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Finite Element Analysis Of The Structural Response Characteristics Of Blast-Resistant Doors According To Support Conditions

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ABSTRACT:- Blast-resistant doors are engineered structures purposed for the protection of lives, important equipment and materials in civil and military facilities including plants, industrial and national assets, shelters or ammunition storage facilities. The present study compares the behavioral change of the blast-resistant door structure according to the boundary conditions provided by hinges and latches. The analytic results revealed that (1) placing a hinge at mid-height of the door was more effective than placing a latch in reducing the deflection at the center of the door and, that (2) placing latches at the upper and lower edges of the door or near the corners of the door was appropriate for reducing the deflection developed along the edges of the door. Moreover, the analysis showed that the resistance-to-deformation of the support member played a predominant role in preventing the deflection of the blast-resistant door among the structural components of the door. The analysis of the strain energy indicated that the proportion of the strain energy absorbed by the door itself increased by a larger rate than the support members with shorter standoff distance. Further study shall be conducted on the change in the structural behavior according to the details of the blast-resistant door.
KEYWORDS:- Blast-resistant door, Support boundary condition, Structural behaviour, FEM analysis

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I. INTRODUCTION

Blast-resistant doors are engineered structures purposed for the protection of lives, important equipment and materials in civil and military facilities including plants, industrial and national facilities, shelters or ammunition storage facilities [1-3]. A survey of the research literature on blast-resistant doors revealed that steel grid structures and steel-concrete composite structures were mainly used to date when dealing with large blasting pressure, and the existence of blast-resistant doors made of carbon fiber reinforced plastic (CFRP) composite material [4-10]. The blast-resistant doors made of steel box and steel grid are lighter than those presenting a composite structure using concrete in the core. This relative lightness offers wider room in the design of their support by hinges or latches. However, it is necessary to consider the addition of longitudinal and transverse steel stiffeners to secure sufficient stiffness in case of high blast pressure. Besides, the doors with steel-concrete composite structure are relatively advantageous in term of stiffness as well as in term of protection against shrapnel, bullets or radioactivity. Therefore, the use of steel-concrete composite door is recommended in absence of concern about the weight when the door is small or in case of large blast pressure. On the other hand, the use of steel grid door is recommendable when the dimension of the door is consequent or when very large blast pressure is not expected.

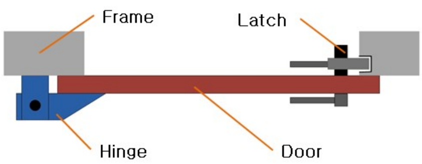
Hinges are installed in the left or right edge of the blast-resistant door to support the weight of the door and to help opening and shutting of the entrance. Moreover, latches are placed on the upper and lower edges as well as on the remaining lateral edge to lock or release the door and to maintain the airtightness. Such hinge and latch members are used not only to operate the blast-resistant door like for opening and closing but also to protect lives and assets by sustaining primarily the blast-resistant door in case of external or internal blasting of harmful substance. The blast-resistant door exhibits different structural behaviors according to the boundary conditions created by the hinges and latches but there is no general design method related to each condition, which means that one must conduct analysis or test separately. This results in the absence of systemized study on blast-resistant doors subjected to common explosives apart from nuclear explosion. To worsen the situation, there is also the difficulty to apply a general design method for each case since very different behaviors will be developed according to the structural details [11, 12].

To prepare for the design of the composite blast-resistant door, the present study analyzes the change in the overall structural behavior of the door with respect to the support conditions in terms of the number and position of the hinges and latches supporting the blast-resistant door. Since our interest focuses on the change of the structural behavior according to the design conditions of the hinges and latches, the blast-resistant door is assumed as a simple steel plate instead of being a composite structure to help the numerical convergence and save computational effort in the analysis. The selected variables are the number and position of the hinge and latch members and the standoff distance between the explosive and the door. The behavioral characteristics of the blast-resistant door system are compared according to these variables by means of the maximum deflection and permanent deflection at the center and corners of the door and the strain energy generated in the door and the support members. The results of the comparison are then used to examine the position of the support members that would be efficient against the blast pressure. Note that the explosive is assumed to be outside the protected structure. The general-purpose finite element (FE) program LS-DYNA [13], that is widely used for explicit analysis like impact analysis or blast analysis, is utilized for the behavioral analysis of the blast-resistant door.

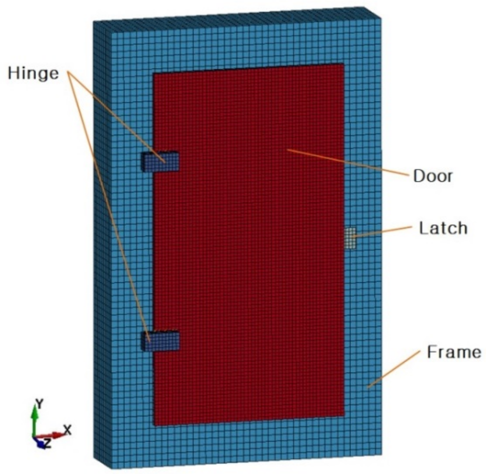
II. FINITE ELEMENT ANALYSIS OF BLAST-RESISTANT DOORS

A. Analysis model and variables

The reference model of the blast-resistant door for the analysis is set as the simplest door structure with the door itself, two hinges installed on the left edge and one latch placed at mid-height of the right edge. The considered door has unique dimensions of 1250×2500×50 (W×H×D, in mm). Table 1 lists the blast-resistant doors considered in the parametric study with different arrangements including the number and position of the hinge and latch members and the standoff distance between the explosive and the door. The analysis assumes that the explosive is located outside the structure protected by the door. Under this assumption, the blast pressure generated by the explosive is sustained by the hinges and latches as well as by the contact with the frame surrounding the perimeter of the door. Fig. 1(b) depicts the structural model of the blast-resistant door system including the door, the supports and the frame.



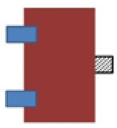
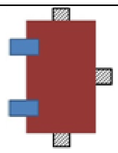
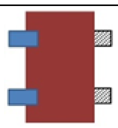
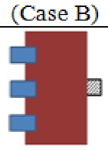
(a) General structure of blast-resistant door system



(b) Reference model of blast-resistant door

Fig.1: FE-model of blast-resistant door

Table 1: Analysis variables and conditions of blast-resistant door (■: hinge, ▨: latch)

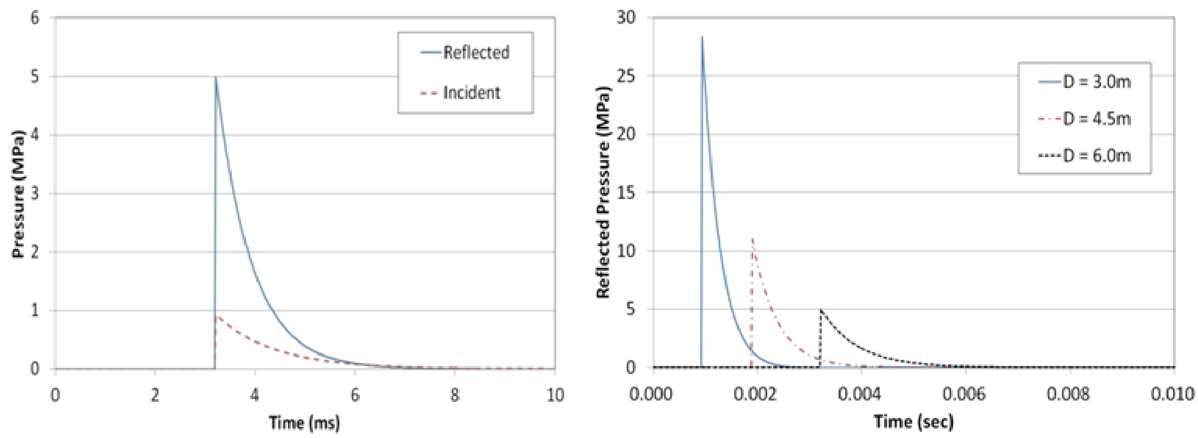
Analysis variables			Analysis constants		
Support boundary conditions		Standoff distance	Explosive charge	Dimensions of blast-resistant door	Yield strength
 (Case A: ref.)	 (Case B)	3.0/4.5/6.0 m (surface blast condition)	TNT 276 lb.	1250×2500×50 mm (W×H×D)	235 MPa (SS400)
 (Case C)	 (Case D)				

All the members composing the structural system were modeled using 8-node solid elements. The boundary conditions of the considered cases are as follows. The displacements of the hinges installed in the left edge of the door are fixed in the x-, y- and z-directions. The displacements of the latches installed in the right edge of the door are fixed in the y- and z-directions, and the displacements of the latch at the top of the door are fixed in the x- and z-directions. The release of the displacement of the latch in one direction intends to simulate the real installation condition of the blast-resistant door system (Fig. 1(a)). Note that the global coordinate system of the structural system adopts the directions along the width, the height and the thickness of the door as the x, y and z axes (Fig. 1(b)).

Considering the purpose of this study, the detailed shape of the support members is simplified in the model. Moreover, the connection between the supports and the door frame is assigned with the support conditions explained above and is thus simplified in the model. On the other hand, contact condition is attributed to the interface between the perimeter of the door and the surrounding frame in order to transfer the blast pressure. The yield strength of SS400 steel used for the door and support members is 235 MPa. In the analysis using LS-DYNA, piecewise linear plastic material model enabling to account true stress and true strain is adopted. Dynamic hardening is also considered since it may occur in case of high velocity loading. LS-DYNA adopts the constitutive equation expressed as a function of the strain rate ($\dot{\varepsilon}$) in Eq. (1) and proposed by Cowper-Symonds [14] to consider the dynamic hardening. In Eq. (1), the coefficients C and p are strain rate parameters and are set as $C = 40$ and $p = 5$ in this study.

$$\text{DHF(Dynamic Hardening Factor)} = 1 + \left(\frac{\dot{\varepsilon}}{C}\right)^{1/p} \tag{1}$$

The blast pressure applied on the blast-resistant door is that generated by the explosion of 276 lb. (about 125 kg) of TNT. Here, considering that 276 lb. of TNT corresponds to a charge-weight ratio of 41% with respect to GP 550 bomb, the calculated charge of 225 lb. was added with about 20% of extra charge. The explosive was placed 5 cm above the ground to simulate surface blast condition. Since the blast pressure is reflected by the ground in surface blast condition, significantly larger blast pressure is applied compared to the original one. The reflecting effect caused by the ground is considered automatically when surface blast is input as initial condition in LS-DYNA. Three standoff distances of 3.0 m, 4.5 m and 6.0 m were chosen between the explosive and the blast-resistant door. Fig. 2(a) plots the distribution curves of the incident pressure and reflected pressure acting on the door for the standoff distance of 6.0 m. Fig. 2(b) compares the reflected pressure with respect to the standoff distance. Here, the incident pressure is the pressure before the blast pressure acts on the structure and the reflected pressure is the pressure reflected when the blast pressure attains the structure and is thus the actual pressure acting on the structure.



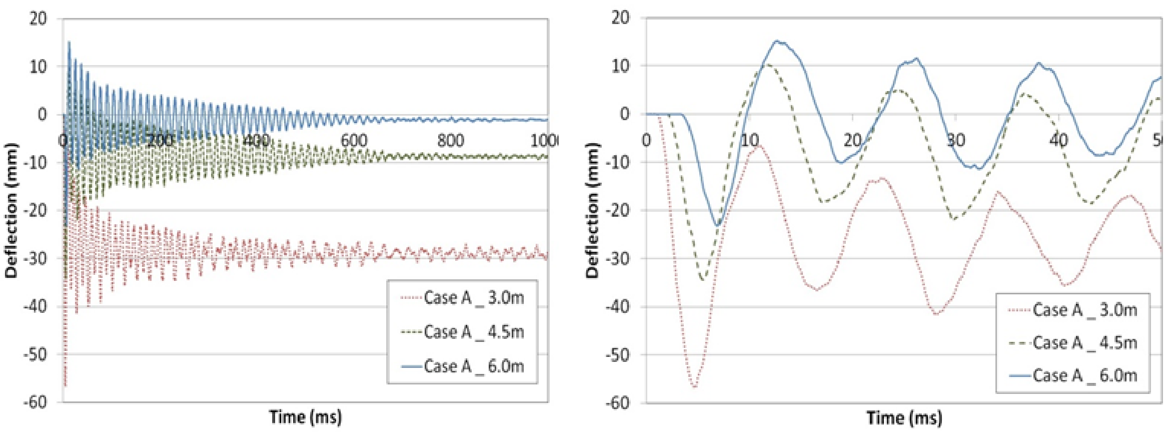
(a) Incident and reflected pressures for standoff distance of 6.0 m **(b) Comparison of reflected pressure according to standoff distance (D)**

Fig.2: Incident pressure and reflected pressure acting on blast-resistant door

B. Analysis results

Analysis was performed using LS-DYNA for case A, the reference model with 2 hinges and 1 latch attached respectively to the left and right edges of the door, and cases B to D with other variables. Fig. 3 compares the analytical results for case A with respect to the standoff distance (3.0 m, 4.5 m, 6.0 m) in term of the deflection-time hysteresis curves at the center of the blast-resistant door. Table 2 compares the maximum deflection and the permanent deflection developed at the center and lower edge of the door in each of the considered cases.

In view of the maximum deflection, the reference model (case A) deflected by 23.1 mm for the standoff distance of 6.0 m, and the maximum deflection increased by 1.48 times and 2.45 times when the standoff distance reduced to 4.5 m and 3.0 m, respectively. For the distance of 6.0 m, a deflection of (+) 14 mm caused by the rebounding force occurred in the direction opposite to the load. For the distance of 3.0 m, an opposite deflection also occurred due to the action of the rebounding force but the overall deflection remained negative. Here, the rebounding force is the force generated by the elastic recovery of the blast-resistant door subjected to the blast pressure. Accordingly, Fig. 4 compares the distribution of the deflection in the blast-resistant door structure. In Figs. 4 (a) and (c), the deflection shows similar pattern in the direction of the acting load but the deflection in the opposite direction presents significant difference. Note that the direction of the acting load is defined as the negative direction (–z-direction) and the opposite direction as the positive direction (+z-direction). One reason of such deflection is that, for the standoff distance of 3.0 m, the door already experienced significant plastic deformation at the time of the maximum deflection in the direction of the acting load. Correspondingly, the stress and strain distributions shown in Fig. 5 indicate that relatively larger stress and plastic deformation were developed around the support member and at the center of the door for the standoff distance of 3.0 m.



(a) Complete time hysteresis **(b) Initial part of time hysteresis (0–50 ms)**

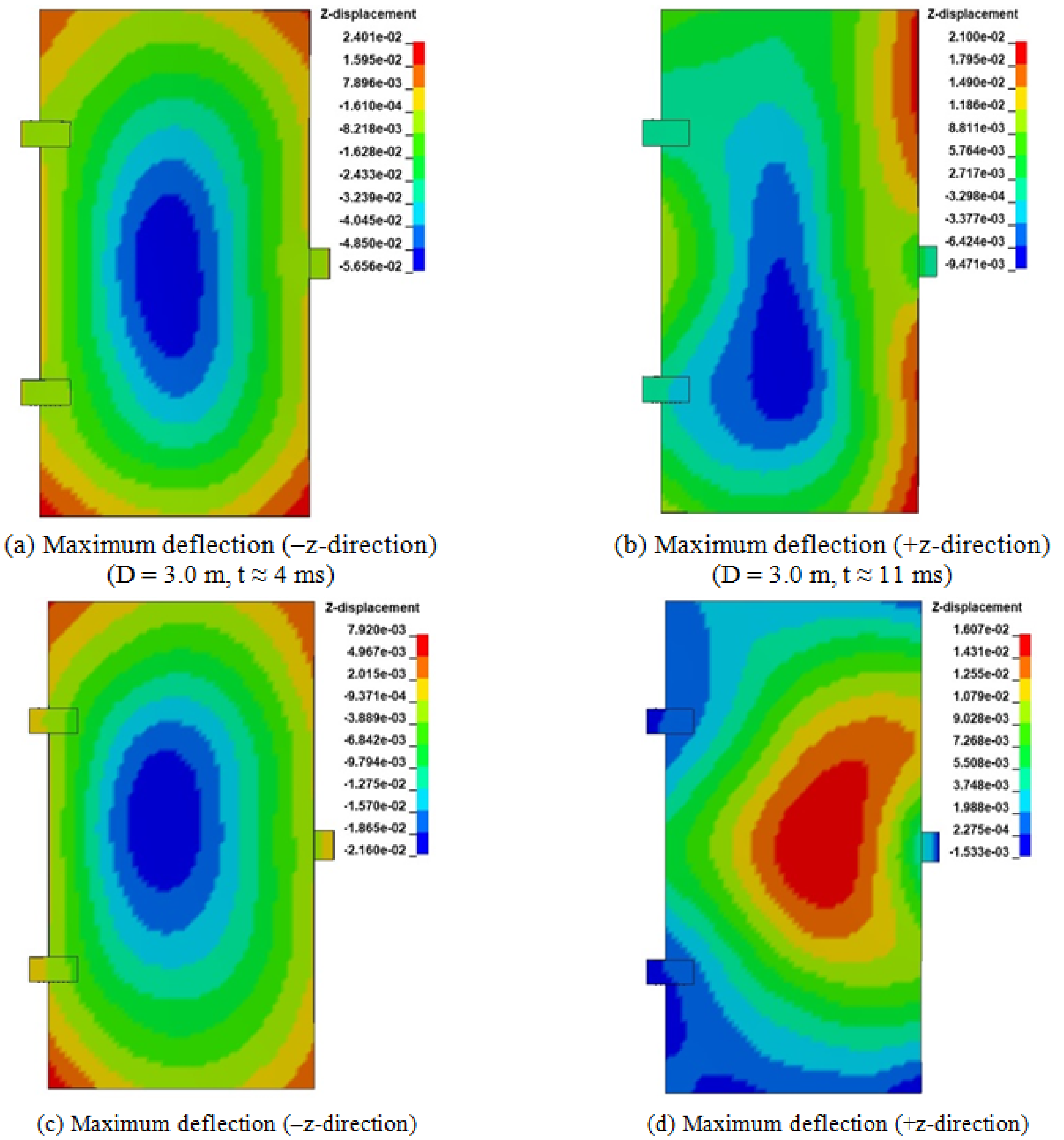
Fig.3: Time hysteresis of deflection at center of blast-resistant door (Case A)

Table 2: Comparison of maximum deflection and permanent deflection per case

Case	Standoff distance (m)	Maximum deflection (mm)		Permanent deflection (mm)	
		Center	Lower edge	Center	Lower edge
A	6.0	-23.1 (1.00)	41.5 (1.00)	-1.0 (1.00)	0.5 (1.00)
	4.5	-34.3 (1.48)	44.3 (1.07)	-8.5 (8.50)	6.5 (13.00)
	3.0	-56.7 (2.45)	67.0 (1.61)	-28.1 (28.10)	20.9 (41.80)
B	6.0	-23.1 (1.00)	21.2 (1.00)	-1.2 (1.00)	1.2 (1.00)
	4.5	-33.8 (1.46)	25.4 (1.20)	-9.4 (7.83)	4.6 (3.83)
	3.0	-55.3 (2.39)	34.4 (1.62)	-28.5 (23.75)	14.9 (12.42)
C	6.0	-24.5 (1.00)	17.3 (1.00)	-1.7 (1.00)	0.5 (1.00)
	4.5	-36.2 (1.48)	21.3 (1.23)	-11.0 (6.47)	3.0 (6.00)
	3.0	-58.8 (2.40)	29.5 (1.71)	-32.2 (18.94)	16.3 (32.60)
D	6.0	-20.1 (1.00)	35.4 (1.00)	-1.7 (1.00)	0.1 (1.00)
	4.5	-30.8 (1.53)	45.9 (1.30)	-7.3 (4.29)	5.4 (54.00)
	3.0	-51.1 (2.54)	73.8 (2.08)	-23.0 (13.53)	24.4 (244.00)

Comparing the size of the maximum deflection developed at the center of the door in each case, case D experienced the smallest deflection. The same comparison for the maximum deflection developed at the edge of the door, the deflection increased by maximum 2.1 times when the standoff distance reduced from 6.0 m to 3.0 m. For the deflection at the corners with respect to the boundary conditions of the support members, case B or case C experienced smaller deflection than case A or case D.

In view of the permanent deflection, case A experienced deflections of 28.1 mm, 8.5 mm, 1.0 mm for the standoff distances of 3.0 m, 4.5 m, 6.0 m, respectively. With reference to the relevant diagram proposed in UFC 3-340-02 [15], the size of the theoretical reflected pressure acting on the door decreased steeply from 34.5 MPa to 11.0 MPa and to 4.8 MPa as much the distance to the explosive increased, which in turn resulted in the reduction of the deflection. For the standoff distance of 6.0 m, only permanent deflection occurred and reached approximately 1.0 mm but, considering the very large deflections observed for the distances of 3.0 m and 4.5 m, it can be assumed that very significant plastic deformation was developed. Fig. 6 provides numerical comparison of the level of plastic deformation developed in the door and its support members according to the standoff distance. It appears that the level of plastic deformation became higher with shorter standoff distance and that the hinge support experienced larger deformation that the door. For the permanent deflection, the edges of the door deflected less than the center of the door. Case D underwent the smallest permanent deflection at the center of the door whereas case B or case C developed smaller deflections at the corners.



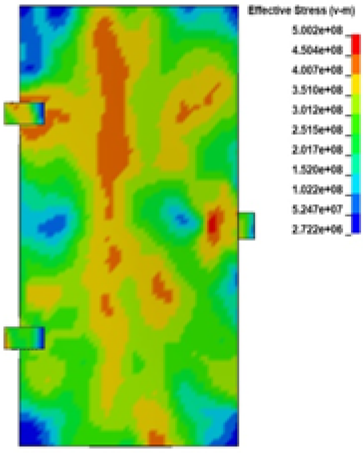
(a) Maximum deflection (–z-direction)
(D = 3.0 m, t ≈ 4 ms)

(b) Maximum deflection (+z-direction)
(D = 3.0 m, t ≈ 11 ms)

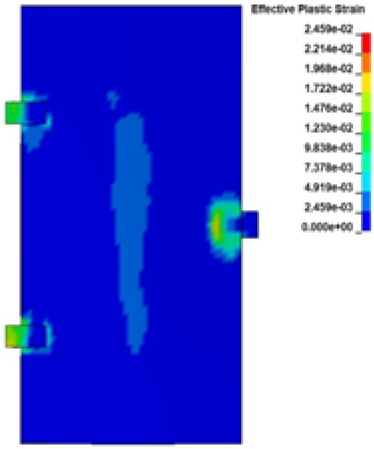
(c) Maximum deflection (–z-direction)
(D = 6.0 m, t ≈ 7 ms)

(d) Maximum deflection (+z-direction)
(D = 6.0 m, t ≈ 13 ms)

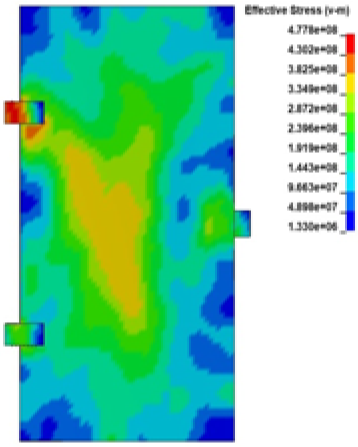
Fig.4: Comparison of deflection pattern (Case A)



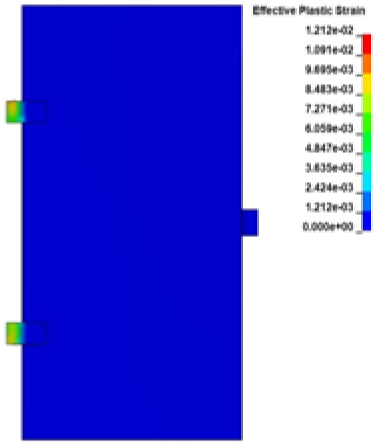
(a) Effective stress at maximum deflection (D = 3.0 m)



(b) Effective plastic strain at maximum deflection (D = 3.0 m)



(c) Effective stress at maximum deflection (D = 6.0 m)



(d) Effective plastic strain at maximum deflection (D = 6.0 m)

Fig.5: Stress and strain distributions (Case A)

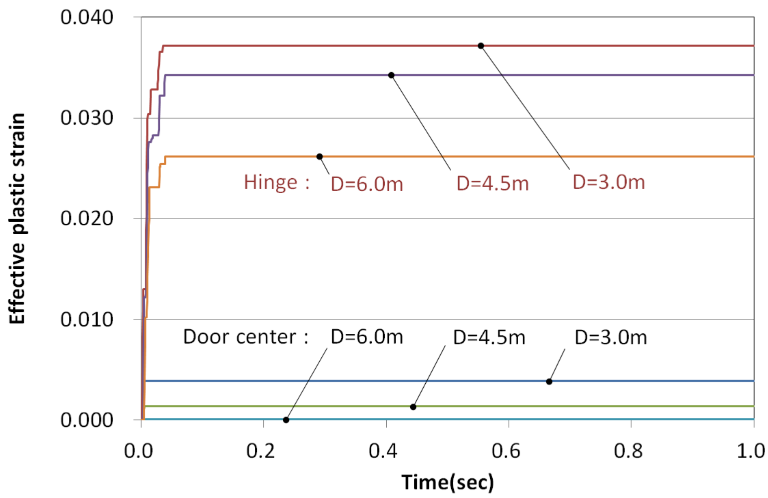
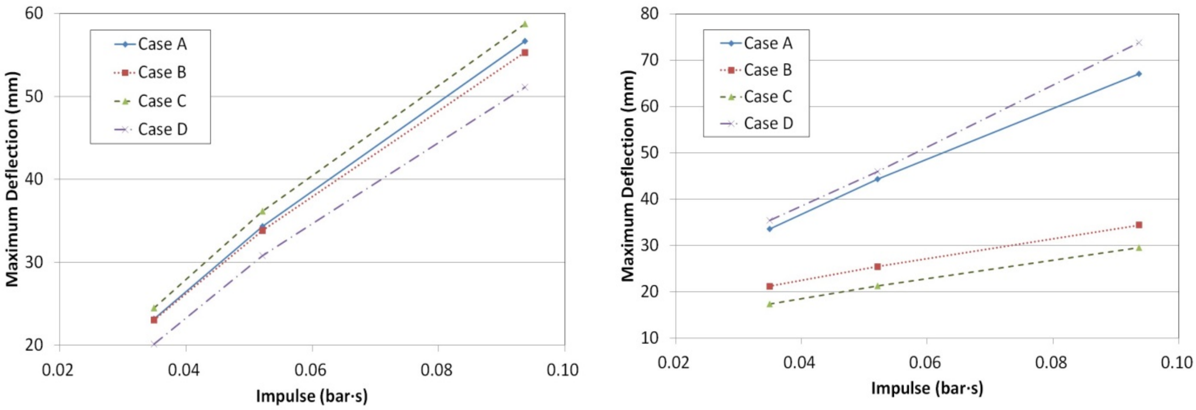


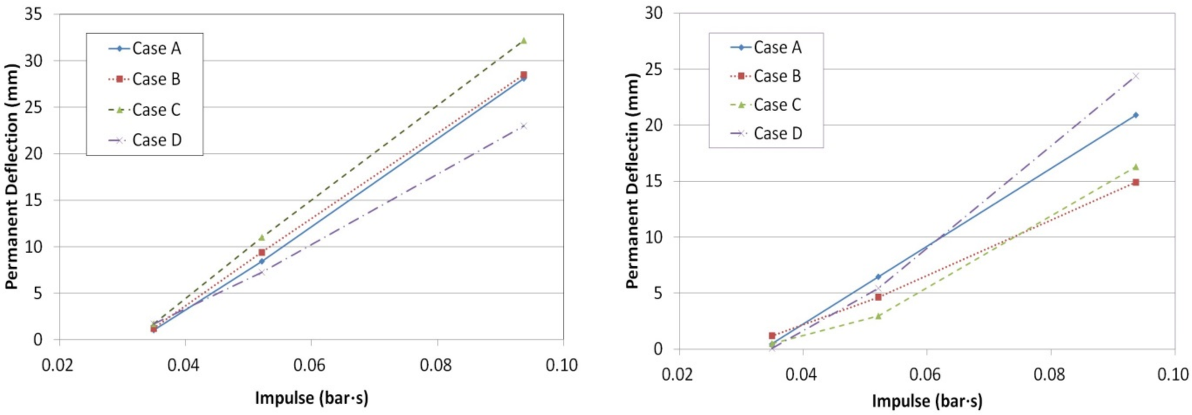
Fig.6: Comparison of effective plastic strain per standoff distance, D (Case A)

Rather than the overall dynamic behavior, the design of the blast-resistant door gives more importance to the damage and the maximum deformation like the maximum deflection or the permanent deflection [16]. In addition, the size of the impulse is the primary factor influencing the deformation and damage of the structure because the explosive releases very large pressure within a very short period of time. Fig. 7 and Fig. 8 compare the relationships between the impulse and maximum deflection and between the impulse and the permanent deflection in the considered cases. In view of the results related to the center of the blast-resistant door, case D requires the largest impulse to generate the same maximum deflection or permanent deflection. In other words, case D experienced the smallest maximum deflection or permanent deflection when subjected to the same impulse. This can be explained by the efficient prevention of the deflection at the center by the hinge installed at mid-height of the door in case D. Besides, case A and case B exhibited similar levels of deflection at the center whereas case C experienced the largest central deflection. Furthermore, the comparison of the results relative to the deflection at the lower edge of the door reveals that case B and case C were more advantageous owing to the presence of the latch at or near the lower edge.



(a) Center of door **(b) Lower edge**

Fig.7: Relationship between impulse and maximum deflection

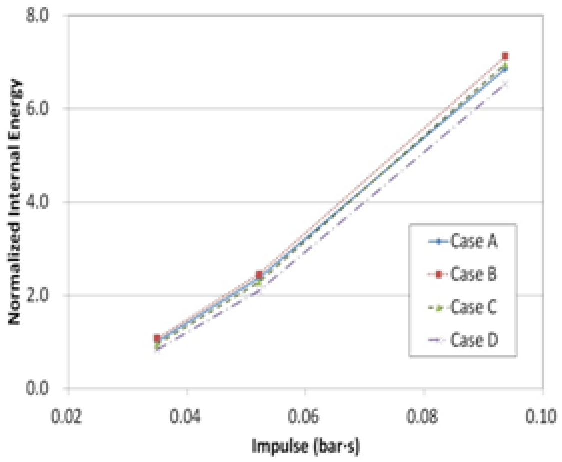


(a) Center of door **(b) Lower edge**

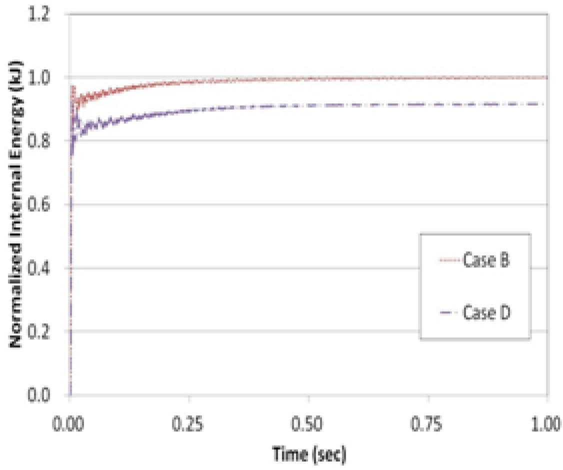
Fig.8: Relationship between impulse and permanent deflection

Fig. 9 compares the internal energy absorbed by the door and the support members as a mean for the comparison of the structural performance developed by the door structure for cases A to D in relation with the boundary conditions given by the standoff distance and supports. Here, the internal energy stands for the strain energy. In view of Figs. 9 (a) and (c), case D with relatively higher constraint level of the door by the support members is seen to develop the largest absorption of the internal energy by the support members. Moreover, case D also presents the lowest internal energy absorption by the door itself. In other words, the relatively largest strain energy absorption is achieved by the support members of case D, which results in smaller deformation of the door itself compared to the other cases. Fig. 9(b) compares the time histories of the internal energy of cases B and D, which showed the largest difference in the internal energy absorbed by the door. It appears that this tendency was already determined at the occurrence time of the maximum deflection. The relatively larger absorption of the strain energy by the supports in case D can be explained as follows. Case D has an additional hinge installed at mid-height of the left edge and, unlike the latch, the hinge has its axial displacement restrained, this means that the door in case D has more restraints than the other cases for which the additional support was a latch. In addition, the position of the additional hinge in case D at the center contributed also in preventing efficiently the deflection.

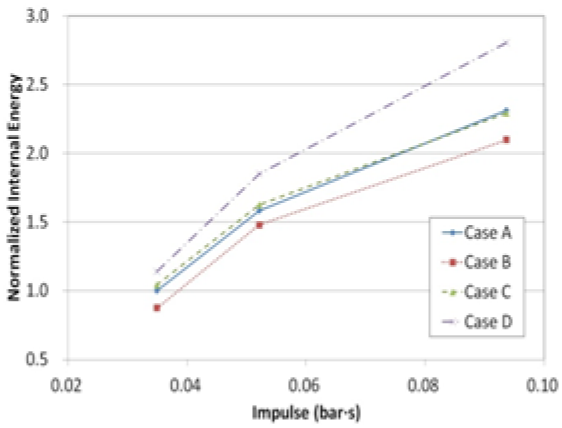
Fig. 9(d) plotting the ratio of the internal energy absorbed by the support member to the internal energy absorbed by the door shows that case D has a larger ratio compared to the other cases. This result is closely related to the contents discussed above. Moreover, another observation is that the increase rate of the strain energy absorbed by the door itself becomes larger than that of the strain energy absorbed by the support as much as the impulse increases due to shorter standoff distance. This means that the door plays a larger structural role than the support when the impulse increases. The present study examined the behavior of the blast-resistant door according to the boundary conditions in terms of the number and position of the supports only but further study shall consider additionally the structural details of the door itself in the analysis.



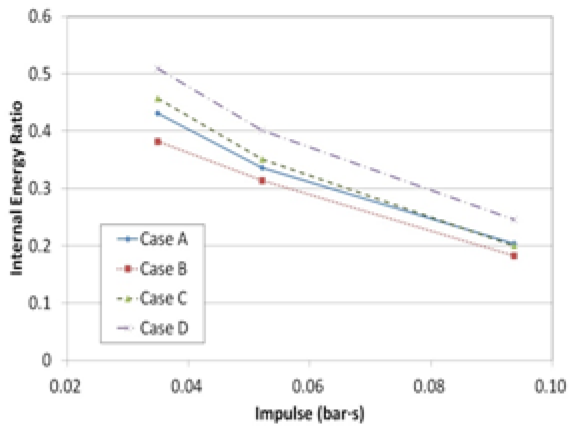
(a) Internal energy absorbed by door



(b) Time histories of internal energy absorbed by door



(c) Internal energy absorbed by support member



(b) Ratio of internal energy absorbed by support member and door

Fig.9: Comparison of internal energy absorbed by blast-resistant door and support member

III. CONCLUSIONS

The rational design of the blast-resistant door structure necessitates to define first the target performance according to the expected blast scenario and then to determine the appropriate structural details. The present study assumed the blast-resistant door as a constant and compared the change in the structural behavior with respect to the distance between the door and the explosive and the support conditions of the door to provide data for the design of the supports of the composite blast-resistant door structure. The analysis revealed that (1) placing a hinge at mid-height of the door was more effective than placing a latch in reducing the deflection at the center of the door and that (2) placing latches at the upper and lower edges of the door or near the corners of the door was appropriate for reducing the deflection developed along the edges of the door. Since each component of the blast-resistant door undergoes different deformation characteristics according to the support condition, the position of each support will act as a critical variable when designing for airtightness for example.

The analytic results also indicated that the resistance-to-deformation of the supports applied as a major factor in the prevention of the deflection of the blast-resistant door. In addition, the analysis of the strain energy showed that the strain energy absorbed by the door itself increased by a larger rate than the support with shorter standoff distance. However, the present study examined the behavior of the blast-resistant door according to the boundary conditions in terms of the number and position of the supports only but further study shall consider additionally the structural details of the door itself in the analysis. Moreover, additional analysis shall also examine whether the front or rear side of the door is more vulnerable to blast in order to address appropriate design.

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