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The Response of Steel Plates Subjected to Close-in Blast Loads

To cite this article: N S A Razak and A Alias 2021 *IOP Conf. Ser.: Earth Environ. Sci.* **682** 012036

The Response of Steel Plates Subjected to Close-in Blast Loads

N S A Razak and A Alias*

Faculty of Civil Engineering Technology, University Malaysia Pahang, 26300, Pahang, Malaysia

Corresponding authors: aizat@ump.edu.my

Abstract. Steel plates are commonly used for civil infrastructures and military vehicles. Since public awareness on the risk of explosion increase, extensive research is performed to improve the blast resistance of structures such as steel plates. This paper presents numerical investigations of the response of unstiffened and stiffened square steel plates subjected to close-in blast loads at different plate orientations. The numerical investigations were performed using finite element software ABAQUS. The target plates were subjected to blast loads produced by Plastic Explosive No.4 (PE4) with the mass range from 10 g to 20 g. The plates were stiffened with two stiffener configurations and in each configuration, the plate was tilted at three different angles of orientation, namely 0°, 15° and 45°. The results were compared against unstiffened square plates. The response of the plate was quantified in terms of the maximum central displacement of the plate. The results suggest tilted steel plates with the presence of stiffeners improves the blast resistance of the steel plates

1. Introduction

Steel plates are used in civil infrastructures, such as offshore platforms and steel plate bridges, and in military such as armoured personal vehicles (APV). Since the 9/11 event and other blast related incidents occurred around the world, there has an increased of public awareness of the risk of explosions. Hence, researchers have made efforts to improve the blast resistance of civil structures and military vehicles. For example, Yuen et al. [1] investigated the response of V-shape plates subjected to close-in blast loads while Part et al. [2] carried out a test on a large steel plate subjected to a far-field blast load. Yuen and Nurick [3] and Langdon et al. [4] have performed experiments and numerical studies to study the behaviour of unstiffened and stiffened steel plates with different stiffener configurations subjected to uniform and localised blast loading, respectively. Zheng et al. [5] also have conducted experimental and numerical studies to assess the response of unstiffened and stiffened steel plates but in a confined environment in a shock tube. Yuen et al. [6] then have investigated the influence of blast pressure orientation from close-in blast loads on the behaviour of unstiffened steel plates. These studies [3]–[6] however, investigated the influence of stiffener configurations and blast pressure orientations on the response of steel plates separately. Therefore, this study investigates the influence of stiffeners and blast orientation the response of stiffened and unstiffened steel plates subjected to close in blast loads.

Performing the blast tests to understand the response of structures subjected to blast loads can be dangerous and costly. Hence, stringent precaution measures are needed such as taken by Razaqpur et al. [7]. They have conducted blast tests for reinforced concrete panels where they initiated the explosive charge 1.5 km away from the blast site after all personnel evacuated to a safe distance. Not only that, the data obtained from this experiment also show some degree of uncertainty when the displacement shown by the similar blast tests were scattered and in some cases, no data were obtained such as experienced by Razaqpur et al. [7] and Nassr et al. [8], respectively. Thus, the reproducibility of experimental results cannot be confirmed [9]. Hence, a numerical simulation is an alternative to experimental test to study various structures subjected to blast loads. Finite element (FE) software, such as ABAQUS is an alternative that can be used to conduct numerical investigations. There are several methods to simulate the blast pressure on the steel plate. Yuen and Nurick [3] use a simple method in applying the blast loads directly on the plates by using a uniform pressure function. Langdon et al. [4] had to use a FOTRAN subroutine to apply the localised blast loads as a pressure on the plates due to the proximity of the test setup. Mehreganian et al. [10] used a more complex method to simulate the blast event which was using fluid structure interaction formulation in ABAQUS to investigate the response of mild steel and armour plates. Although this method could be considered as a more realistic representation of blast simulations, it requires expensive computer resources and could take longer computational time. An alternative to simulate blast events in ABAQUS is by using CONWEP blast loading built-in function. This function allows the simulations to have lesser computational time and lesser computer resources due to its simplicity. Although simple, the CONWEP function has shown good correlations with the experimental data [11, 12]. Hence, this study uses the CONWEP function to simulate the blast loads on the unstiffened and stiffened steel plates at different orientations.

2. Methodology

In this paper, ABAQUS was used to developed finite element (FE) models to simulate the response of steel plates subjected to blast loading using the already available experimental data published by Yuen et al. [6]. In the experiment Plastic Explosive No.4 (PE4) was used as the explosive where the mass was varied between 10 g and 20 g. The stand-off distance (SOD) was a constant and fixed at 40 mm from the centre of the target plate. The SOD was measured between the centre of the plate and the point of detonation as shown in Figure 1.

2.1. Model Geometry

The dimension of target steel plate in this study was 400 mm×400 mm with a thickness of 2 mm similar to the plate used by Yuen et al. [6]. The target plate was secured between two 20 mm thick and 50 mm width clamping frames leaving a deformable area of 300×300 mm. It was assumed that the diameter of the bolts used to secure the plates between the clamping frames was 16 mm. The FE models were developed based on the full plate and clamp geometry as depicted in Figure 1. The steel plate, the clamps and the bolt were modelled using solid, linear eight-node brick (C3D8R) with reduced integration and hourglass control continuum element. All degree of freedoms on Clamp 2, as labelled in Figure 1, was constrained from translational and rotational movements. The FE models for stiffened plate were similar to Figure 1, except that the stiffeners were added to the target steel plate. The stiffeners were extruded from the plate thus, were created from the same section as the steel plate in ABAQUS.

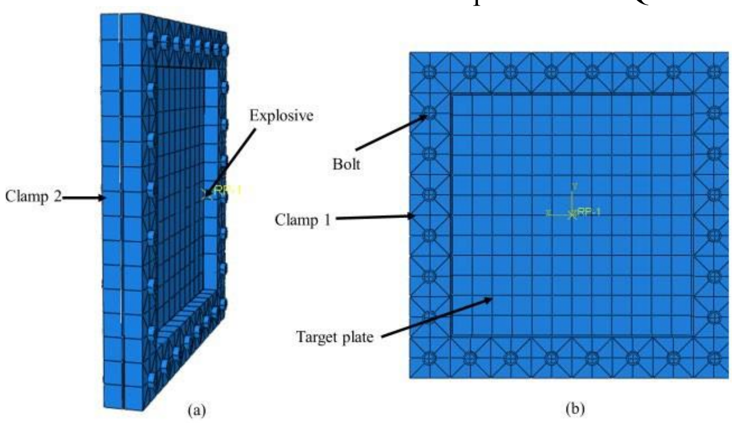

Figure 1. Finite element model of the steel plate, clamps, and bolts

2.2. Blast load modelling

The blast load was modelled using the CONWEP function built-in in ABAQUS. This function only available in ABAQUS/Explicit. The CONWEP is an empirical equations that can be used to apply the blast load on any structural geometry [12]. The CONWEP blast model does not consider any confinement or tunnel effects, the shape of the explosive charge, and effect of shadowing objects but it takes into account the stand-off distance, the mass of explosive and the inclination of the target plate [12, 13]. In CONWEP, the mass of the explosive was based on TNT equivalence thus, the mass of PE4 was converted into TNT equivalence using conversion factors [13]. The conversion factors were between 1.82 and 1.85 depending on the scaled distance of each blast case. The conversion factors were determined in accordance to an empirical equation proposed by Bogosian et al. [14].

2.3. Material modelling

The density of the steel plate was taken as 7850 kg/m^3 with an assumed Young's modulus to 200 GPa and a Poisson's ratio of 0.3. The yield strength of the steel plate of 222 MPa. The stiffeners were assumed to have a similar material property as the steel plate. The steel bolts were assumed to have a yield strength of 640 MPa. The steel plate and the bolts were modelled in a nonlinear fashion where both components will behave elastically until the yield strengths were exceeded. Once exceeded, both components behave as plastic materials with hardening. The behaviour of clamps was not the interest of this study thus was assumed as an elastic material. Therefore, the yield strength is neglected.

Steel is a rate-sensitive material where the yield strength and the ultimate tensile strength of steel are influenced by the strain rates. The blast loads impact on the steel plate lasted only a few milliseconds and as a result, the steel plate could be subjected to high strain rates. The influence of strain rates in the steel plate was captured using the Cowper-Symonds (CS) material model. The CS material parameters used in this study were D = 40.4 s^{-1} and q = 5 [10, 15] . The influence of strain rates on the clamps and bolt was neglected.

2.4. Contact Interactions

The interactions between the plate, clamps and bolts were simulated was defined using contact pair algorithm in ABAQUS. Surface-to-surface contact with finite sliding formulation was used where the interactions between components surfaces were defined normal and tangential behaviour between the surfaces. The tangential behaviour was defined using penalty frictional formulation where the friction coefficient 0.3 was used for steel-steel interactions. The default 'hard' contact formulation was used to model the normal behaviour between interacted surfaces and the surfaces were allowed to separate after contact.

2.5. Angle of Orientation

The experimental program conducted by Yuen et al. [6] has two arrangements where in the first arrangement the explosive disc was tilted at difference angles (15°, 30° and 45°) with respect to the target steel plate. In the second arrangement the steel plate was tilted at two different angles, 15° and 45°. The results from these two arrangements were compared against baseline data based on 0° angle of plate and explosive disc. In this study, the FE models were developed in accordance to the experimental setup of 0° angle and the second arrangement. Thus, there were three angles of orientations of the target plate which were 0°, 15° and 45° as shown in Figure 2.

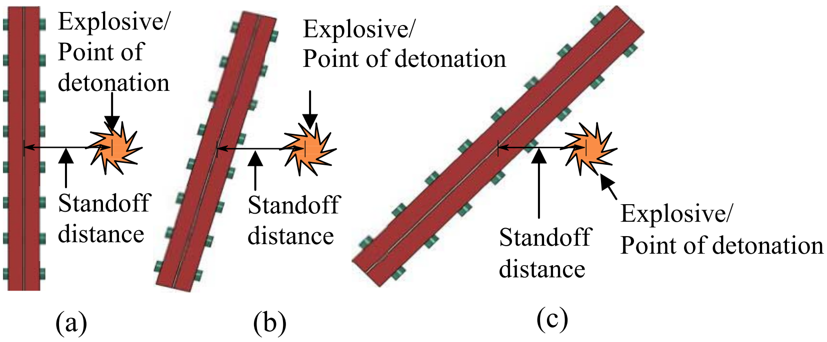

Figure 2. Target plate was tilted with respect to the explosive at (a) 0°, (b) 15° and (c) 45°.

2.6. Configuration of Stiffeners

Once the FE models were validated against experimental results, the FE models were modified to include the stiffeners. Two stiffeners configurations were used in this study namely single stiffener and cross-stiffener as proposed by Yuen and Nurick [3] where the results were compared against unstiffened steel plates. The stiffeners have a similar rectangular cross-section with a 3 mm width and 7 mm depth, which similar to the dimension used by Yuen and Nurick [3]. In this study, the stiffeners were extruded from the steel plates from the model in ABAQUS. Therefore, the stiffeners were assumed as connected to the plates throughout the analysis, which means that the effect of separation of the target plate from the stiffeners was ignored. Figure 3 shows the configuration of unstiffened plate, single stiffener plate and cross-stiffeners plate. All stiffened plates were also investigated for their response at different angles of orientation, which were 0°, 15° and 45°.

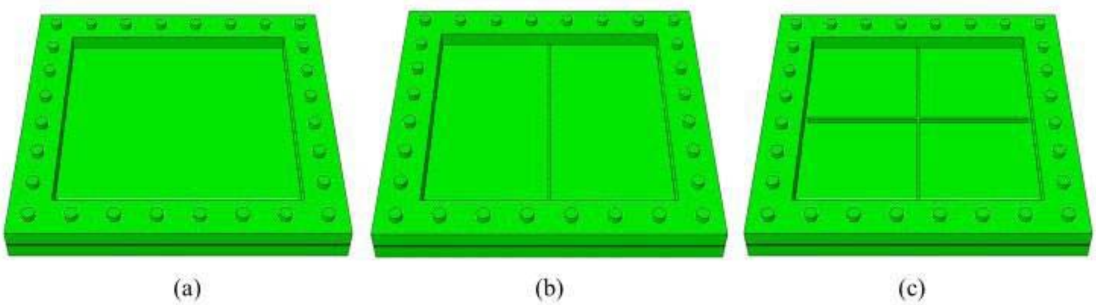

Figure 3. Configuration of stiffeners of (a) unstiffened, (b) single stiffener and (c) cross-stiffeners steel plates.

3. Results and Discussions

From the study the optimum mesh size for the steel plate was determined to be 0.5 mm which translated to just over 210000 elements in the FE model. Then, a validation study was performed based on the unstiffened steel plate with 0^o plate angle and the mass of PE4 used was between 8 g and 20 g. Table 1 and Figure 4 show the comparison between the maximum displacement of the steel plates from the FE analyses and the experiment conducted by Yuen et al. [6]. Maximum displacements were measured at the middle of the plate. It can be seen the FE analyses give a mixed result when compared to the experimental data. The FE analyses underestimated the maximum displacement at maximum 14% and overestimate the displacement up to 6% higher than the experiment. These variations could be considered as acceptable because the variations are much lower compared to other numerical investigation results such as performed by Mehreganian et al. [10]. Hence, the FE model setup could be considered as appropriate.

Table 1. Maximum displacement of unstiffened steel plate at 0° angle

Plate ID	PE4 (g)	FE (mm)	Experiment (mm)	FE/Exp
P1	8	20.74	22.1	0.94
P2	10	24.60	28.3	0.87
P3	12	28.75	33.3	0.86
P4	14	34.99	37.1	0.94
P5	16	41.28	40.0	1.03
P6	18	47.12	44.5	1.06
P7	20	52.58	Torn	-

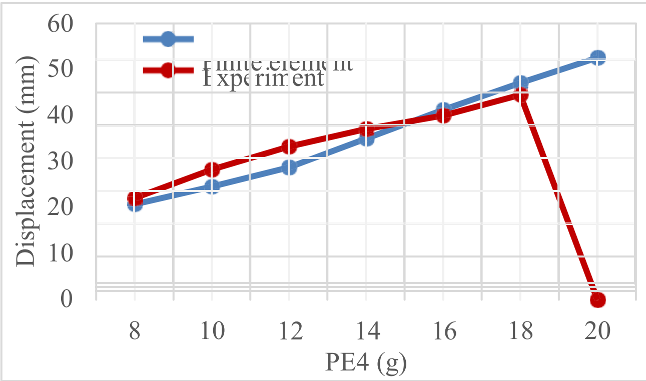

Figure 4. Comparison between finite element (FE) results and experimental result for unstiffened plates with 0° angle

3.1. Influence of Orientation of Angle

In this study, three different angles as shown in Figure 2 were used to observe the displacement of the unstiffened and stiffened steel plates when subjected to blast loads. Table 2 tabulates the maximum central displacement of steel plates at different tilt angles from the FE analyses. The maximum displacements for all cases were obtained at the centre of the steel plates. Thus, it should be noted not all cases recorded maximum displacement at the middle of the plate due to the orientation of the plate. Figure 5 shows that the central displacement of the steel plates decreases as the angle of plate increases. However, the results from Figure 5(b) and Figure 5(c) also suggest that the angle has less influenced on central displacement of the stiffened plates with 15° angle. This response is the opposite to the unstiffened plates where the difference is quite significant. The influence of the angle of orientation is more pronounce when the angle is at 45° both for unstiffened and stiffened plates.

From the FE analyses, although the overall displacements at the centre of the plates reduce when the angle increases, that would not necessarily decrease the displacement for the overall plate. The reason is the orientation angle shifts half of the target surface to be nearer to the explosive as illustrated in Figure 6. Although the standoff distance to the centre of the plates is maintained at 40 mm, the angle causes the standoff distance for the target surface above the centre line become closer to the explosive. Meanwhile, the stand-off distance at the lower part of the plate becomes further from the explosive as shown in Figure 6(b) and Figure 6(c). Therefore, the blast loads on the target plate are different at the upper, centre and lower part. As the upper part is closer to the explosive, the highest displacement of the steel plates shifted to a point between the centre of the plate and the upper clamps support as depicted in Figure 7. Nevertheless, for consistency purposes, only the maximum displacement at the centre of the plate was recorded and compared in this study.

Table 2. Central maximum displacement of steel plates.

Stiffener Configurations	PE4 (g)	0° (mm)	15° (mm)	45° (mm)
Unstiffened	10	24.60	21.60	16.00
	12	28.75	26.10	18.90
	14	34.99	31.00	21.60
	16	41.28	36.30	24.30
	18	47.12	41.50	26.60
	20	52.58	46.30	29.00
Single-stiffened	10	21.10	19.80	15.63
	12	25.10	24.63	18.67
	14	30.40	30.04	21.21
	16	35.30	34.29	24.07
	18	40.30	38.93	26.38
	20	44.73	43.27	28.64
Cross-stiffened	10	19.04	17.97	14.21
	12	23.00	22.60	17.11
	14	28.20	27.72	19.73
	16	33.40	32.36	22.13
	18	37.50	36.42	24.40
	20	42.00	40.47	26.52

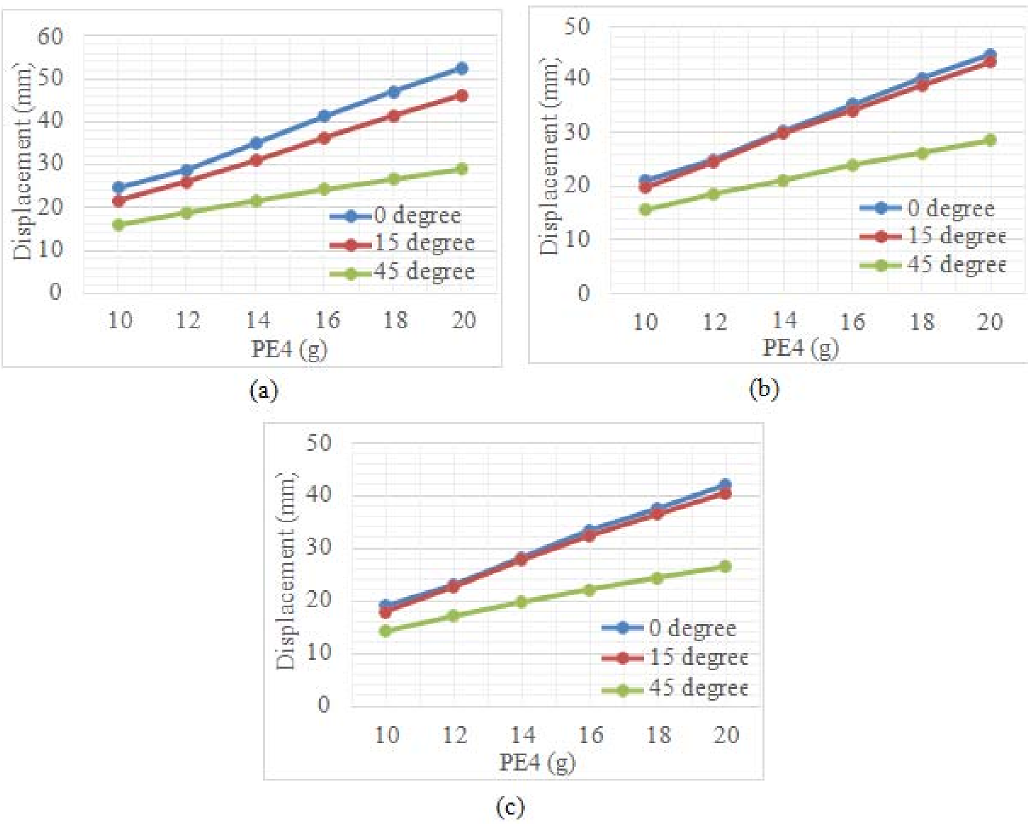

Figure 5. Central maximum displacements for (a) unstiffened, (b) single-stiffened and (c) cross-stiffened plates at different angle of orientations

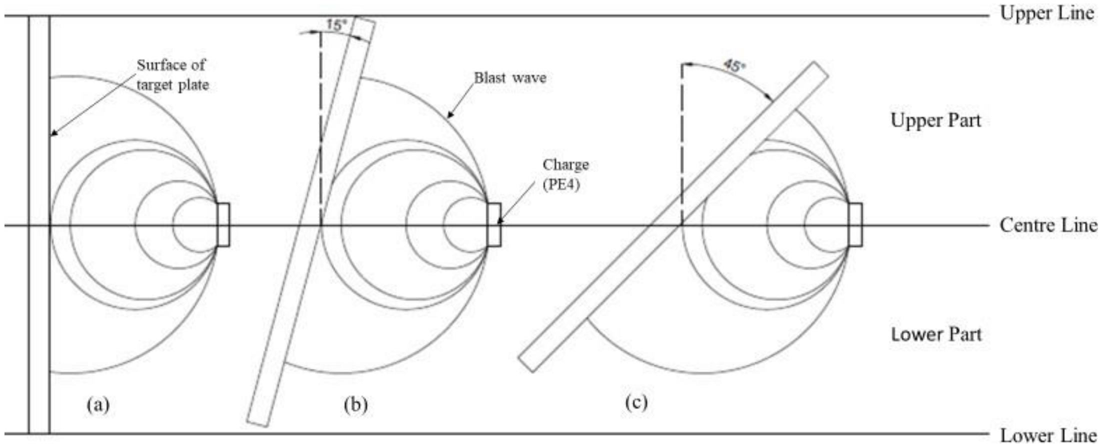

Figure 6. Influence of orientation at (a) 0°, (b) 15° and (c) 45° angle.

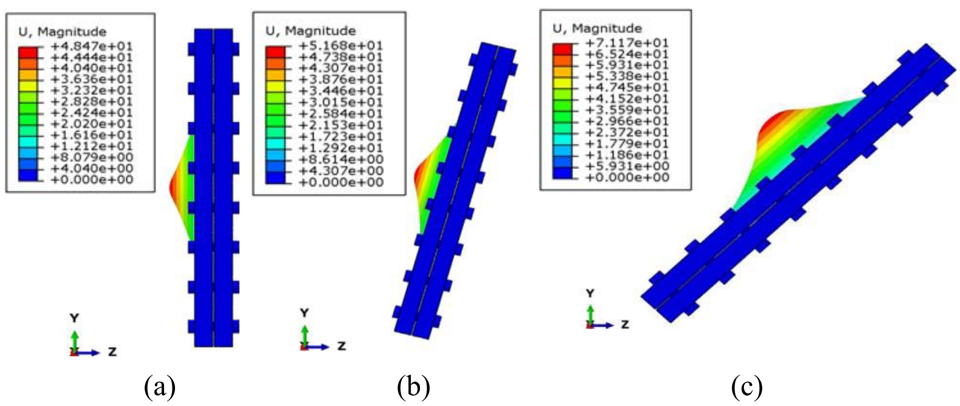

Figure 7. Deformation of unstiffened plate with (a) 0°, (b) 15° and (c) 45° angle subjected to 20 g PE4.

3.2. Influence of Configuration of Stiffener

Figure 6 illustrated the influence of stiffener configurations to the response at different plate angles. In general, cross-stiffener configuration give the lowest maximum central displacement of the steel plates at all plate angles followed by single-stiffener and unstiffened plates. Thus, it could be suggested that the cross-stiffener improve the response of the steel plate for plate angle up to 45° based on the central displacement of the steel plates.

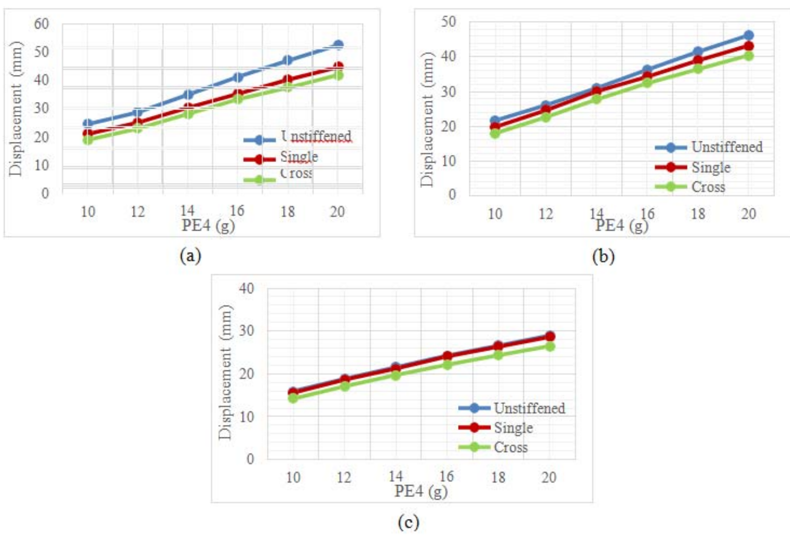

Figure 8. Central maximum displacement of steel plates at tilt angle (a) 0°, (b) 15° and (c) 45°

4. Conclusion

The FE results suggest the angle of orientation of the plates and the configuration of the stiffeners have positive influences on the response of the steel plates according to the maximum central displacement of the steel plates. Both parameters could reduce the maximum central displacement of the steel plates. Even though the displacement at the centre of the plate is reduced, the displacement of the plates at the point closest to the explosive may not necessarily decrease when the plates are tilted. When the plates are tilted, the location of the maximum displacement on the target plate shifted to a point between the centre of the plate and the clamp boundary. From the point of view of design and application, the angle of orientation could be optimized to improve the plate response. Thus, more in-depth studies should be conducted to find the optimum angle of orientation.

5. References

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