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Blast behavior of steel infill panels with various thickness and stiffener arrangement

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Abstract. Infill panel is the first element of a building subjected to blast loading activating its out-of-plane behavior. If the infill panel does not have enough ductility against the loading, it breaks and gets damaged before load transfer and energy dissipation. As steel infill panel has appropriate ductility before fracture, it can be used as an alternative to typical infill panels under blast loading. Also, it plays a pivotal role in maintaining sensitive main parts against blast loading. Concerning enough ductility of the infill panel out-of-plane behavior, the impact force enters the horizontal diaphragm and is distributed among the lateral elements. This article investigates the behavior of steel infill panels with different thicknesses and stiffeners. In order to precisely study steel infill panels, different ranges of blast loading are used and maximum displacement of steel infill under such various blast loading is studied. In this research, finite element analyses including geometric and material nonlinearities are used for optimization of the steel plate thickness and stiffener arrangement to obtain more efficient design for its better out-of-plane behavior. The results indicate that this type of infill with out-of-plane behavior shows a proper ductility especially in severe blast loadings. In the blasts with high intensity, maximum displacement of infill is more sensitive to change in the thickness of plate rather the change in number of stiffeners such that increasing the number of stiffeners and the plate thickness of infill panel would decrease energy dissipation by 20 and 77% respectively. The ductile behavior of steel infill panels shows that using infill panels with less thickness has more effect on energy dissipation. According to this study, the infill panel with 5 mm thickness works better if the criterion of steel infill panel design is the reduction of transmitted impulse to main structure. For example in steel infill panels with 5 stiffeners and blast loading with the reflected pressure of 375 kPa and duration of 50 milliseconds, the transmitted impulse has decreased from 41206 N.Sec in 20 mm infill to 37898 N.Sec in 5 mm infill panel.

Keywords: steel infill panel; ductility; maximum displacement; blast loading; nonlinear analysis

1. Introduction

As terrorist attacks and their related damages have grown worldwide, paying attention to response of building against severe loads including the blast loading is so important. The proper analysis and design of a structure under blast loading requires the proper understanding of blast phenomenon and the dynamics of the main parts of the structure. A blast is able to cause structural failure, collapse of walls leading to damage in infill panels of structure and death of people.

In typical buildings, the first elements subjected to blast loading are their infill panels and thus should have proper behavior against blast loads, i.e., they must dissipate the effects of blast loading without being severely damaged. In fact infill panels are divided into concrete, brick and steel infill systems. The feature which is so important in blast loading is the degree of ductility and dissipation energy. The American Society of Civil Engineers' (ASCE 2011) document for blast design of petrochemical facilities defines the allowable deformation of individual components based on the desired level of protection and type of component for different construction material types. Panel walls are used as protective covers of steel structures in industrial applications such as petrochemical plants. ASCE publication for design of blast resistant building in petrochemical facilities has an overall review on the characteristics of metal panel walls, and qualitatively discusses about both resistant and ductility of metal walls with different thickness and configurations.

Steel infill panels have been the subject of very little blast research in the past. Some researchers have studied the ductility and blast loading in different systems. As for ductility and high resistance of steel, Wierzbicki and Florence (1970) studied steel plates fixed under applied stress and revealed that steel has high ductility and resistance at yield point. Dharaneepathy and Sudhesh (1990) studied the optimum stiffening arrangement. They investigated the frequency of these plates and introduced the arrangement which had the most natural frequency and the minimum rise. Smilowitz (2002) argued that the reason for reduction in damages caused by in World Trade Center in 1994 was the flexibility of steel structure. Mendis and Ngo (2003) investigated the high concrete structure against blast and concluded that the ductility of structure is more important compared to resistance. Salim *et al.* (2005)

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studied the performance of blast-retrofit wall systems under static and dynamic field tests simulating large vehicle bombs. They presented the analytical modeling and experimental evaluation of steel-stud wall systems under blast loads and stated that properly anchored steel studs as effective solutions for construction of blast resistant walls are responsible for resisting the blast load and absorbing the energy from the explosion. Sabuwala *et al.* (2005) analyzed the behavior of beam's steel joints to column with the analysis of limited element against the blast loading reached this conclusion the strengthened joints have less displacement and stress and is more suitable against blast compared to not strengthened joints. The research carried out by Dipaolo and Woodson (2006) in US Army Corps of Engineers indicated that steel wall studs facing severe blast loading show high resistance.

Jacob *et al.* (2004, 2007) reported a series of experimental results and numerical predictions for clamped mild steel quadrangular plate of different thickness and varying length to width ratios subjected to localized blast loads of varying size. Hrynyk and Myers (2008) investigated the out-of-plane behavior of URM arching walls with modern blast retrofits by testing the walls in the laboratory under static conditions and stated that the retrofit systems reduced or prevented the masonry debris scatter upon collapse. Azevedo and Alves (2008) investigated the behavior of plates under various impulsive loading. After replacing the rectangle-like impact with real blast loading, they checked the precision of action. Also, after they studied various forms of impact loading, they concluded that under special circumstance, the response of structure influenced by theses impacts is equal. Pandey (2010) presented a comparative study of non-linear response of reinforced concrete nuclear containment cylindrical shell subjected to impact of explosion of different amounts of blast charges. He found that the outer reinforced concrete shell protects the inner shell especially for designing against impact and blast loading. Investigating the plastic and visco-plastic behavior of models, he reported a series of results with dissimilarity in deflections of the shell under impact and blast loading. The relevance to this study is in considering the plastic behavior of models with finite element analyses and thus the effect of strain rate against blast loading.

Snyman (2010) studied the geometrical similar scaling of steel plates through various blast loading experiments and raised the importance of material properties when attempting to demonstrate "similarity" in the mid-point deflection. Using mild steel with a low Carbon content to model the quadrangular thin plates against blast loading and studying the effect of various blast loading on steel plates, he concluded that the material properties such as the strain rate sensitivity of the plates affected the mid-point deflections. The main relevance to this paper is that he investigated the behavior of mild steel plates against various blast loading and he considered the effect of strain rate in mid-point deflections.

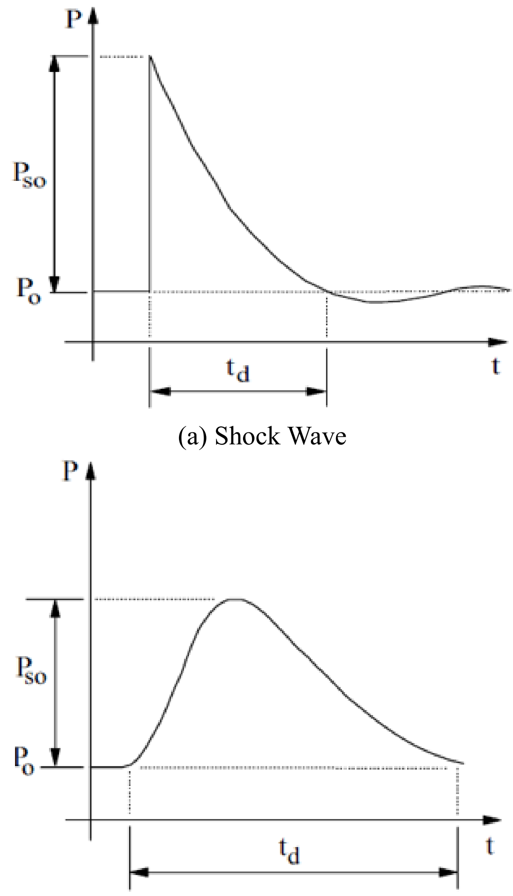
Considering the blast load as shock wave with an appropriate duration for the design of petrochemical facilities, Moghimi and Driver (2010) studied the overall performance of a steel plate shear wall exposed to in-plane and out-of-plane blast loads (like this research) using numerical methods. Blast resistance capacities were assessed according to both total absorbed strain energy and maximum structural displacement. They showed that the changes in dynamic properties of the system obtained from a model incorporating only material plasticity are not necessarily competent tools for accurately estimating the extent of damage in the system subjected to blast loads. Also, they stated that it is not a precise method to use a sample fracture model based on maximum strain criteria, because the fracture strain would be constant for all stress states. Alisjahbana and Wangsadinata (2011) investigated the behavior of orthotropic damped plates with different stiffener configurations (like this paper) subjected to a stepped triangular blast loading. They investigated the effect of using the various damping ratios in their models. They concluded that the duration of blast loading is one of the most important parameters which greatly affects the overall behavior of the stiffened orthotropic plate. Also, they stated that the inclusion of damping in calculating the dynamic response of the system will result in a much stiffer responses. Nguyen and Tran (2011) studied the dynamic response of vertical wall structures under blast loading and concluded that the amount and distance of explosive material has an effect on a dynamic response of wall structures. Olmati *et al.* (2013) worked on two main issues relevant to the structural assessment of buildings subjected to explosions. The first issue was about the evaluation of the structural robustness of steel frame structures under blast damage and the second issue was regarding the evaluation of blast pressures acting on structural elements using Computational Fluid Dynamic (CFD) techniques. The robustness curves showed a suitable tool that can be helpful for risk management and assessment. Also, they claimed that the variation of relevant CFD analysis outcome (e.g., pressure) due to the variation of the analysis parameters is indeed significant. Elsanadedy *et al.* (2014) like this paper analyzed the progressive damage of common multi-story steel structures so as to determine the degree of susceptibility of structures against blast loading. They used a commercial finite element (FE) package (LS-DYNA) to simulate the building response under blast generated waves and concluded that the steel structure even with 500 kg charge (TNT) is able to get progressively damaged and in order to inhibit the progressive collapse potential of the investigated steel building, the stand-off distance of blast must be increased (more than 2 m) by restricting the access of the vehicles to the building.

After some experiments were conducted on steel shear wall system by Moghimi and Driver (2014) they concluded that wall system has high energy dissipation. Mazek (2014) studied the sandwich steel structure performance under the impact of blast wave effect considering a 3D numerical model to study the pyramid cover system (PCS) to strengthen sandwich steel structures using finite element analysis. He concluded that the PCS layer improves the sandwich steel panel performance under impact of TNT explosive charges. Mazek and Wahab (2015) used the rigid polyurethane foam (RPF) to strengthen the buried structures under blast load. They concluded that the RPF improves the buried structure performance under the blast loading. Geretto *et al.* (2015) conducted a series of experiments about square mild steel plates subjected to blast loads in three different degrees of confinement and investigated the effects of confinement as well as the effect of plate thickness on the final plate deformations. They showed that the plate subjected to full confined explosion presents the greatest outward bulging deformation compared to the plate subjected to the unconfined and partially confined explosion. Smith *et al.* (2016) worked on response analysis of reinforced concrete block infill panels under blast and indicated that the wall peak deflection response can be accurately predicted using simplified dynamic models. Al-Thairy (2016) investigated a modified approach for the SDOF analysis of axially loaded steel columns under blast load accounting for the strain rate effect by Cowper-Symonds and neglecting the damping effects because the duration of the blast event was very small (2.1 to7.3 msec). He used the ABAQUS software for finite element analyses of steel columns. After studying the generated pressure-impulse diagrams, he concluded that increasing the axial force decreases the impulse at which the column fails. After conducting experimental research on stiffened steel plates under blast loading, Zheng *et al.* (2016) found that the final deformation of stiffened steel plates is more sensitive to thickness of plate than size of stiffeners attached to plate. Zhang *et al.* (2016) studied the dynamic response of foam-filled corrugated core sandwich panels subjected to air blast loading. Their test results demonstrated that the panels with back side filling strategy did not show better blast performance compared to the unfilled panels, even though extra weight was expended due to the addition of foam fillers. Zoghi and Mirtaheria (2016) investigated the effects of infill panels on progressive collapse analysis of steel building. They used the alternative path method (AP) to assess its resistance against progressive collapse. The results showed that modeling the infill panels can increase stability of the structure to resist progressive collapse even if more than one column removed.

Ductility of out-of-plane behavior of steel infill is dependent on plate thickness and stiffener arrangement. Therefore, in this research, stiffness and ductility of out-of-plane behavior of stiffened steel infill panels are investigated under a wide range of blast loads with different duration and reflected pressure considering both material and geometric nonlinearities. Using over 250 different models to investigate the ductile behavior of steel infill panel, as a distinctive feature of this study, a comprehensive study on stiffener arrangements and various thicknesses of infill panels is presented under various blast loads with different duration and reflected pressure. Furthermore, to examine the ductile behavior of infill panels, their maximum displacements obtained from deformation contours are used. The reliability of the numerical model is verified with results presented by Markose and Rao (2017). The ABAQUS software is used for nonlinear analysis while the strain rate and damping effect in all analyses are taken into consideration. The analysis results can be used as some applicable recommendations for steel plate infill design.

2. Blast loading

When a blast occurs, a violent release of energy occurs producing a high-intensity shock front that expands outward



(a) Shock Wave

(b) Pressure Wave

Fig. 1 Characteristic shapes of blast waves (ASCE 2011)

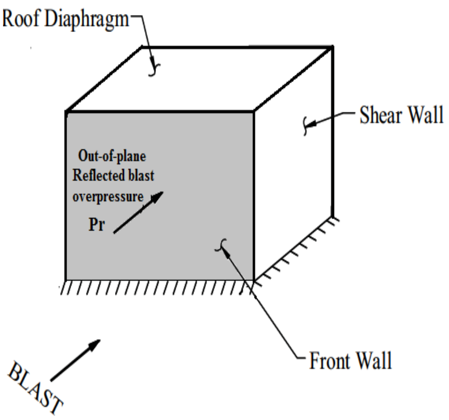
from the surface of the explosive. As this shock front, also called a blast wave, travels away from the source, it loses strength and velocity. Fig. 1 shows characteristic shapes of blast waves (ASCE 2011). A highly impulsive loading consists of a relatively high pressure applied quickly, while a static loading consists of a pressure that slowly rises to its peak value over a long period of time. If the duration of a blast pressure applied to a structure is very short compared to the natural frequency of the structure, the load can be considered as pure impulse (Biggs 1964).

Impulsive loading due to blast is generally prescribed by two parameters of peak reflected over pressure Pr and duration of loading td. The amounts of these parameters are dependent on the weight and distance of explosive from the structure.

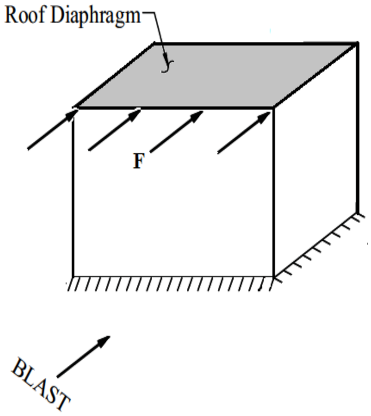
There are no codes or industry standards for determining what blast overpressures should be used. Commonly used criteria include SG-22 (withdrawn), and CIA (being revised). Both documents specify at least two blast overpressures for buildings spaced 30 meters from a vapor cloud explosion hazard as follows (ASCE 2011):

1- High pressure, short duration, triangular shock loading: Side-on overpressure of 69 kPa with a duration of 20 milliseconds.

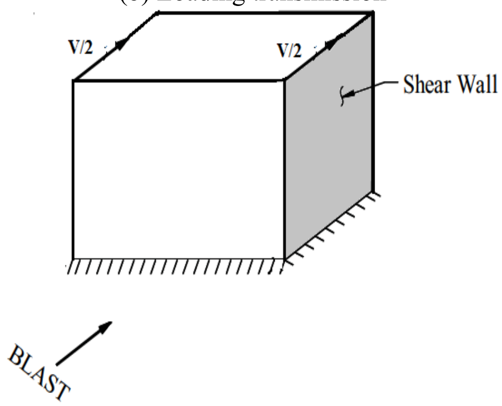
2- Low pressure, long duration, triangular loading: Side-on overpressure of 21 kPa with a duration of 100 milliseconds.



(a) Out-of-plane behavior



(b) Loading transmission



(c) In-plane behavior

Fig. 2 Blast loading path in structural elements

In this research, twenty-five types of triangular impulsive loading are considered in analyses investigating different models of steel infill panels. The first loading is considered with the peak of 75 kPa and the loading time durations of 10,20,30,40 and 50 msec, and the other loadings have the peak of 150, 225,300 and 375 kPa with the same durations.

3. Numerical model of steel infill panel

The blast loads are typically applied to the exterior walls and roof and are transmitted through various structural members to the foundation. It is therefore necessary to establish a continuous load path with consistent tracking of the dynamic loads through the structure to ensure a safe design (ASCE 2011).

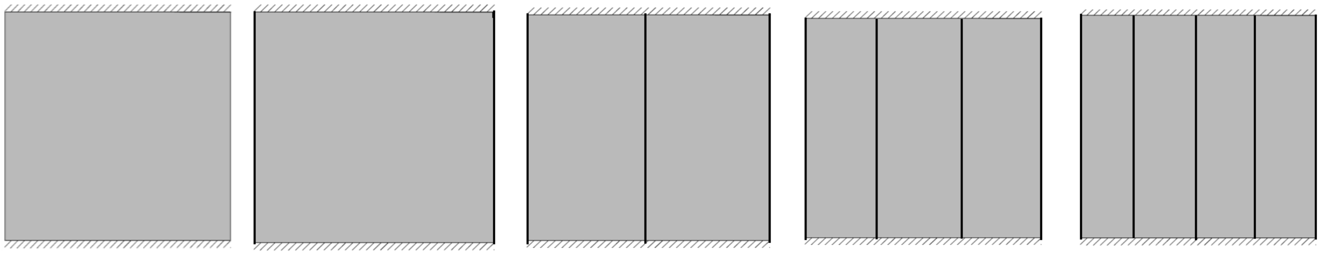
The structural system studied in this research consists of steel infill wall in front of explosion wave, in such a way that steel wall is the first structural element exposed to impulsive loading. It is obvious that the loading path through other structural elements under such loading directly depends on infill panel boundary conditions. In case of connection of infill wall to the structural columns, a large portion of blast loading transmits to the columns and loss of columns occurs due to reduction of buckling resistant, and consequently progressive collapse may occur. As suggested by Elsanadedy *et al.* (2014), only two horizontal edges in top and bottom of the infill plate are connected to adjacent structural elements, i.e. beams or foundation but connecting two vertical edges to columns should be really avoided.

This arrangement of boundary conditions has advantages. First, the columns as the main elements in gravity loading path are kept safer from a large amount of lateral loading especially when the blast pressure is negative (vacuum) although the effect of the negative phase of the blast load can be neglected in this paper, because the distance from the infill panel to the blast load is small (0.41 m). As the blast pressure is positive during the most of blast duration, the main load on the plate is compression and in this case the plate can transmit amount of the blast pressure even if the infill plate is not connected to the column. Second, as the blast pressure is negative, load is tension and the connection between the plate and the column transmits the tension force to the column and may cause failure and this arrangement of boundary conditions can decrease the probability of progressive collapse due to loss of columns in this case. Finally, connecting the only upper and lower edges of infill wall to top and bottom floor diaphragm has another advantage that can transfer the overpressure due to out-of-plane action of infill wall into horizontal rigid floor diaphragms. So, no constraint is considered parallel to vertical edges of infill wall. As shown in Fig. 2, F is the load per unit length applied to the floor diaphragm as a reaction of out-of-plane behavior, and based on previous description, impulsive load is proportionally distributed throughout the steel infill and the in-plane behavior of the steel infill wall will be activated.

According to ASCE (2011) design recommendations for blast resistant buildings in petrochemical facilities, full attention should be paid to the connection details of steel plate to the supporting structural members to avoid tearing of steel plate due to stress concentration. It is desired that in out-of-plane action, steel panels act as sacrificial structural elements which can dissipate input energy with plastic large deformations. The front wall subjected to out-of-plane behavior can be sized to provide acceptable design for industrial plant applications (Moghimi and Driver 2014). In this paper, out-of-plane behavior of steel infill panel with various stiffening arrangement and plate thickness under blast loading is studied.

3.1 Material characterization and modeling

Material characteristics are very important in efficiency of infill wall. As noted in previous sections, in-plane



P5, P20	P5 S2 100, P20 S2 100	P5 S3 100, P20 S3 100	P5 S4 100, P20 S4 100	P5 S5 100, P20 S5 100

Fig. 3 Overall arrangements of infill panels

behavior of infill wall as a dissipative element is directly related to material ductility and ultimate resistance of member rather than its stiffness. Nowadays a large variety of steel alloys is produced for different industrial purposes. High energy absorption characteristic of these alloys in cyclic loading makes them more suitable for sacrificial energy absorbent structural elements. As the ductility plays a major role in the energy dissipation due to the loading, mild steel that has comparatively suitable ductility, is commonly used in typical buildings, therefore in this research mild steel is adopted as the material specification of infill panels.

The ABAQUS commercial code is used for finite element analyses of steel plates, and the classical metal plasticity with isotropic hardening is implemented in numerical models. In this study, the plasticity with isotropic hardening is implemented in numerical models and in order to consider the effects of the progressive damage, the Johnson Cook (JC) damage has been used. The JC damage model (Johnson and Cook 1983) is often used to handle the simulations which employ high strain rate. The coefficients of the damage used in this study are according to study by Markose and Rao (2017).

It is well known that strength of material depends on loading rate. There are two general approaches for considering rate dependent behavior of materials. The former is defining a dynamic increase factor (DIF) which actually acts on the strength of the material in high rate loading and vary for different types of stresses like bending and shear ones. The DIF is applicable as an overall factor which increases the strength of material regardless of the variations of strain rate in different locations of structural members. Therefore, it seems to be a rough solution for considering strain rate effect. In fact, it is an approach to considering strain rate in common analysis and design procedures for engineers. The DIF method is fully described in UFC 3-340-02 (2008). The latter method is implementation of material models which are developed based on the strain rate. In this method stress strain relationship in plastic range also depends on the strain rate. One of commonly used formulation for this purpose is the power law which is provided by ABAQUS code (2012).

In this research the Cowper-Symond is used for considering strain rate dependency (Jones 2011). Another aspect of material characteristic is damping. The damping effect is considered via Rayleigh damping coefficients in all types (Clough and Penzien 1993). In this study, the steel with modulus of elasticity of 210 GPa, density of 7800 kilograms per cubic meter and Poisson's ratio of 0.3 are used. The type of steel is ST37 with the yield and ultimate stresses of 240 and 370 MPa respectively. In order to achieve a suitable design, the analysis of infill panels is conducted depending on the various plate thickness and stiffening arrangement of infill panels.

3.2 Geometry of models

Dynamic response of steel infill panel depends on the plate width and thickness. It is desired that a well-designed infill panel can act more ductile against loading. Several researchers have tried to improve the behavior of shear wall in seismic applications. A parametric study on infill panel components can give a good sense to achieve a proper design which satisfies required performance including both deformation minimization and energy absorption maximization. Therefore, in this study a set of analyses consisting of 250 models are carried out with different panel geometric assumptions and different blast loadings to investigate the out-of-plane behavior of steel infill panels. An applicable descriptive conclusion from these analyses helps engineers to make true decisions about detail design of infill steel panels. The geometries of models with different arrangements of stiffeners are represented in Fig. 3. As explained in section 3 of this paper, two vertical edges of panels are assumed to be free. Two horizontal edges are assumed to be restrained in three directions and can rotate freely about the edge line. All dimensions of infill panels are three by three and the distance of stiffeners and their edges is equal.

Concerning the labeling of Fig. 3 models, the thickness of infill panels and stiffeners is equal in all models meaning that if the thickness of panel is 5 or 10 mm, the thickness of stiffeners is 5 or 10 mm. In this labeling, the number coming after letter P indicates the thickness of infill panels and stiffeners in millimeter. If the model has a stiffener, Letter S has been used and the number of stiffeners is equal to the number that comes after letter S. The number mentioned after stiffener states the height of stiffeners based on millimeter. For instance, the infill panel P5 S5 100, is a kind of infill panel whose thickness of panel and stiffener is 5 mm and has 5 stiffeners with 100 mm height. Triangle impulse load is used for the analysis and study of the various models of out of plane infill. The 4-node doubly curved shell element in ABAQUS software with reduced integration, S4R, was used to model the steel infill panels. S4R is a 4-node, quadrilateral, stress/displacement shell

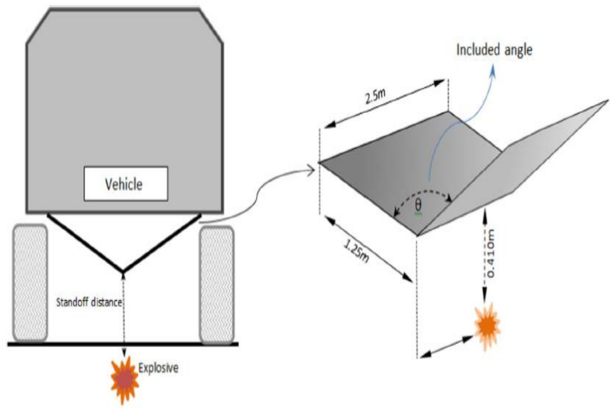


Fig. 4 Schematic diagram of the V-shaped plate (Markose and Rao 2017)

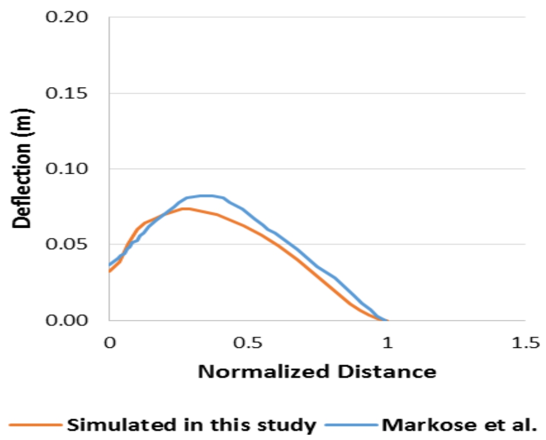
Table 1 Material parameters of mild steel (Iqbal *et al.* 2015)

Description	Notations	Numerical value
Yield stress constant	A (MPa)	304.33
Strain hardening constant	B (MPa)	422.007
	n	0.345
Viscous effect	C	0.0156
Thermal softening constant	m	0.87
Reference strain rate	ε0	0.0001 s^{-1}
Melting temperature	θmelt(K)	1800
Transition temperature	θtransition(K)	293
Fracture strain constant	D1	0.1152
	D2	1.0116
	D3	-1.7684
	D4	-0.05279
	D5	0.5262

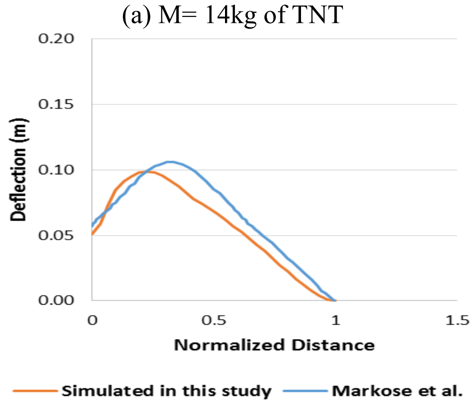
element with reduced integration and a large-strain formulation (Tavakoli and Kiakojouri 2014). Also, the explicit analysis was used for the nonlinear dynamic analysis.

To mesh the models, the structured mesh was used. The size of mesh elements was considered 0.06 m as Kadid (2008) investigated the behavior of stiffened plates subjected to blast loading with considering the effect of various sizes of meshes (0.03, 0.06 and 0.12 m) and stated that unstiffened plates are not sensitive to the mesh size. However, he said that for the plate with one stiffener, it can be observed that the influence of meshing can be important, especially for longer time duration. In this regard, Turkmen and Mecitoglu (1999) have found that refining the mesh leads to considerable changes in the response of stiffened plates. This difference in the response between stiffened and unstiffened models can be explained by the fact that the stiffeners can be subjected to almost pure bending and that using only one first order reduced integration element through the depth of the stiffener is not sufficient to model the accurate response of plate subjected to blast loads.

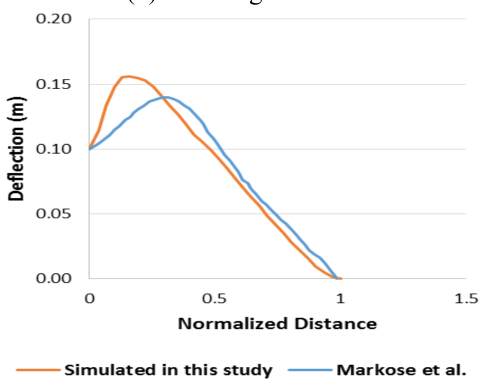
3.3 Result verification



(a) M= 14kg of TNT



(b) M= 17kg of TNT

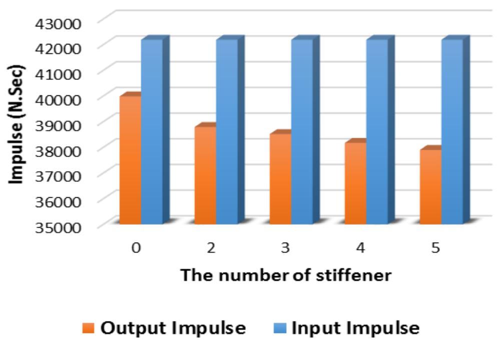


(c) M= 21kg of TNT

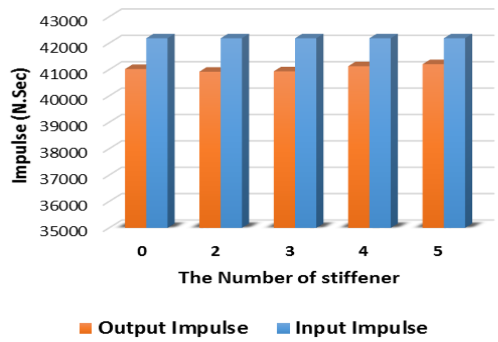
Fig. 5 Variation in measured value of surface deflection of 145° plate in this study and Markose and Rao

To verify the accuracy and reliability of the numerical model, a series of numerical analyses of V shaped plates under blast loads is carried out. Markose and Rao (2017) investigated the effectiveness of different V-shaped plates for finding its response under different plate angles, mass and eccentricity of the TNT charge. Their results were used for verification as they validated their study with experimental results reported by Yuen *et al.* (2012). A schematic diagram of the shaped plate that they used for the numerical simulation is shown in Fig. 4. Two edges of the plate are fixed to the body of the vehicle.

The solid elements defined in ABAQUS have been used for the simulation of the plates under blast loading conditions. The V-shaped plates have fixed boundary



(a) Infill panels with 5 mm thickness



(b) Infill panels with 20 mm thickness

Fig. 6 Comparing output and input impulses of steel infill panels due to their ductility behavior under the blast loading with Pr=375 kPa, Td=50 msec

conditions along the two sides parallel to the centerline while the two remaining sides are left unconstrained. The material selected for the V-plate is mild steel and the plate thickness is 16.66 mm. The mild steel plate with E=203 GPa, ν=0.3 and ρ=7850 kg/m3 is selected. They used the Johnson Cook (JC) damage model (Johnson and Cook 1983) to handle the simulations which employ high strain rate and temperature effects.

Three explosive charges of 14, 17 and 21 kg are detonated at 0.41 m standoff distance directly under the hull. Table 1 shows the material parameters for the analysis that used by Markose and Rao (2017).

In the following, the results of this study and Markose and Rao (2017) are compared in Fig. 5. This figure shows surface deflection of 145° plate for increasing mass of the explosive.

As shown, there is a fairly suitable correlation between results of this study and those by Markose and Rao (2017). It is observed that the numerical data for 14 kg of TNT gives a better fit with the experiments as compared to the explosive charges weight of 17 and 21 kg. This inconsiderable difference can be due to the creation of local high-pressure zones due to reflection of the shock waves from the uneven geometry.

4. Numerical results and discussions

4.1 Ductility

The basic aim for blast resistant design is to contain the damage and to prevent progressive collapse. Therefore, large inelastic deformations can be tolerated, provided that rupture is not imminent. Ductility capacity of a structure basically represents its inelastic deformation capacity. As the inelastic deformation capacity increases the energy dissipation capacity increases.

Ductility aspect is an important point in design against impulsive loading. Several studies considered the nonlinear effects of materials in structural members subjected to shock loading, by single degree of freedom approach. A collection of studies was summarized by Baker *et al.* (2012). After conducting several tests, Smith and Hetherington (1994) concluded that structures with low ductility were sensitive against blast loadings. Front steel infill panel as a sacrificial element, absorbs the energy due to large plastic deformation. Energy absorption can directly influence on transmitted load and impulse to the supporting elements. In fact, it is desired that out-of-plane behavior to act as a shock isolator and to reduce demands of the main structure.

Fig. 6 shows the effect of ductility behavior of steel infill panels on the reduction of transmitted impulse from infill panels to main structure. In this figure, output impulse is the transferred impulse from infill panel to main structure and input impulse is what enters infill panel. In Fig. 6, the infills under blast loads with highest blast severity are brought in which the highest one is related to the reflected pressure of 375 kPa and duration of 50 milliseconds.

Fig. 6 reveals that 5 mm infills dissipate more impulse compared to 20 mm infills. In the 5 mm infill, as the number of stiffeners increases, transmitted impulse to main structure decreases. In 20 mm infill panels compared to 5 mm infill panels, the number of stiffeners has less effect on reduction of transmitted impulse to main structure. Fig. 6 indicates that the increase of the infill panel thickness increases the transmitted impulse. In the 20 mm infill, it is clear that reduction of transmitted impulse is very slight compared to 5 mm infill.

The bar charts of Fig. 6 indicate that if the criterion of steel infill panel design is the reduction of transmitted impulse to main structure, an infill panel with lower thickness must be used. For example in steel infill with 5 stiffeners, the transmitted impulse has decreased from 41206 N.Sec in 20 mm infill to 37898 N.Sec in 5 mm infill. Fig. 6 also indicates that steel infill panel with out-of-plane behavior has a proper ductility especially in severe blast loadings and these infill panels with ductility behavior can decrease the transmitted impulse to main structure.

4.2 Energy dissipation

Ductility and energy dissipation of a building are directly related. Energy absorption and energy dissipation capacities are often used interchangeably in the literature on the design for accidental loading. Strength and ductility are necessary to achieve high energy dissipation. High energy dissipation capacity is achieved through the use of appropriate structural materials and details. These details must accommodate relatively large deflections and rotations in order to provide redundancy in the load path. High strength with low ductility is undesirable for conventional

Table 2 Plastic energy dissipation against triangular 75 kPa, 10 msec impulse

Panel name	P5	P20	P5-S2-100	P20-S2-100	P5-S3-100	P20-S3-100	P5-S4-100	P20-S4-100	P5-S5-100	P20-S5-100
Plastic dissipation (j)	1593	0.163	1858	2.763	2646	174.321	3250	106.564	3617	63.642

Table 3 Plastic energy dissipation against triangular 375 kPa, 50 msec impulse

Panel name	P5	P20	P5-S2-100	P20-S2-100	P5-S3-100	P20-S3-100	P5-S4-100	P20-S4-100	P5-S5-100	P20-S5-100
Plastic dissipation (j)	520831	125609	489493	117161	471301	111877	452008	105486	435226	99620

Table 4 Deformation response against blast loading of 75 kPa with duration of 10 msec

Panel name	P5	P20	P5-S2-100	P20-S2-100	P5-S3-100	P20-S3-100	P5-S4-100	P20-S4-100	P5-S5-100	P20-S5-100
Maximum Displacement (mm)	70	25	39	24	72	17	62	14	57	11
Plastic rotation (degree)	2.7	1.0	1.5	0.9	2.7	0.6	2.4	0.5	2.2	0.4
Performance level	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low

Table 5 Deformation response against blast loading of 375 kPa with duration of 50 msec

Panel name	P5	P20	P5-S2-100	P20-S2-100	P5-S3-100	P20-S3-100	P5-S4-100	P20-S4-100	P5-S5-100	P20-S5-100
Maximum Displacement (mm)	330	110	328	101	328	100	326	97	316	93
Plastic rotation (degree)	12.4	4.2	12.3	3.9	12.3	3.8	12.3	3.7	11.9	3.5
Performance level	High	Low	High	Low	High	Low	High	Low	Med	Low

design, and ever less desirable for blast resistant design.

As previously noted, blast loads pass through the infill panels to reach the main structure. At this stage, the intensity of the blast load is reduced and dissipated through large deformations. In this study, steel infill panel has high ductility. Therefore, energy dissipation of steel infill panel is high.

In order to examine the energy dissipation of different infill panels, the values of plastic dissipation, as a criterion to investigate the ductile behavior of steel infill walls, have been presented in Tables 2 and 3. These values represent the amount of energy dissipation by infills with different plate thicknesses and stiffener arrangements. In these two tables, the infills under blast loads with highest and least blast severity are brought in which the least one is related to the reflected pressure of 75 kPa and duration of 10 milliseconds.

Table 2 shows that infills with 5 mm thickness considerably affect the energy dissipation. The values of this table reveal that 5 mm infills dissipate more energy compared with 20 mm infills as increase in the thickness of infill panel leads to decrease of energy dissipation by 99.9 percent. Moreover, as the number of stiffeners increase, energy dissipation also increases in the infills as in the 5 mm infill, using 5 stiffeners results to energy dissipation increase by 127 percent compared to the case in which no stiffener is used. Therefore, it might be asserted that increasing the number of stiffeners significantly affect the energy dissipation by steel infill panels. However, in the 20 mm infill, it is observed that energy dissipation is very slight and these values are trivial compared to that of 5 mm infill. The reason for this might be in the plasticity of infills as 5 mm infill is remarkably plasticized while the 20 mm infill is less plasticized. Increasing the thickness of infill panel results in an increase in the plate stiffness, and so the energy dissipation capacity of the infill panel decreases. This case is clearly obvious in Table 2. In other words, when the severity of blast is least (reflected pressure of 75 kPa and time duration of 10 msec), the infill panel with more thickness is not plasticized enough and cannot dissipate the large amount of energy as it is about 0.163 j in the 20 mm plate with no stiffener in Table 2. But this infill in highest blast severity is plasticized enough showing its ability of energy dissipation. This case is obvious from the Tables 4 and 5. In Sec. 4.3, it is stated that 20 mm panel acts in elastic range in 75 kPa, 10 msec triangular impulse while in 375 kPa, 50 msec triangular impulse, even 20 mm panel shows more ductility. According to Table 2, it is observed that the 20 mm infill panel does not have enough energy dissipation, so this infill is not suitable against blast loading and instead, the 5 mm infill has significant effect on energy dissipation and is more suitable under this kind of blast.

Regarding the increasing number of stiffeners, it is logical that increasing number of stiffeners results in an increase in the plate stiffness and it causes decrease in the energy dissipation of the infill panels. This case is entirely obvious in Table 3 with blast pressure of 375 kPa and duration of 50 msec but in Table 2 increasing the number of stiffeners shows different results. It shows that in the least blast severity in this study, increasing the number of stiffeners has effective role on increasing the energy dissipation. In this regard, it can be state that stiffeners can absorb energy and increasing the number of stiffeners in this kind of blast can dissipate more energy.

Table 3 represents the values related to plastic energy dissipation in blast load with further severity. The table shows that 5-mm thick infill panel considerably influences energy dissipation. However, unlike Table 2, it is noticed that in blasts with high intensity (reflected pressure of 375 kPa and duration of 50 milliseconds), increasing the number of stiffeners in 5 mm and 20 mm infill panels reduces energy dissipation by 16% and 20% respectively. Given this point, it might be concluded that making use of stiffeners in blasts with low intensity sustains more impact on energy dissipation while in blasts with high intensity for example, blast of 375 kPa and duration of 50 milli seconds, stiffener use has no suitable impact on energy dissipation. As with 20 mm infills, Table 3 reveals that as blast intensity increases, the 20 mm infill is more plasticized compared to that in Table 2 and it has further effect on energy dissipation. Table 3 also indicates that the increase of the infill panel thickness might decrease the energy dissipation by 77 percent.

In general, Tables 2 and 3 show that in blasts with low intensity, the 5 mm infill with the highest number of stiffeners leads to remarkable energy dissipation while in blasts with high intensity, the 5 mm infill with no stiffener leads to maximum energy dissipation. A similar trend was reported by Tavakoli and Kiakojouri (2014). They worked on the nonlinear dynamic response of square steel stiffened plates under blast loadings. After they studied various stiffener configurations, they concluded that with the addition of more stiffeners, plastic energy meaningfully

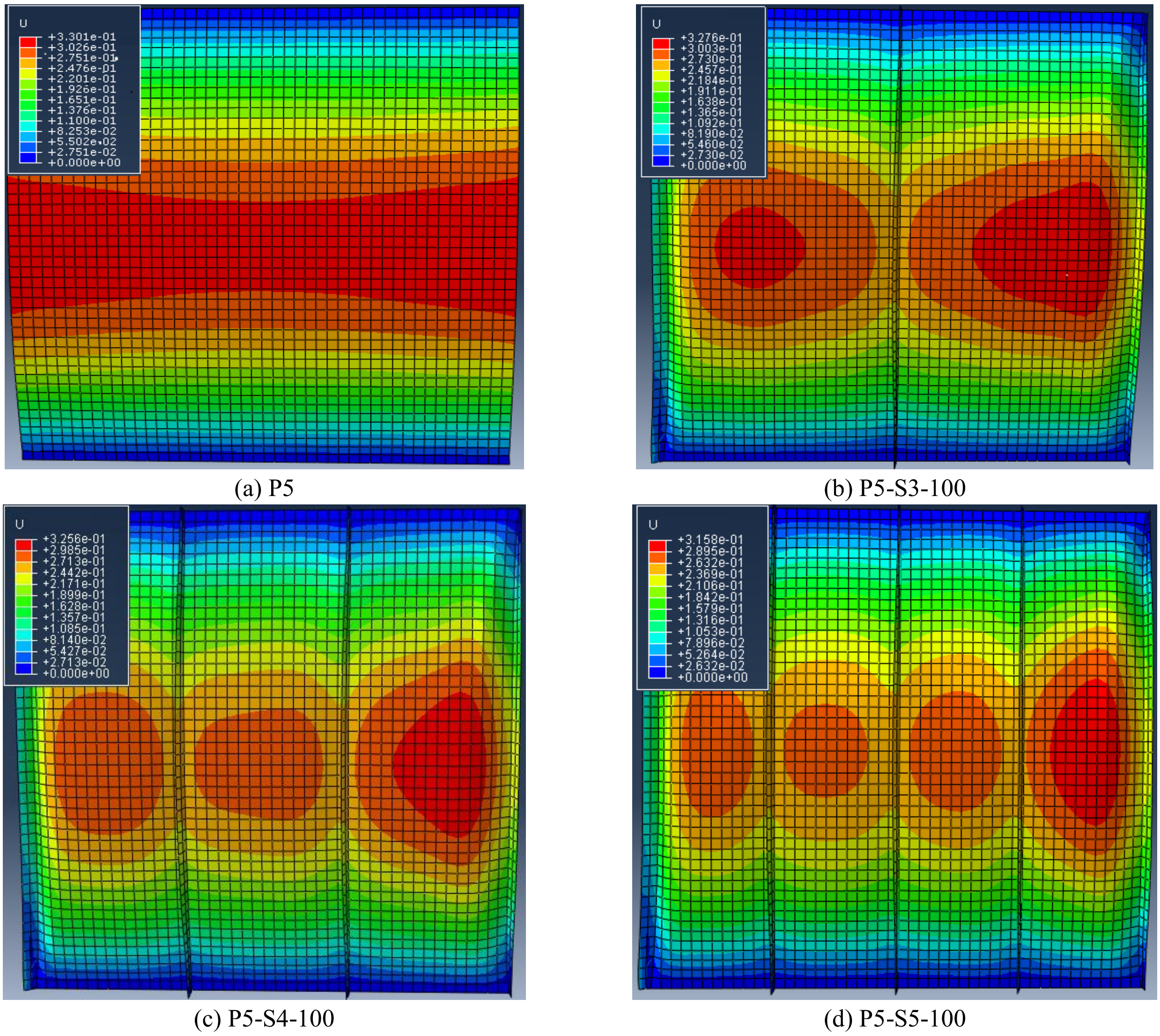


Fig. 7 Deformation contours for blast loading of 375kPa with duration of 50 msec

decreased.

Table 2 and 3 show that in blasts with high intensity compared with low intensity, the number of stiffeners has less effect on energy dissipation. In blast load with further severity, increasing the number of stiffeners and the thickness of infills increases the stiffness of infill panels and it can reduce the plastic dissipation.

4.3 Building damage levels

The maximum dynamic responses of structural components intended to resist the blast loading need to be limited against the desired blast levels of protection or blast design objectives (Moghimi and Driver 2014). The American Society of Civil Engineers' (ASCE 2011) document for blast design of petrochemical facilities defines the allowable deformation of individual components based on the desired level of protection and type of component for different construction material types. The description of building damage levels are stated in the following (ASCE 2011):

In the low damage level, building can be used; however, repairs are required to restore integrity of structural envelope. Total cost of repairs is moderate in this damage level. In the medium damage level, building should not be occupied until repaired. Total cost of repairs is significant in this damage level. In the high damage level, key components might have lost structural integrity and building might collapse due to environmental conditions (i.e., wind, snow, rain). Building should not be occupied. Total cost of repairs approaches replacement cost of building.

Maximum deformations for all types of steel plate against reflected blast overpressure of 75, 375 kPa and duration of 10, 50 milliseconds are represented in Tables 4 and 5.

Table 4 is related to 75 kPa-10 msec impulse analysis results regardless of the maximum deformation location. The results show that the maximum deformation is increased by decreasing the plate and stiffener thickness. It means increasing the stiffness causes less ductility of panel in a given level of loading. Plastic rotations demonstrate that the response level is limited to low damage range according to definitions represented in American Society of

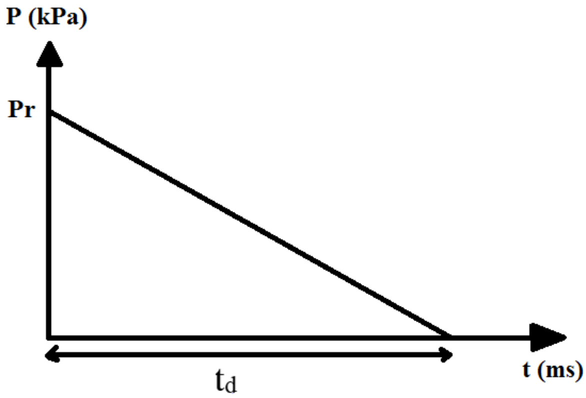


Fig. 8 Blast loading considered in this study

Table 6 Applied blast loadings with the various reflected pressures and durations

Number	Pr (kPa)	Td (msec)	Number	Pr (kPa)	Td (msec)
1	75	10	14	225	40
2	75	20	15	225	50
3	75	30	16	300	10
4	75	40	17	300	20
5	75	50	18	300	30
6	150	10	19	300	40
7	150	20	20	300	50
8	150	30	21	375	10
9	150	40	22	375	20
10	150	50	23	375	30
11	225	10	24	375	40
12	225	20	25	375	50
13	225	30			

Civil Engineers' (ASCE 2011) document. It is also concluded that in this level of loading, 20 mm thick panel mostly acts in elastic range.

Table 5 is related to 375 kPa- 50 msec impulse analysis results regardless of the maximum deformation location. Increasing the level of loading to 375 kpa and 50 msec triangular impulse causes an increase in damage level according to performance criteria. It is obvious from Table 5 that in this level of loading even thicker panel shows more ductility. This case is also extractable from Tables 2 and 3. In this level of loading, damage level of 5 mm thick panel is increased to high, however damage is limited to low level category for 20 mm thick panels.

Deformation contours in different stiffener arrangement for 375 kpa, 50 msec triangular impulsive loading are demonstrated in Fig. 7. It is clear that the maximum deformation belongs to middle of vertical edges of panels. For minimizing edge deformations it is recommended to add stiffeners in vertical edge. This solution improves the out-of-plane performance of the panel.

Another notable point is that according to Tables 4 and 5, the performance of the different panels with the same thickness regardless of stiffener arrangement is the same in relatively high impulses, but Fig. 7 shows that adding stiffener can control deformations in critical area of panel surface. In an overall view increasing the stiffness of the panel by increasing the plate thickness or adding stiffener can improve the blast performance of the plate from deformation limitation aspect.

5. Various blast loadings

To simplify the blast resistant design procedure, the generalized blast wave profiles shown in Fig. 1 are usually idealized, or linearized, as illustrated in Fig. 8 for a shock wave (ASCE 2011). Fig. 8 shows a typical shock load and its linearized triangular step-type load. Positive-phase of blast loads are used in all analyses of this study. Pr is the reflected blast overpressure. Td is the positive-phase duration, or the duration of the linearized triangular step-type load. In Table 6, a wide range of triangle blast loadings with reflected blast overpressure of 75, 150, 225, 300 and 375 kPa and durations of 10, 20, 30, 40, and 50 milliseconds for every reflected blast overpressure and for all infill panels in Fig. 3 is used. In addition, the curves of maximum displacement of the steel infill panels under various blast loadings are taken from contours of deformation using ABAQUS program.

It should be noted that concerning all infill panels of Fig. 3 and different blast loadings of Table 6 applied to all infill panels, 250 models are used in this paper in order to study the comprehensive behavior of steel infill panels against various blast loadings. In the following, the results of maximum displacement of steel infill panels with various stiffener arrangement and thickness under blast loading of Table 6 are presented and discussed.

6. Parametric study on blast behavior of steel infill panels

As for the importance of study on steel infill panel's behavior under blast loading with various reflected pressure (Pr) and duration (Td), all infill panels with different stiffener arrangement and thickness are studied in detail in this section. The curves of maximum displacement of the steel infill panels are taken from contours of deformation using ABAQUS program.

Figs. 9 and 10 compare maximum displacement of steel infill panels under blast loads with reflected pressures of 75 and 150 kPa with different durations. It is clear from Figs. 9 and 10 that in the reflected pressures of 75 and 150 kPa, the more duration of blast, the more maximum displacement of infill panels. The obtained results indicate that the increase in thickness of infill plate from 5 to 20 mm results in considerable decrease in maximum displacement of infill. When the steel infill becomes more rigid caused by the increase in thickness of infill panel, the maximum displacement of steel infill panels decreases.

Regarding the use of different stiffener arrangements of the infill panels, it can be observed in the bar charts of Figs. 9 and 10 that the stiffener arrangement has a regular pattern in the infill panels with 20 mm thickness so that the maximum displacement reduced with rising elastic hardness

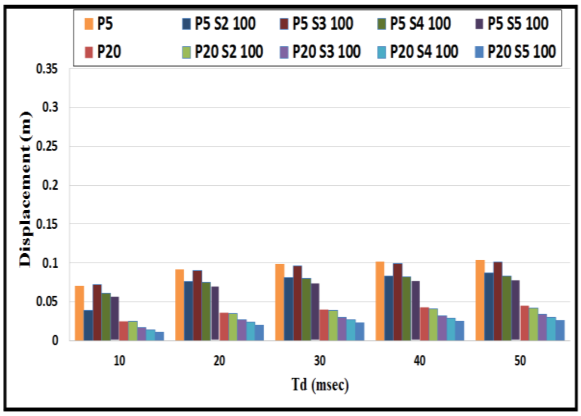


Fig. 9 Comparing maximum displacement of steel infill panels under blast loading of 75 kPa with different durations

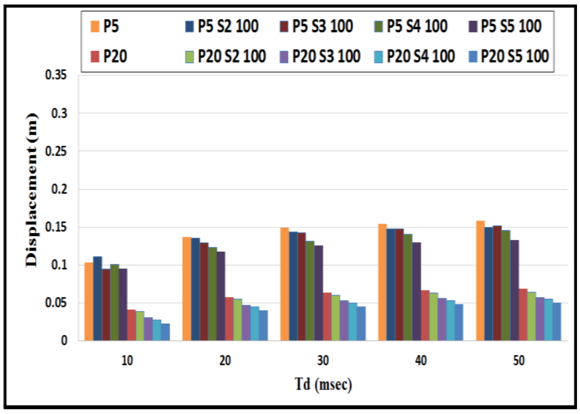


Fig. 10 Comparing maximum displacement of steel infill panels under blast loading of 150 kPa with different durations

by increasing the number of stiffeners. In some cases, there was not any regular pattern and the interpretation of results is difficult. This is justifiable due to the complexity and the nonlinearity of the blast phenomenon.

Figs. 11 and 12 show the maximum displacement of steel infill panels under blast loads with reflected pressures of 225 and 300 kPa. Like what shown in Figs. 9 and 10, similar pattern is observed in Figs. 11 and 12. Figs. 11 and 12 show that the thickness of the infill panels significantly impact on the behavior of infill in a way that the increase of the infill panel thickness from 5 mm to 20 mm results in decreasing the maximum displacement. Comparison of the maximum displacements shows that thicker plate sustains less ductility under blast loadings. As for the effect of stiffeners based on the graphs in Figs. 11 and 12, it is shown that the stiffener arrangement does not have remarkable impact on displacement of infill panels. In other words, it can be concluded that the maximum displacements of steel infill panels are more sensitive to thickness of panel than stiffener arrangement and change in thickness of panel has more effects on change in maximum displacement.

A similar trend was reported by experimental and numerical investigations by Zheng *et al.* (2016) indicating that the final deformation of stiffened steel plates is more

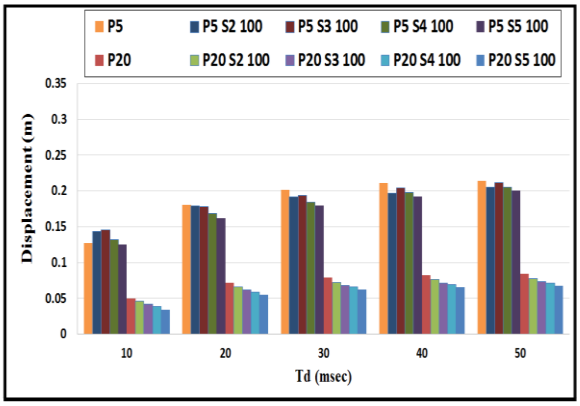


Fig. 11 Comparing maximum displacement of steel infill panels under blast loading of 225 kPa with different durations

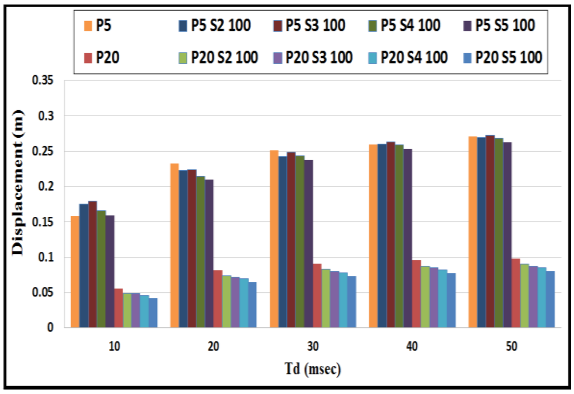


Fig. 12 Comparing maximum displacement of steel infill panels under blast loading of 300 kPa with different durations

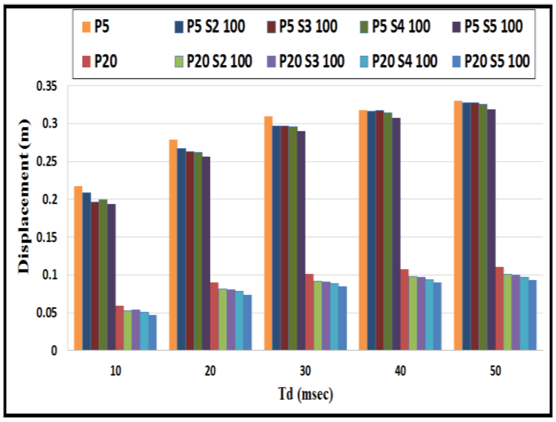


Fig. 13 Comparing maximum displacement of steel infill panels under blast loading of 375 kPa with different durations

sensitive to thickness of plate than stiffeners attached to the infill plate.

The reduction in maximum displacement of infill affected by the increase in the thickness of plate is evident. Also, the infill panels with 5 stiffeners have more effect on reducing maximum displacement of infill panel with 5 and 20 mm thicknesses. In other words, numerical results show that thicker plates exhibit less ductility. These results are obtained from reviewing Fig. 13. Concerning Figs. 9-13, it is obtained that the increase in stiffness of steel infill panel affected by an increase in the thickness of plate leads to considerable reduction in its maximum displacement. The effect of plate thickness is so evident in high blasts.

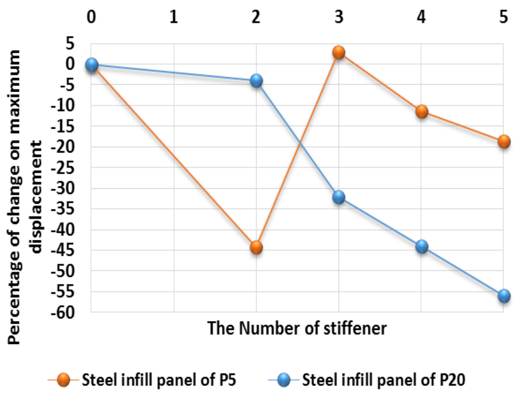
Based on these studies of figures, it can be concluded that intensity of blast loading has a direct effect on maximum displacement of steel infill panels. As the reflected pressure or duration of blast loading increases, using an infill panel with different thickness leads to more increase in its maximum displacement. In other words, it can be stated that increasing the impulse is the key parameter regardless of the values for blast pressure or the blast duration.

It can be concluded that the maximum displacements of steel infill panels are more sensitive to their thickness than stiffener arrangement. Regarding the use of different stiffener arrangements of the steel infill panels, it can be observed in Figs. 9-13 that the stiffener arrangement had a regular pattern specially in the infill panels with 20 mm thickness so that the maximum displacement is reduced with rising elastic stiffness by increasing the number of stiffeners. In some cases, there is not a reasonable pattern such that the interpretation of results is difficult.

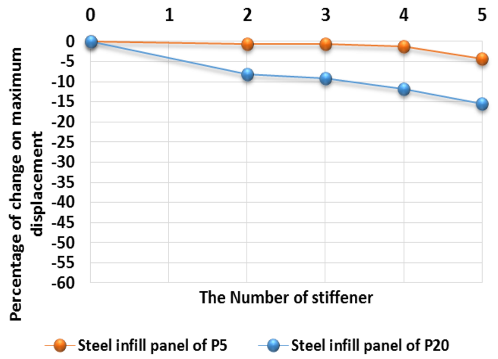
6.1 Maximum displacement reduction percentage

To simply compare the effect of stiffener arrangement and the infill panel thickness in terms of maximum displacement, Figs. 14 and 15 show the reduction values. Fig. 14 is pertinent to the effect of different stiffener arrangements on the maximum displacement of infill panels; and Fig. 15 is related to the effect of different thicknesses of steel infill panel on the maximum displacement in percentage. These curves consider two blast loads with reflected pressure of 75 kPa, duration of 10 milli-seconds, and reflected pressure of 375 kPa and duration of 50 milli-seconds.

The vertical column of the diagrams reveals the change of maximum displacement of the infill panels in percentage. In Fig. 14, infill panels with different stiffener arrangements are compared to those with no stiffener. The P20 and P5 infill panels with no stiffeners show basic cases and the infill panels with various stiffener arrangement and thickness are compared with these two infill panels and the values that affect the infill displacement are expressed in percentage. Negative percentage shows that using infill panel in that case leads to decrease of maximum displacement and positive percentage indicates that using infill panel in that case causes an increase in the maximum displacement. Fig. 13 with reflected pressure of 75 kPa and duration of 10 milli-seconds shows that increasing the number of stiffeners in the P20 infill leads to a regular decrease in the displacement. However, such a trend is not observed in the P5 diagram as using 3 stiffeners leads to a sudden increase in the displacement or in other words, it makes the change percentage positive. The reason for this might be in the complexity of blast phenomenon. As Fig. 14 shows, increasing the number of stiffeners in most cases leads to a decrease in the infill panel displacement as in the blast with reflected pressure of 75 kPa and duration of 10 milli-seconds, the P20 infill with 5 stiffeners might decrease



(a) P_r = 75 kPa, T_d = 10 msec



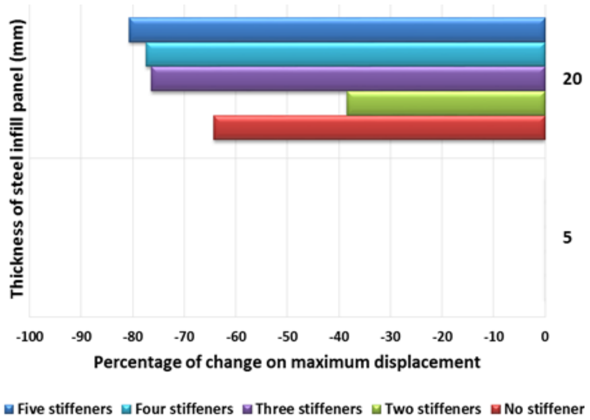
(b) P_r=375 kPa, T_d=50 msec

Fig. 14 Reduction of maximum displacement with different stiffener arrangements

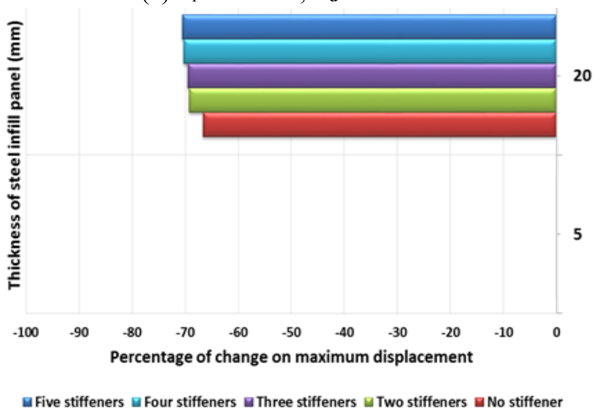
the displacement by 56 percent in the infill with no P20 stiffener. However, this reduction is by 45 percent in P5 infill with two stiffeners.

As Fig. 14 with reflected pressure of 375 kPa and duration of 50 milli seconds shows, increasing the number of stiffeners causes more change in the infill maximum displacement as using 5 stiffeners in the P5 infill leads to a 5 percent decrease of maximum displacement and in P20 leads to a 15 percent decrease of maximum displacement compared to the case in which there is no stiffener in the infill. Comparing the curves of Fig. 14 reveals that as the blast load intensity increases from reflected pressure of 75 with duration of 10 milli-seconds to reflected pressure of 375 kPa with duration of 50 milli-seconds, the change in maximum displacement of the infill panels decreases. The present study shows that in the highest blast load, the number of stiffeners leads to at most 16 percent reduction in the infill maximum displacement while in the lowest blast load with reflected pressure of 75 kPa and duration of 10 milli-seconds, the displacement reduction might be up to 56 percent.

Fig. 15 reveals the effect of infill panel thickness on the infill maximum displacement. In these diagrams, x axis shows the 5 and 20 mm thicknesses and y axis shows the reduction percentage of infill maximum displacement. As Fig. 15 reveals, increasing the infill panel thickness from 5 to 20 mm leads to a decrease in the infill maximum displacement. Furthermore, from curves of Fig. 15 with reflected pressure of 75 kPa and duration of 10 milli-seconds, it might be stated that in infills with two stiffeners,



(a) P_r = 75 kPa, T_d = 10 msec



(b) P_r = 375 kPa, T_d = 50 msec

Fig. 15 The effect of infill plate thickness on reduction of maximum displacement

increasing thickness from 5 to 20 mm leads to a 39 percent decrease in the infill maximum displacement. Moreover, the figure also implies that increasing the infill panel thickness significantly decreases the maximum displacement as in Fig. 15(a), it has caused up to 81 percent decrease in the infill maximum displacement.

Fig. 15 shows that in blast load of 375 kPa and duration of 50 milli seconds, increase of infill panel thickness leads to a remarkable decrease in displacement up to 70%. In addition, examining Figs. 14 and 15 reveal that in the studied blast loads, changing the number of stiffeners has less effect on the infill displacement compared to changing the infill panel thickness. The study also indicates that increasing the number of stiffeners in blasts with low intensity and those with high intensity leads to maximum displacement of infill by 55 and 15 percent respectively. However, increasing the infill panel thickness from 5 to 20 mm in blasts with low intensity shows a displacement decrease by 81% while in blasts with high intensity this displacement decrease is by 70%.

7. Conclusions

In this paper, out-of-plane behavior of steel infill panel with various stiffener arrangement and plate thickness under blast loading was studied. Two main features of blast loading including duration and reflected pressure have direct effects on maximum displacement of steel infill panel in a way that the increase or decrease of each of these two parameters leads to the increase or decrease in infill panel maximum displacement. The increase in the elastic stiffness caused by an increase in infill panel thickness results in considerable reduction in maximum displacement of steel infill panel and adding stiffener can improve the performance of the plate in terms of limiting deformation. The results of this study indicate that this type of infill panel with out-of-plane behavior shows a proper ductility especially in severe blast loadings.

Intensity of blast loading has a direct effect on maximum displacement of steel infill panels. As blast load increases from 75 kPa and duration of 10 milli-seconds to 375 kPa and duration of 50 milli-seconds, it is noticed that stiffener arrangement slightly affects the infill displacement; but, the infill panel thickness significantly affects the infill maximum displacement. Maximum displacement of steel infill panels is more sensitive to thickness of panel than stiffener arrangement.

In blasts with low intensity, increasing the number of stiffeners leads to an increase in energy dissipation by 127 percent compared to the case in which no stiffener is used (as to 5 mm infill). Further, increase of the thickness of infill panel leads to decrease of energy dissipation by 99.9 percent (as to infill with no stiffener). Therefore, in blasts with low intensity, 5 mm steel infill with 5 stiffeners has the highest effect on energy dissipation. In blasts with high intensity, increasing the number of stiffeners leads to decrease of energy dissipation by 20 percent and increasing the panel thickness leads to decrease of energy dissipation by 77 percent. Thus, in blasts with high severity, 5 mm steel infill with no stiffener has the highest effect on energy dissipation. In fact, examining the ductile behavior of steel infills shows that using infill panels with less thickness has more effect on energy dissipation.

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