method. In dynamic analysis, natural period consists of important parameters, namely mass and stiffness parameters. Meshing sensitivity study is performed by varying the meshing size from 200 to 10 mm. Hexahedral meshing type is selected. 3D CAD model is displayed in Figure 3.

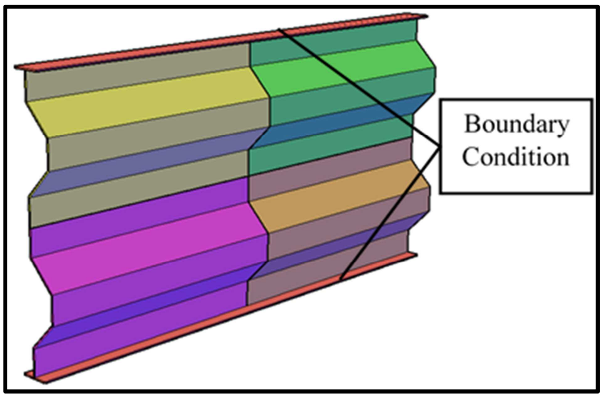

Figure 3: CAD Model of Corrugated Plate.

Only 1st mode natural period is captured and compared, to produce fair comparison. It is discovered that 40 mm meshing size and hexahedral meshing type are the optimum configurations. The 1st mode natural period reaches its convergence in 40 mm meshing size, in 0.0854 seconds. The results can be seen in Figure 4.

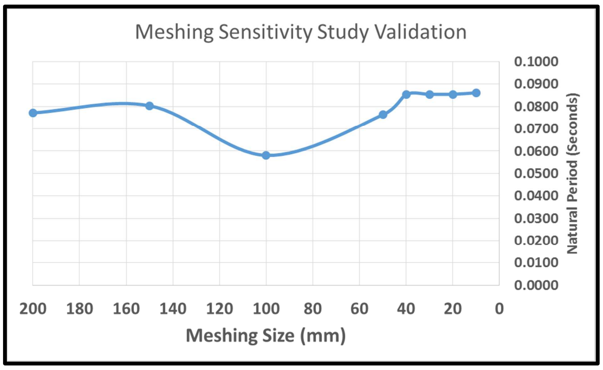

Figure 4: Meshing Sensitivity Analysis.

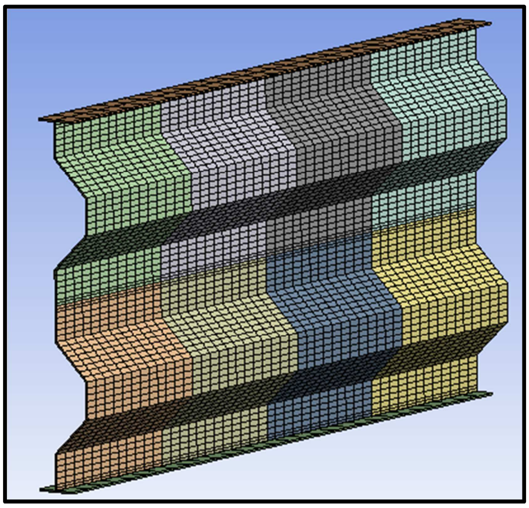

Figure 5: Meshing Result

3.0 BLAST LOADING

The blast source consists of 5, 20, and 50 kg of TNT to represent light, medium, and heavy explosions, respectively, [7] with 10 m blast radius. The blast loading detonation empirical function as provided by Bangash [8] is used, as shown at (1):

$$P(t) = P_0 + P_s\left(1 - \frac{t}{t_p}\right)e^{\left(-\frac{at}{t_p}\right)} \quad (1)$$

Where:

P (t)	= Overpressure at time t	*(kg/m²)*
Ps	= Maximum Overpressure	*(kg/m²)*
t	= Time	*(s)*
t_p	= Blast duration	*(s)*
a	= Negative time constant	

The maximum overpressure, P_s, and blast duration, t_p, are determined by scaled distance method as stated in [8]. Scaled distance calculation is shown at (2):

$$Z = \frac{R}{W^{1/3}} \quad (2)$$

Where:

Z = scaled distance ($ft/lb^{1/3}$)
R = explosion distance (ft)
W = explosives weight (lb)

The cube root term results from geometric scaling laws in which charge radius varies in proportion to all distances, and thus the charge weight is proportional to the cube of the charge diameter. For detailed scaled distance curve, please refer to [8]. To use these empirical curves, one computes the scaled distance by dividing the explosion radius from the charge to the point of interest by the cube root of the charge weight, in this case, explosion radius is the blast radius, 10 m.

Due to the maximum blast load duration calculated from scaled distance curve is 1.348 seconds at M05, therefore maximum analysis time is set into 2 (two) seconds with 0.04 timestep. The blast loads result is displayed in Figure 6.

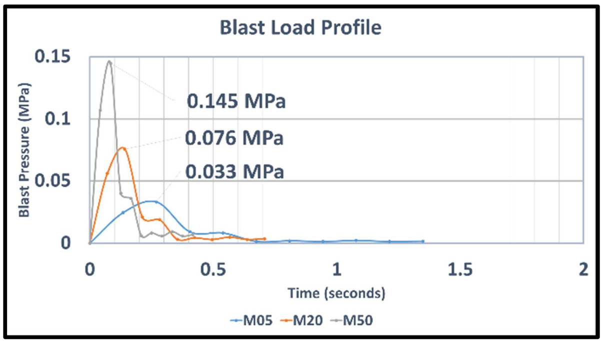

Figure 6: Blast Loading in the Model

4.0 RESULT AND DISCUSSION

From the analysis result, it is discovered that the corrugated plate could resist all the blast load from light to high explosion without undergoing material erosion.

4.1 Deformation Response

Deformation for the case of fixed boundary condition tends to be higher than the pinned boundary condition; overall deformation response is displayed in Figure 7 and Figure 8.

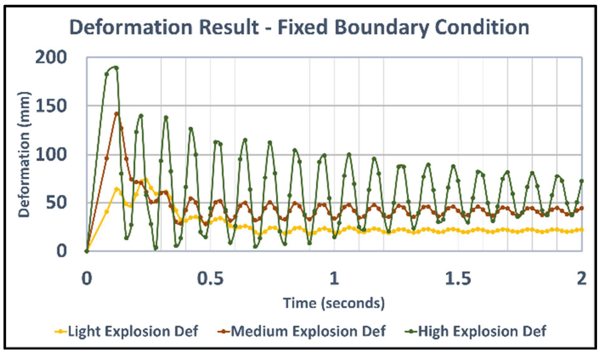

Figure 7: Deformation Response for the Case of Fixed Boundary

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Condition

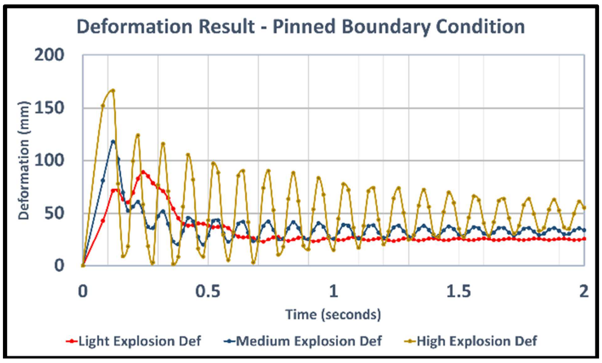

Figure 8: Deformation Response for the Case of Pinned Boundary Condition.

Both for pinned and fixed boundary conditions, the higher the blast load, the higher the response and the oscillation after the blast load ends. Fixed support gives better response in light explosion, whilst in medium and high explosion, pinned support gives better responses. Pinned support gives 8.18 % better in maximum deformation response, averagely. The graphical comparison is displayed in Figure 9.

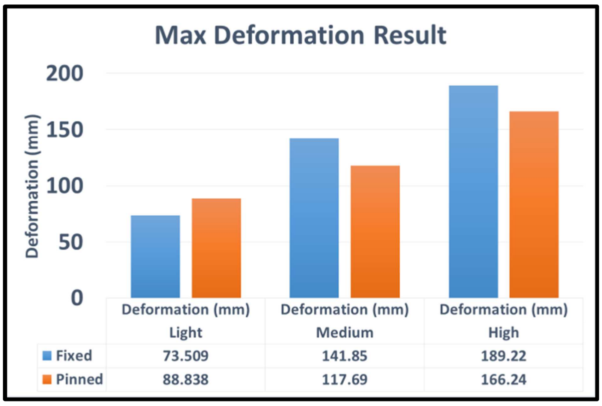

Figure 9: Maximum Deformation Comparison

At the end of the analysis (t = 2 seconds), the deformation is captured. In all blast load condition, the plate undergo plastic deformation, even the maximum stress hasn't been reached the maximum plastic stress. Just as the maximum deformation response, the end deformation response for fixed support at light explosion gives better result. The comparison can be seen in Figure 10.

Reversely, in medium and high explosions, pinned support gives better end responses. Pinned support gives 18.69 % better in end time (2 seconds) deformation response, averagely. But keep in mind, that the excessive vibration is still occurred at the end of the analysis. The result can be different if the analysis time is extended.

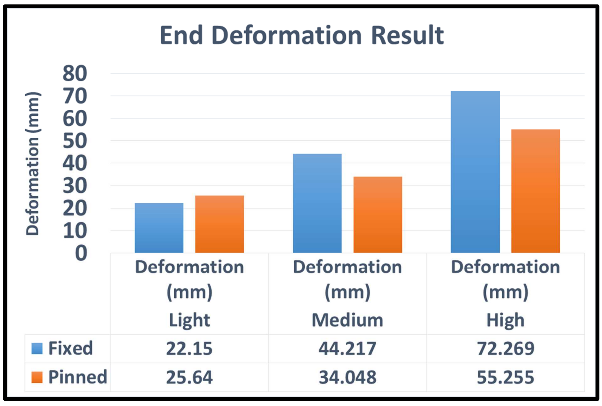

Figure 10: End Deformation Comparison

4.2 Stress Response

Stress on the fixed boundary condition case tends to be higher than the pinned boundary condition one; overall stress response is displayed in Figure 11 and 12. At light explosion blast load, the maximum stress is 228.44 MPa and 269.72 MPa for fixed and pinned condition, respectively. The stress result gives different tendency in medium and high blast load, in medium explosion blast load, the maximum stress is 397.02 MPa and 304.31 MPa for fixed and pinned condition, respectively. Whilst the maximum stress at high explosion load is 558.14 MPa and 427.27 MPa for fixed and pinned condition, respectively

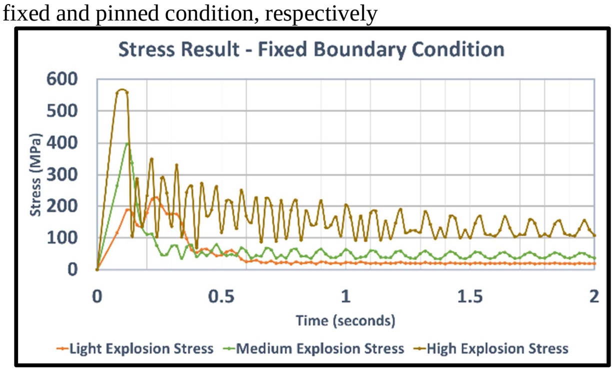

Figure 11: Stress Response for the Fixed Boundary Case

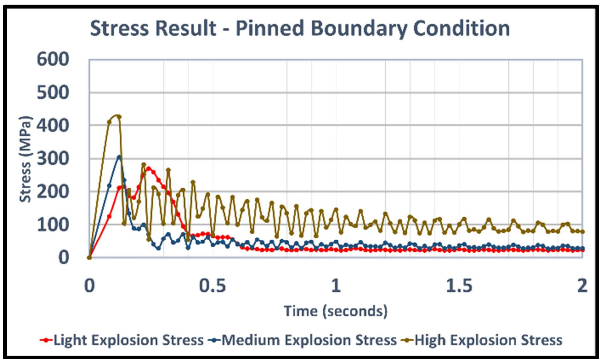

Figure 12: Stress Response for the Pinned Boundary Case

Both in the pinned and fixed boundary conditions, the higher the blast load, the higher the stress response, and just similar to deformation responses, the stress responses tend to have excessive vibration subsequent to the blast loading.

Fixed support gives better response in light explosion, whilst in medium and high explosion, pinned support gives better responses. As shown in Figure 13 the pinned support gives 16.69 % better in maximum stress response, averagely.

Despite all the maximum stress hasn't been reached its plastic stress, however the response still gives nonzero end time deformation. It is probably due to the unfinished vibration at the analysis time. In other words, for further analysis, the simulation time should be extended.

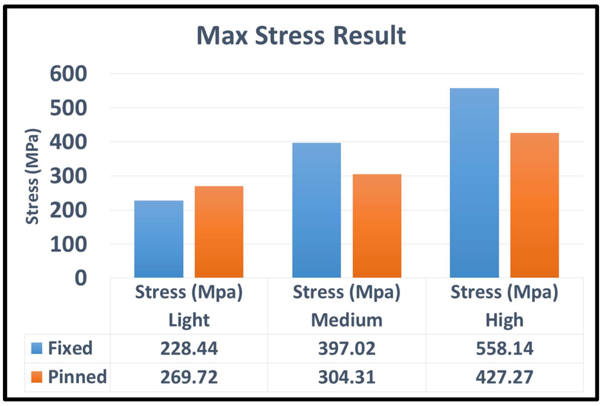

Figure 13: Maximum Stress Comparison

4.3 Performance Criteria for Blast Resistant Wall

ASCE: Design of Blast Resistant Building in Petrochemical Facilities [3] gives 4 (four) levels of protection from explosion loads. In order to give safe protection to the occupant, whilst still in the range of reasonable economic consideration, the performance criteria is set at Level II: *Damage is expected, such that the building is not likely to be economically repairable, but progressive collapse is unlikely*.

The response parameters define the structure damage level, namely ductility limit (μ) and support rotation (θ). The equation of ductility limit is shown in (3).

$$\mu = \frac{x_m}{x_y} \tag{3}$$

Where:

Xm = Maximum deformation
Xy = Static deformation at yield stress

Whilst the support rotation equation is shown in (4) as depicted in Figure 14.

$$\theta = \tan^{-1}\left(\frac{2x_m}{L_{min}}\right) \quad (4)$$

Where:

x_m = Maximum deformation
L_{min} = Shortest distance from maximum deformation to support

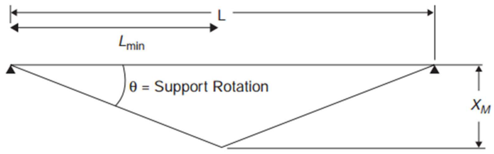

Figure 14: Support rotation [1]

Performance criteria limits the maximum value of μ and θ onto following, as stated in Table 3.

Table 3: Performance Criteria for Level II Protection

Component	Moderate Damage	
	μ_{max}	θ_{max}
Steel Plates	10	6

The ductility limit calculation requires static stress at maximum yield stress. Table 4 and 5 shows the calculation result summary of the corrugated plate static stress, under uniform pressure.

Table 4: Stress and Deformation at Yield (Fixed)

Pressure (MPa)	Stress (MPa)	Deformation (mm)
0.0864	584.99	91.416

Table 5: Stress and Deformation at Yield (Pinned)

Pressure (MPa)	Stress (MPa)	Deformation (mm)
0.08636	584.97	91.275

Calculation result shows that the horizontally installed corrugated plate only successfully resists the light explosion from 10 m distance, both in fixed or pinned boundary condition as can be seen in Table 6 and 7. Although all the ductility limit results satisfy the criteria, but the support rotation failed to comply the minimum requirement. It is statutory that both criteria should be satisfied in order to produce a blast resistant wall.

Therefore, this type of corrugated plate should only be used if the designated blast load is in light explosion range.

Table 6: Performance Criteria Result (Fixed)

Blast Load	Fixed		
	μ	θ (degree)	Result
Light	0.804	4.406	OK
Medium	1.552	8.466	FAILED
High	2.070	11.358	FAILED

Table 7: Performance Criteria Result (Pinned)

Blast Load	Pinned		
	μ	θ (degree)	Result
Light	0.973	5.148	OK
Medium	1.289	7.040	FAILED
High	1.821	10.008	FAILED

5.0 CONCLUSION

There are several conclusions could be drawn based on the analysis result:

1. In light explosion, response of the fixed support case is better than the pinned support case. Reversely, in medium and high explosion, response of the pinned support is better than the fixed support.
2. The pinned support case gives 8.18 % better in maximum deformation response, and 16.69 % better in maximum stress response, averagely.
3. The horizontally installed corrugated plate should only be used if the designated blast load is in light explosion range. Based on performance criteria stated on ASCE: Design of Blast Resistant Building in Petrochemical Facilities codes, this configuration only successful to resist light explosion.

6.0 FURTHER WORKS

Further analysis could be performed, based on this paper unsolved problems:

1. The resonance effect needs to be analyzed to investigate the cause of excessive vibration subsequent to the blast loading.
2. The simulation time needs to be extended beyond 2 (two) seconds, in order to investigate the end time of the excessive vibration.
3. Strengthening plan should be configured in order to increase the performance.
4. Considering to install the plate vertically, in order to obtain better response result.

REFERENCES

1. Dusenberry, D.O., (2010). *Handbook for Blast Resistant Design of Buildings*. New York: John Wiley & Son.
2. Rajendran, R., Lee, J.M, (2009). “Blast Loaded Plate”. *Journal of Marine Structures*. 22-99-127.
3. Kadid, A., (2008). “Plates Subjected to Uniform Explosion Loading”. *Journal of Civil Engineering and Management*.
4. Tavakoli, H.R., Kiakojoroi, F., (2012). “Numerical Dynamic Analysis of Stiffened Plates under Blast Loading”. *Latin American Journal of Solids and Structures*
5. Riyanto, R.D., Handayanu, Hadiwidodo, Y.S., (2014), “Design of Blast Resistant Stiffened Plate”. *Proceeding of 9th International Conference on Marine Technology*. 2014.
6. Faruqi et. al., (2010). A Parametric Study for the Efficient Design of Corrugated Blast Wall Panels Used in Petrochemical Facilities. *ARPN Journal of Engineering and Applied Sciences Vol. 5, No. 11, November 2010*. Asian Research Publishing Network
7. ASCE, (2010). *Design of Blast Resistant Building in Petrochemical Facilities.* USA: American Society of Civil Engineers Press.
8. Bangash, M. *Shock, Impact, and Explosion: Structural Analysis and Design*. London: Springer Press.