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Dynamic structural response characteristics of new concept blast walls under hydrocarbon explosions

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Abstract
Offshore installations activities entail the hazard of explosion accidents with potentially severe consequences to safety of workers, integrity of system, pollution of the environment, and economic losses. Blast walls are generally used for the purpose of reducing the explosion consequences. This study introduce a new concept of blast wall (perforated blast wall) which can disrupt loaindg pressure during the explosion. A dynamic finite element analysis was performed to investigate the effects of the geometric characteristics on the performance of perforated blast walls. A series of computations were performed varying with opening size, plate thickness and opening layout associated with Blockage Ratio. A proposal formula was derived as a function of those design parameters for easily expecting the dynamic structural response characteristics.

Keywords
Explosion loads, perforated blast wall, dynamic structural analysis, nonlinear finite method

1 INTRODUCTION

During the installation or operation, offshore installations can be threatened extreme or accidental events in association with site-specific met-ocean, operational conditions, or other factors. These events sometimes have catastrophic consequences that lead to heavy casualties, property damage, and pollution. In particular, hydrocarbon explosions can occur on all platforms because they are usually related to the release of hydrocarbon. To reduce the significant loss of structural integrity against the explosion, a substantial amount of effort have been directed towards mitigation system which can reduce the effect of accidents on the exposed structure (API, 2006; DNVGL 2010&2014; ABS, 2013; LR, 2014; ISSC, 2015; Oil & Gas, 2007).

Passive mitigation systems are preferred as they do not rely on the detection and deployment mechanisms, but they are always activated. There are four approaches in the passive mitigation system including impedance mismatching, sacrificial cladding, blast deflection and blast and shockwave disruption (Langdon et al., 2010).

Blast walls which are one of the blast wave mitigation measures are commonly placed around main structures and/or accommodation to disrupt the blast wave and protect human and structures from the explosion loads. Fundamentally, flat plate or corrugated shape of general blast wall are typically used. However, they are more likely to lead a large blast loads when explosion occurred because air flow can be perfectly blocked by them. If the wall has a large blast force, it can collapse together with main structures due to connection. So, it is an issue to reduce the force on panel even if walls should prevent the blast load to the structures. To decrease amount of the blast force on the panel, this study suggests the perforated blast walls which has opening can be a great help air flow by openings of the blast walls.

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There is some information available in the open literature about the dynamic structural response characteristic of perforated plates under hydrocarbon explosions. Langdon et al. (2010) studied the effect of opening size and plate thickness on the response of perforated plate. More specifically the hole size of perforated plate effectively reduced the damage imparted to the target plates by reducing the mid-point deflection and increasing the tearing threshold impulse. Langdon et al. (2011) also investigated the effect of separation distance on the response of the perforated plates in tunnel-like structures. It is shown that the influence of blockage ratio was more significant at lower separation distances.

Rakvåg et al. (2013) carried out modest alterations to the geometry of a pressure-loaded structure in the form of holes do not seem to degrade the structural resistance when the impulse is sufficiently low not to cause the plate to fail based on the experiments and numerical simulations. It is because that the decrease in stiffness caused by the pre-formed holes is compensated by a reduced load area and hence pressure load.

However, it has remained the concerns about the lack of structural strength blast walls due to the openings. There is no doubt that the blast walls with large opening area has lower blast force than general one while having considerable structural response. It is important to satisfy both decreasing the blast force on the wall by making holes, and keeping their strength. The aim of this study is finding the effect of openings on the blast wall which can play a role of blast wave mitigation measure without losing the structural strength.

In order that, a series of computations were performed varying with opening size, plate thickness and opening layout. In this study, the blockage ratio is adopted to generalize various perforated blast wall. Blockage ratio is defined in order to analyze synthetically the effect of openings on the dynamic structural strength. It is equal to the ratio of solid part's area compared to un-perforated plate. It is defined by Eq. (1) as following;

$$Blockage\ Ratio\ (BR) = \frac{A_P}{A_T} = \frac{A_T - A_O}{A_T} = 1 - \frac{A_O}{A_T} = 1 - N\frac{\pi d^2}{4}\cdot\frac{1}{L^2} \tag{1}$$

where A_P is the solid area of the perforated plate, A_T is the total area of un-perforated plate, A_O is the total area of openings, d is the opening diameter, N is the total number of the openings, and L is the side length of square plate.

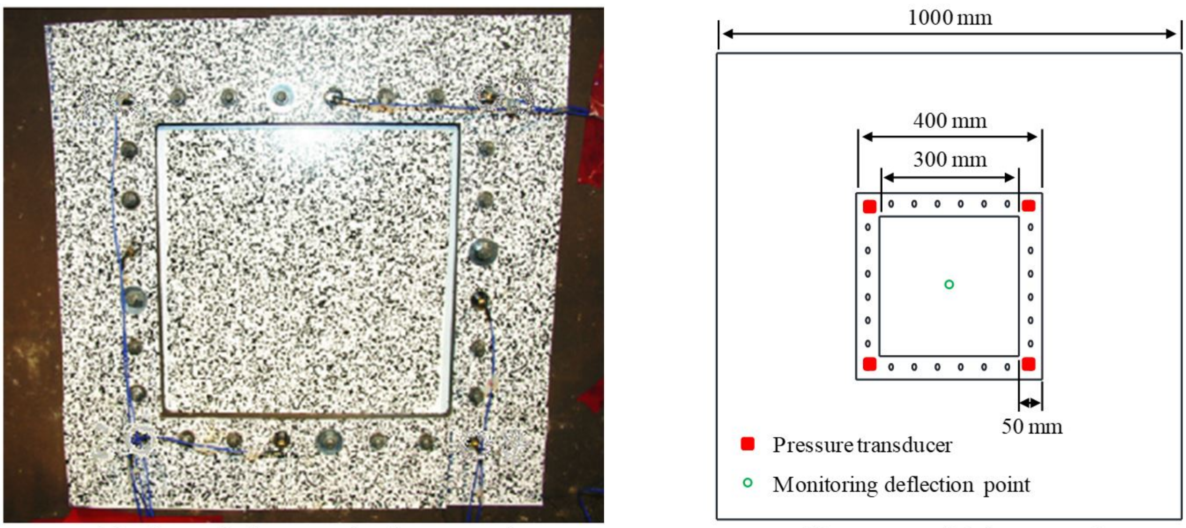
Also, a proposal formula of dynamic structural response characteristic is derived as a function of these design parameters.

2 VALIDATION BETWEEN TEST AND NUMERICAL METHODS

A small-scale of free air blast test performed by Spranghers et al. (2013) were used to validate the reliability between numerical analysis and experimental results. The description of the experimental setup about materials and the conditions refers to the reference. The experimental target and its main dimensions are shown in Figure 1. Table 1 summarized the properties and dynamic characteristics. The Cowper-Symonds parameters (Cowper and Symonds, 1957) are applied to computations to reflect dynamic yield stress by considering the effect of the strain rate. It is defined as Eq. (2).

$$\frac{\sigma_{Yd}}{\sigma_Y} = 1.0 + \left(\frac{\dot{\varepsilon}}{C}\right)^{1/q} \tag{2}$$

where $\dot{\varepsilon}$ is strain-rate, σ_{Yd} is dynamic yield stress, σ_Y is static yield stress, and C and q are material coefficients which are distinguished according to material characteristic respectively. These coefficients are determined on the basis of the test results (Paik and Thayamballi, 2003).



(a) The real photograph of test panel (b) Test panel (Plane view)

Figure 1: A schematic of test model (Spranghers et al., 2013).

Table 1: The material properties of three components (Spranghers et al., 2013)

Part	Test specimen	Clamp frame	Support frame
Material code	EN AW-1050A H24	EN AW-7022	EN 10025-S235
ρ (g/cm^3)	2.71	2.70	7.90
E (GPa)	69	70	210
ν	0.33	0.33	0.27
t (mm)	3	10	15
σ_Y (MPa)	83	450	235
C (1/s)	6500	6500	6500
q	4	4	4

The reflected pressures are measured from high frequency pressure transducers at the four corners of the clamping frame during the detonation. The experimental results of measured reflecting pressure are presented in Figure 2. The idealized time-pressure history as nonlinearly decaying on the basis of experimental conditions applied to the finite element model in ANSYS/LS-DYNA (2017).

The Belytschko-Lin-Tsay shell formulation is used for recommended type as a default which is based on Reissner-Mindlin kinematic assumption (5DOF in local and 6DOF in global) and it gives extremely computational cost effective solution by using one-point integration (ANSYS/LS-DYNA, 2017). Figure 3 shows the finite element model with boundary conditions which are the same as experiment condition. Nodes are fixed at the corner of support frame to describe the four supporting plates. Nodes in contact regions are connected each other.

In this experiment, the four identical tests were performed to identify the response of square plate under free air explosion. The out of plane displacement of the center point was captured using 3D high-speed digital camera (Spranghers et al. 2013), as shown in Figure 4. A result in the numerical simulation is added to the experimental curves. Obviously, the numerical result for time-displacement histories at the center of plate is fully included into the experimental region.

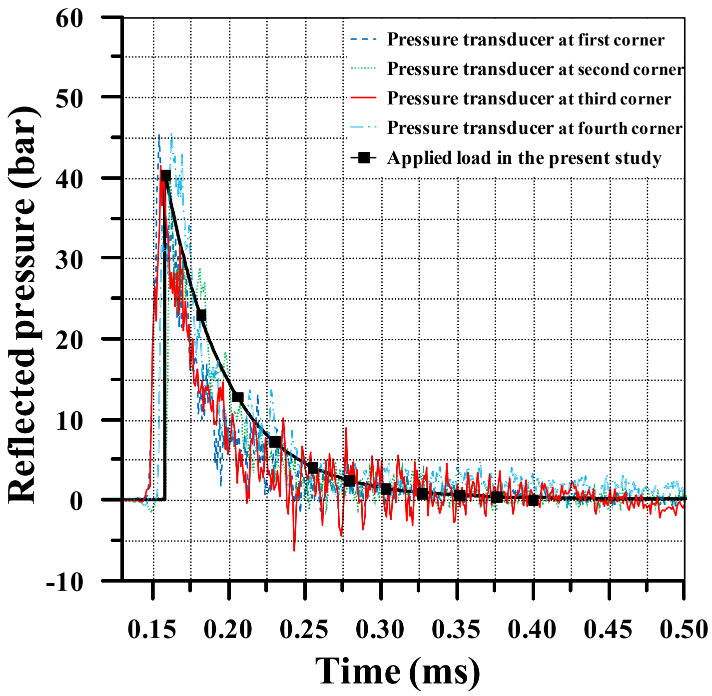


Figure 2: Measured reflecting pressure with idealized curve used in numerical study (Spranghers et al., 2013).

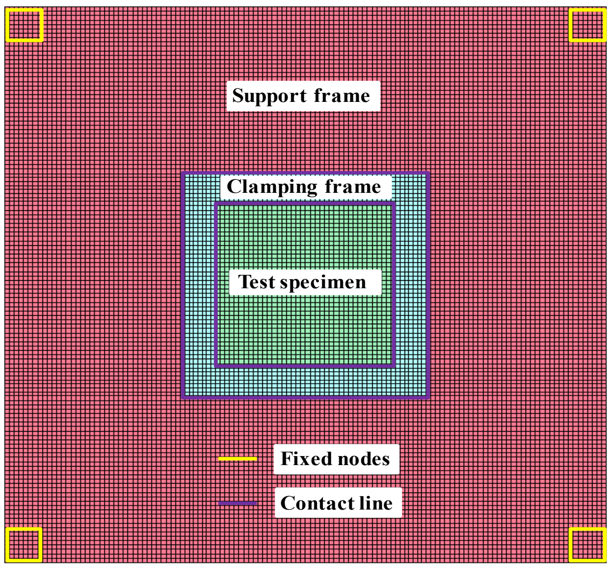


Figure 3: FE model of target structure for validation.

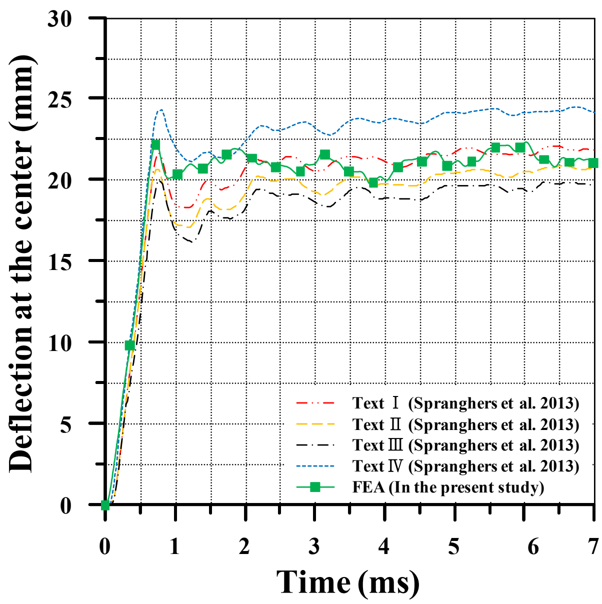


Figure 4: Time-displacement curves at the center of test specimen.

3. DYNAMIC STRUCTURAL RESPONSE OF PERFORATED BLAST WALLS

It is recommended that blast walls should be located in typical offshore installations to protect personnel and critical safety equipment by preventing the escalation of hydrocarbon explosions (Czujko, 2001). Proposed blast walls in the present study has openings on the wall not to block the flow of air inside, as shown in Figure 5. It is consisted of perforated plate and support. One of perforated plate is measured as 1x1 (m) fasten a support member with a bolt.

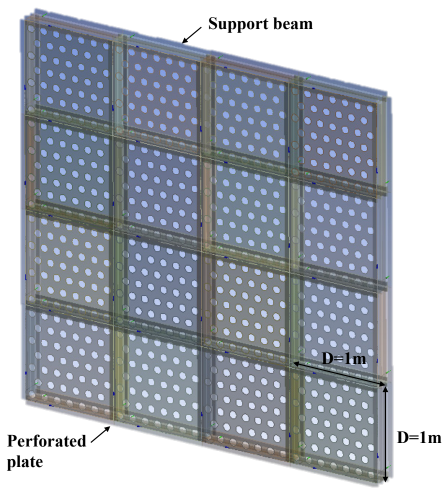


Figure 5: Scheme of perforated blast wall proposed in the present study.

3.1. Model scenarios

To verify the structural strength of perforated blast wall compared to original one, various consideration for opening was conducted, as shown in Table 2 and Figure 6. A Circle shape of opening is considered to avoid additional stress concentration around the opening. Figure 6 shows number and layout of opening in the study divided into two types according to line pattern: staggered line for diagonal and straight line for square. And six kinds of opening diameter is presented, from 40 to 300 mm. In case of blanks in the table, it is excluded that the number is not realized as the diameter increases, or the distance between openings becomes smaller that the specific diameter. Also, the plate thickness was varied to 1 to 8 (mm) with the interval of 1 mm to investigate the effect of thickness on the blast walls.

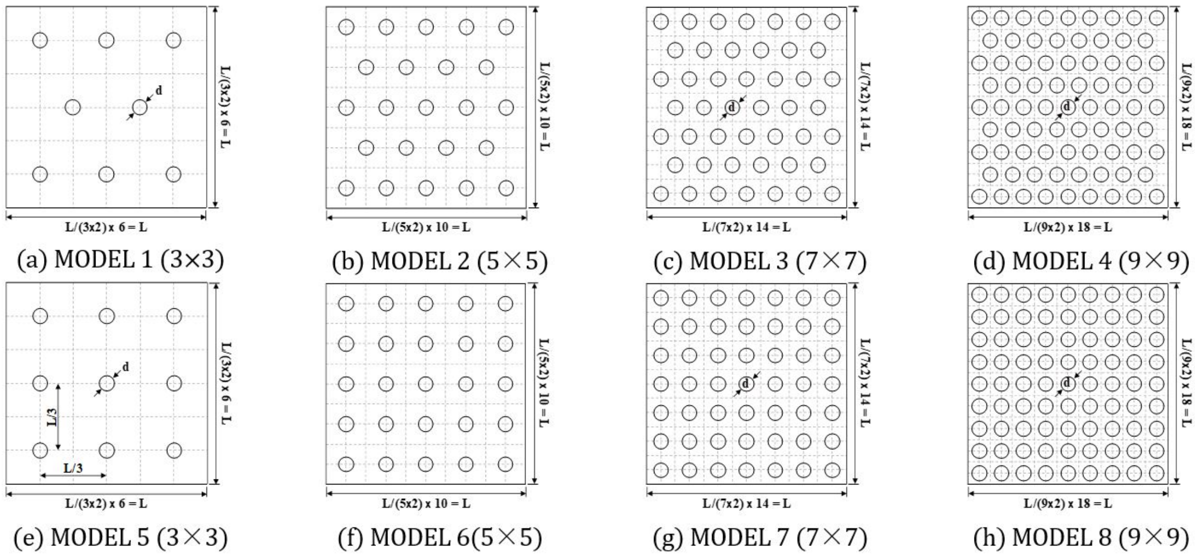


Figure 6: A schematic of eight kinds of perforated plates.

Table 2: Eight different models varying with opening characteristic and its blockage ratio (BR).

Pattern	Opening diameter (mm)	40	80	120	160	200	300
Diagonal	Model 1	0.990	0.960	0.910	0.839	0.749	0.435
	Model 2	0.971	0.884	0.740	0.538	-	-
	Model 3	0.942	0.769	0.480	-	-	-
	Model 4	0.903	0.613	-	-	-	-
Square	Model 5	0.989	0.955	0.898	0.819	0.717	0.364
	Model 6	0.969	0.874	0.717	0.497	-	-
	Model 7	0.938	0.754	0.446	-	-	-
	Model 8	0.898	0.593	-	-	-	-

3.2. Finite element models

A simulation with more fine elements has an additional computational cost to obtain the results with higher accuracy. It is crucial that a s certain element size is determined to ensure that the results of an analysis are not affected by changing the size of the mesh. Mesh sizes of approximately 8mm, were applied to the entire finite element model as shown in Figure 7. The high spiffiness supporting member could restraint the translation and rotation of plate at the bolting connection. Therefore, all fixed boundary condition were applied at the edge of the perforated plate, as shown in Figure 7.

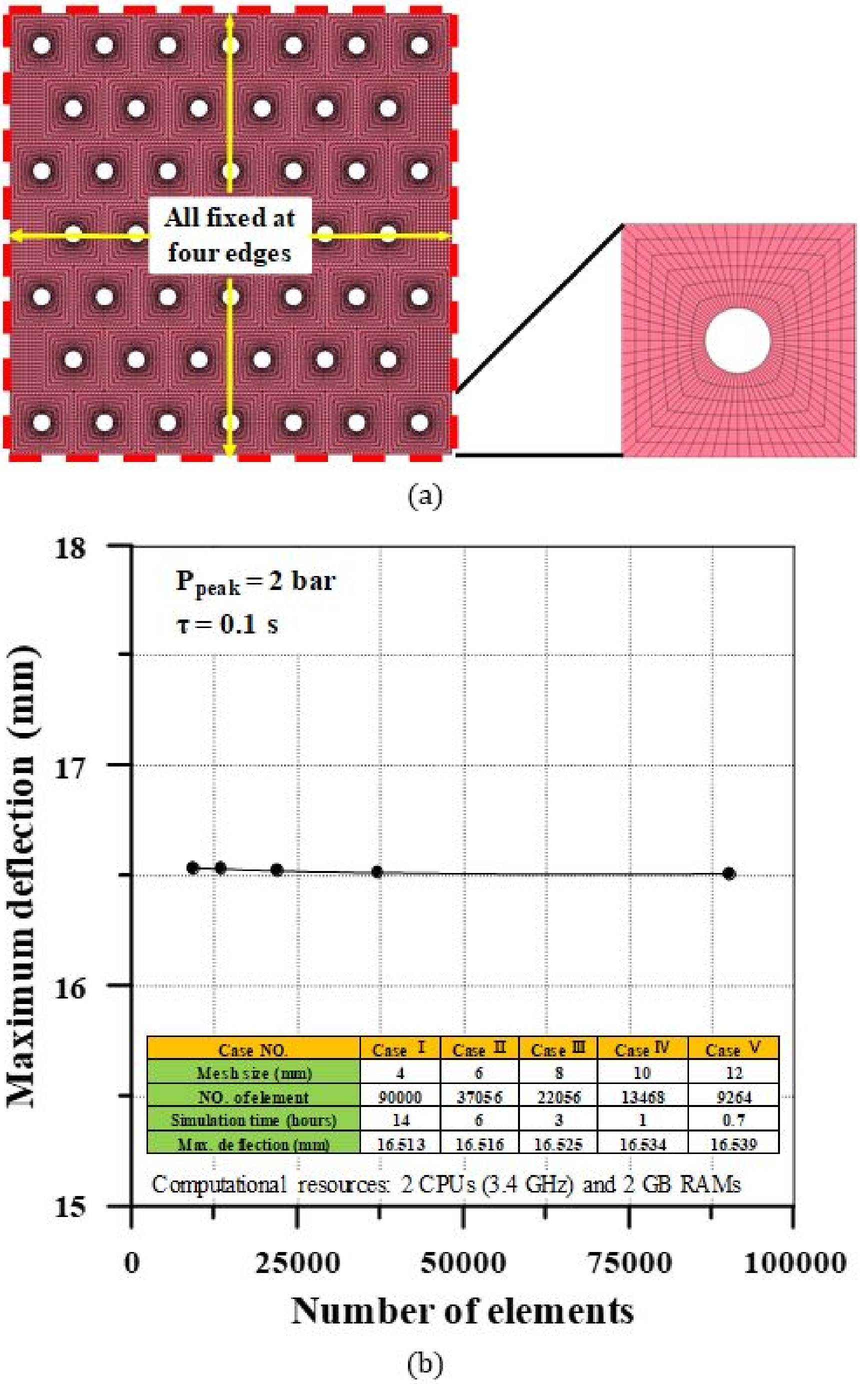


Figure 7: (a) Finite element model applied to mesh convergence study and (b) results of the study.

Carbon steel such as mild or tensile steel commonly used to manufacture the blast walls due to cost benefit and welding problem compared to stainless steel. The mild steel, elastic modulus (E) of 205.8 GPa, static yield strength (σ_Y) of 235 MPa, the Cowper-Symonds coefficients C of 40.5, q of 5.0, are used (Paik and Thayamballi, 2003). The dynamic material model is represented as plastic kinematic bilinear with the material strain rate parameters.

For loading case, industries are generally using 1bar of explosion pressure for design accidental load against the explosion. Especially, Paik and Czujko (2010) suggested design explosion loads with 10^{-4} /yr of exceedance frequency obtained from explosion load exceedance curve. Among of them, peak pressure of 1.01 bar with 0.1 s duration, the load is represented as triangular shape loads without negative part, is selected which is similar to well-known explosion design pressure.

4. Results of finite element analysis

For structural assessment of blast wall, the deflection is usually adopted for the criteria, because the deflection can be directly related to the structural stiffness (FABIG, 1996; Czujko, 2001). Figures 8 and 9 present BR versus maximum deflection at the center of the perforated blast walls depending on thicknesses respectively.

They present an increase tendency of maximum deflection as a decrease of BR for the different plate thickness because the bending rigidity decreases as increasing the size of hole (O'Donnel & Langer, 1962).

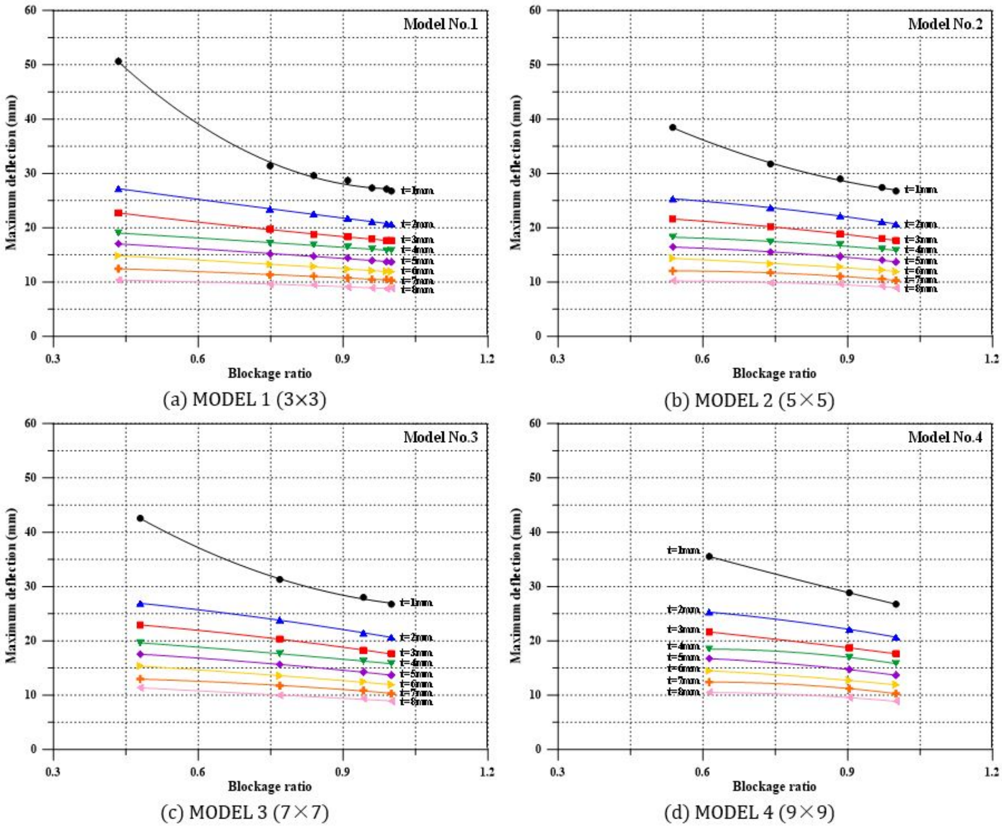


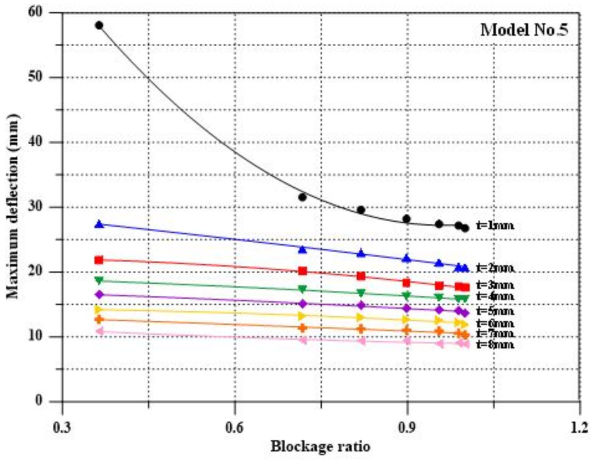
Figure 8: Maximum deflections of the staggered-based perforated blast walls with the thicknesses of plate.

It is observed that more sensitive change is shown at the thinner plate while effect of BR is negligible at the thicker plate. Particularly, 1-mm-thickness plate has nonlinear behavior, it is shown that the deflection rapidly increases as decreasing the BR. On the other hand, dynamic structural response of the plate except for 1-mm-thickness presents linear behavior.

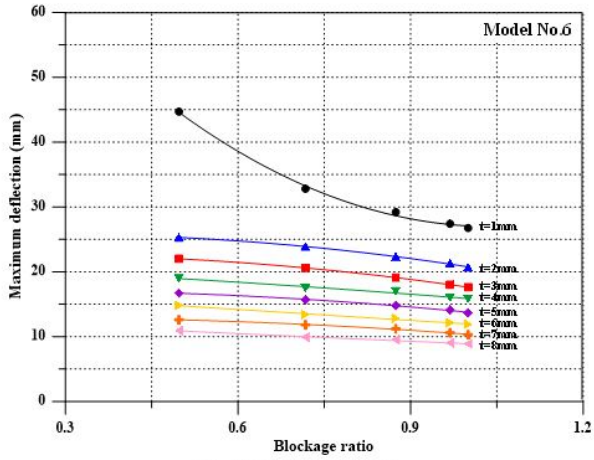
It is also investigated that thickness change cause a big difference in the dynamic structural response compared to variation of BRs. Bending rigidity is generally three times proportional to the plate thickness. It means that cross-section area is more important factor than the area which is applied to the load to resist bending behavior.

With regards to opening layout (diagonal and squared shape), a slight discrepancy of deflection is observed because of the number of opening (i.e., square pattern has more vacant space in the same plate) as shown in Figure 6. It is expected that the diagonal pattern has higher stiffness than the squared one when they have same layout (e.g., 3x3, 5x5 etc.) and opening size, due to the cross section area. It is shown significantly as thinner plate and lower BR. It could be concluded that opening can help the air flow fluently and reduce the its weight without losing its strength at the thicker plate.

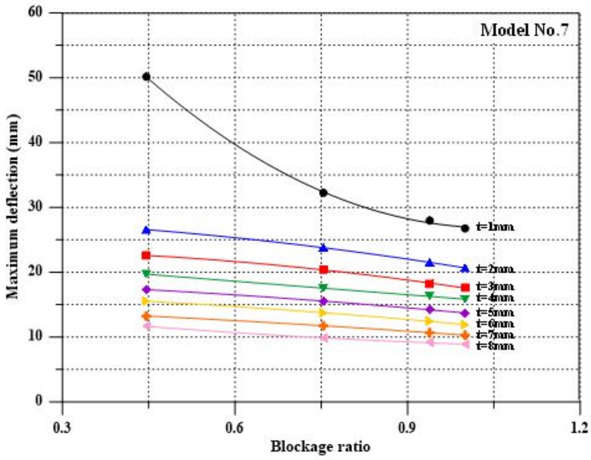
It is also investigated that thickness change is more affected on the dynamic structural response compared to variation of BRs. The reason is that the main load bearing mode in perforated blast walls are membrane stretching and the membrane stress is increased as thinner thickness.



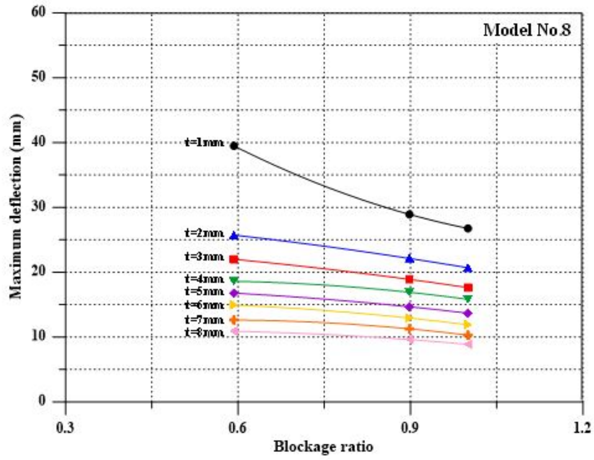
(a) MODEL 5 (3×3)



(b) MODEL 6 (5×5)



(c) MODEL 7 (7×7)



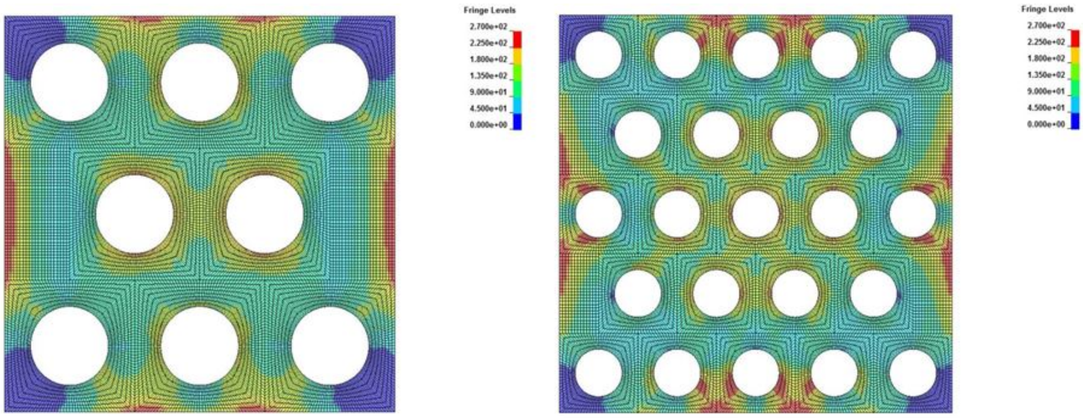
(d) MODEL 8 (9×9)

Figure 9: Maximum deflections of the straight-based perforated blast walls with the thicknesses of plate.

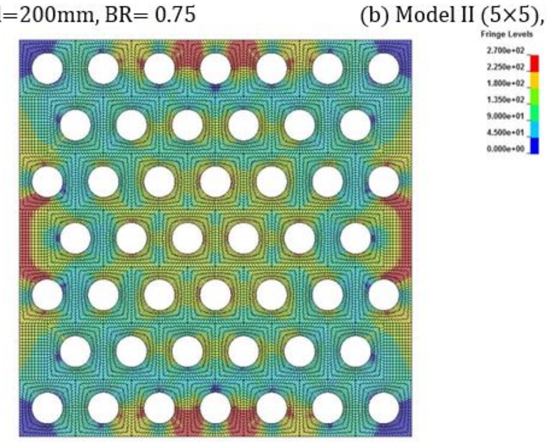
Obviously, the variation of BR influenced the dynamic structural response. But the opening layout is not important parameter to the structural intensity when the similar BR is applied.

In order to insight into the quality of post-process, Figure 10 presents the stress distribution of diagonal patterned plates which have similar BR when the maximum deflection occurred. In the ductile plate, the plastic hinges usually occur in maximum moment areas which are to exceed the yield stress of the materials. Maximum moment usually presents at the fixed support and along lines from corners to middle of thin plate.

From the Figure 10, it can be realized that the plastic hinges occur along diagonal lines of plate and at the fixed support lines, meanwhile, the stress concentration is observed obviously around the opening at the mid-plate with smaller opening size.



(a) Model I (3×3), d=200mm, BR= 0.75 (b) Model II (5×5), d=120mm, BR= 0.74

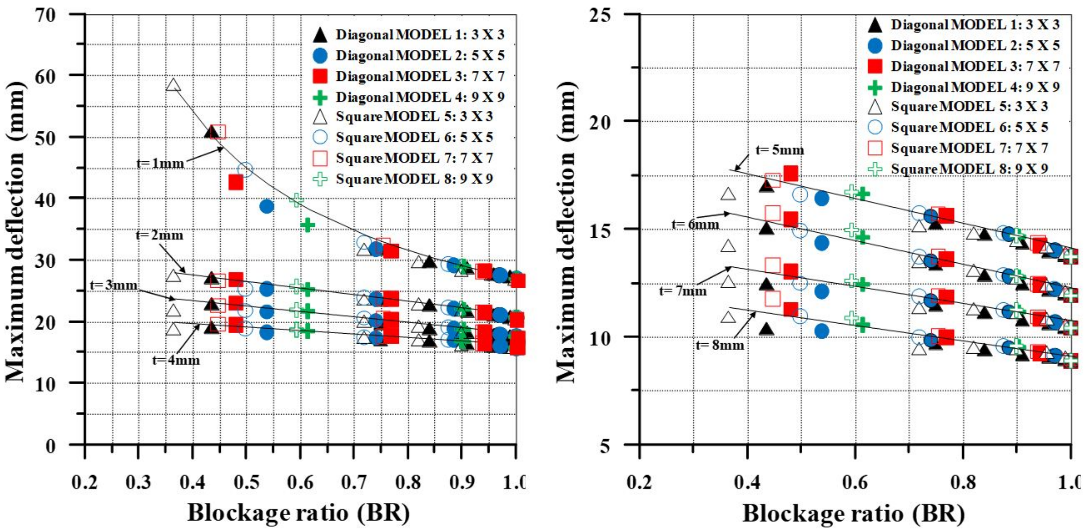


(c) Model III (7×7), d=80mm, BR= 0.77

Figure 10: Stress distribution of diagonal patterned blast walls which have similar BR.

5. Development of empirical formula for perforated blast walls

With the results of finite element analysis considering i) 2 kinds of pattern type, ii) 4 kinds of number of holes, iii) various hole sizes, and iv) eight thickness as shown in Figure 11, an empirical formula which calculates a maximum deflection under design explosion load (maximum pressure: 1bar and duration time: 0.1s) is developed in this study.



(a) Thin thickness (1 to 4mm) (b) Thick thickness (5 to 8mm)

Figure 11: Summary of maximum deflection of perforated blast walls according to BRs.

From Figure 11, it can be realized that the nonlinear structural characteristics appears distinctly along with the either thickness or BR decrease. It is also presented that the opening arrangement type has little influence on the dynamic structural response of perforated blast walls compared with both thicknesses and BRs. In addition, the thickness is most sensitive to dynamic structural response of perforated blast walls.

In order to consider the effect of plate thickness and BR on the maximum deflection for whole cases, the fitting curve was derived as a form of linear function for each thickness using BR parameters, as Eq. (3), and they are merged as function of BR and plate thickness as Eq. (4) which is finally suggested in the present study.

$$\delta_{\max} = 17.57/BR + 9.02 \text{ for} \tag{3.a}$$

$$\delta_{\max} = -10.67 \cdot BR + 31.55 \tag{3.b}$$

$$\delta_{\max} = -8.77 \cdot BR + 26.54 \tag{3.c}$$

$$\delta_{\max} = -5.73 \cdot BR + 19.70 \tag{3.d}$$

$$\delta_{\max} = -5.74 \cdot BR + 21.75 \tag{3.e}$$

$$\delta_{\max} = -5.47 \cdot BR + 17.61 \tag{3.f}$$

$$\delta_{\max} = -3.96 \cdot BR + 14.59 \tag{3.g}$$

$$\delta_{\max} = -3.60 \cdot BR + 12.62 \tag{3.h}$$

$$\delta_{\max} = \begin{cases} 17.57/BR + 9.02 & t = 1\ mm \\ (1.11t - 11.84)BR + (-3.03t + 35.77) & 2mm \le t \le 8mm \end{cases} \tag{4}$$

where $\delta_{\max}$ is maximum deflection at the midpoint of plate; t is the thickness of the plate; BR is the Blockage Ratio.

Every formula should be needed to verify their accuracy. So, the deflections calculated by developed formula are compared with the results of FE analysis. The accuracy of the Eq. (4) is checked in Figure 12. In this figure, each point is one case which involves the geometric characteristic of design parameter. The value in x-axis represents maximum deflection which is obtained from the FE method, meanwhile, the value in y-axis represents maximum deflection is outputted from the derived proposal formula above. From this figure, proposal formula is suitable to describe the dynamic structural response of the perforated blast wall.

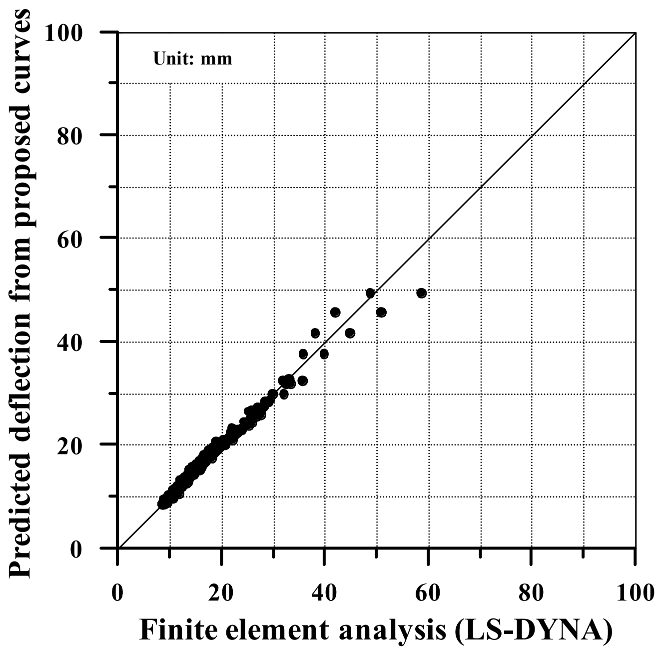


Figure 12: Comparison of FEA with empirical equation.

6. Conclusions

This paper analyzed the effect of geometric characteristics on the dynamic structural response of the perforated blast walls. According to the purpose of this study, the commercial computational software, ANSYS/LS-DYNA, was carried out to determine the dynamic structural response of the perforated blast walls. The following conclusions can be drawn on the basis of the results:

Both thickness and BR are more sensitive to the dynamic structural response of perforated blast walls than opening arrangement type. In addition, the thickness has the highest sensitivity.

Via the visual inspection of perforated blast walls in ANASYS/LS-DYNA, the all plastic hinges occurred in plate edges. It is proven again that the decrease in mass associated with the increasing maximum deflection under hydrocarbon explosion.

The FE simulation results for maximum deflection are in good agreement compared with the SDOF method. Derivation of the empirical equation is contributed to obtain the considerable results, quickly and easily. In the future, the derived proposal formula is useful in design of the perforated blast walls and it can be used to benefit the offshore industry via to improving design guidance and optimization of the perforated deck plates, perforated blast walls and perforated blast relief panels.

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