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A Basic Study on Shock Resistant Design for Explosion Pit

Tatsuya Yamamoto[1,a*], Masatoshi Nishi[2,b], Masahide Katayama[3,c] and Kazuyuki Hokamoto[4,d]

[1]Graduate School of Science and Technology, Kumamoto University, 2-39-1 Kurokami, Chuo-ku, Kumamoto 860-8555, Japan

[2]National Institute of Technology, Kumamoto College, 2627, Hirayamashinmachi, Yatsushiro City, Kumamoto 866-8501, Japan

[3]ITOCHU Techno-Solutions Corporation, 3-2-5, Kasumigaseki, Chiyoda-ku, Tokyo 100-6080, Japan

[4]Institute of Pulsed Power Science, Kumamoto University, 2-39-1, Kurokami,Chuo-ku, Kumamoto City, Kumamoto 860-8555, Japan

[a*]168d8555@st.kumamoto-u.ac.jp, [b]nishima@kumamoto-nct.ac.jp, [c]masahide.katayama@ctc-g.co.jp, [d]hokamoto@mech.kumamoto-u.ac.jp

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Abstract. The mechanism of damage on the structure of an explosion pit which belongs to the Institute of Pulsed Power Science, Kumamoto University is investigated. Here, three-dimensional model with square opening (door) is used to simulate by numerical simulation. The numerical result with the actual egg-type model implies that firstly the cracks occurred at the corners of the door and grew larger. In addition, the numerically simulated results with a spherical form model are also demonstrated to study on optimizing the design of an explosion pit.

1. Introduction

There are many researches and applications by using explosive. To assess such experimental safety, the explosive pits are used. Therefore, it is important to study how and where the damage of the explosion pits and some researches on the damage of such explosion pit have been made by Duffey and Romero [1] etc.

For the purpose of obtaining such knowledge especially from the viewpoint of safety design, this investigation was conducted for the explosion pit located at the Institute of Pulsed Power Science (IPPS), Kumamoto University built in 2001. It consists of the reinforced concrete covered with inner steel liner of 25 mm in thickness, and the whole structure of the pit is egg-type form, consisting of hemispherical upper and lower parts and main cylindrical structure in the middle which is welded with the former two parts. After the use of the pit for more than 10 years subjected to high-explosive detonation, some damages on the outer surface of the reinforce concrete were confirmed [2]. The authors conducted numerical simulation with two-dimensional axisymmetric model in the previous research and its simulated result clarified that some damages were caused by the repeated expansion and contraction caused by blast wave at the middle of cylindrical structure, the upper part and the bottom part [2].

Some damages confirmed on the outer concrete were observed as follows : (i) the circumferential direction at the steel wall in the middle of cylindrical structure, (ii) the upper part, (iii) around the door located at the side surface of cylindrical structure. Although the damages (i) and (ii) were also shown by two-dimensional axisymmetric analysis as reported earlier [2], there still remains the cause of the damage (iii) unclear. Therefore, the numerical simulations with three-dimensional model was performed in this study. In addition, the numerically simulated results for a spherical form model which had a same inner volume with the actual egg-type form model are also demonstrated. In comparison with the actual egg-type form pit, the simulated results in this study indicated that a spherical form model had the good resistive characteristics against the impulsive load like explosion for its symmetrical property.

Numerical Simulation

Setup of numerical simulation. In order to investigate the cause of the cracks, the numerical simulations were performed for the case of TNT detonation. The setup for the actual egg-type form model is shown in Fig. 1. A three-dimensional model simplifying the actual structure is used for the numerical simulations. The internal structures in the pit were disregarded, like H-section steel girders, gratings, etc., in the present numerical analysis because they are less affected to cracks on the surface of outer concrete.

The actual egg-type form model and the spherical form model are shown in Fig. 2; they were used for numerical simulation to study on optimizing the design of an explosion pit. Here, two models have the same inner volume and the thicknesses of the thinnest concrete parts in both models are 0.5 m. The bottom of the concrete is constrained to the rigid floor, and the explosive is placed at the geometric center of the internal pit.

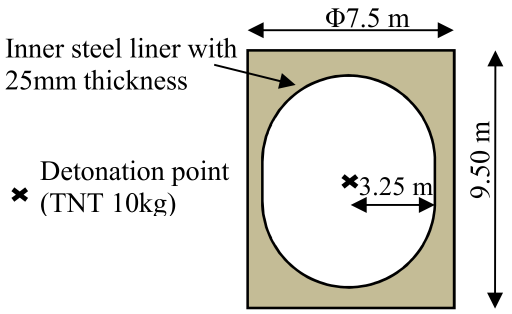


Figure 1 Setup of numerical simulation.

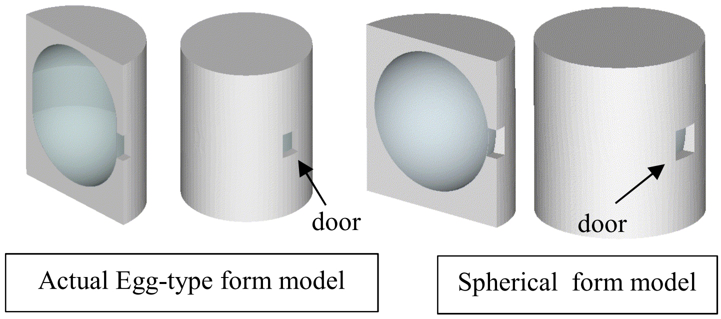


Figure 2 Two models for numerical simulation.

Material modeling. The concrete and the inner steel liner were modeled by Lagrangian elements, air and TNT in the pit were modeled by Eulerian elements. In the simulations, is taken into account the interactions between both Lagrangian vs Lagrangian elements and Lagrangian elements vs Eulerian elements.

The porous equation of state and the Drucker-Prager strength model [3] were used for the concrete. The material of the inner steel liner with 25 mm thickness was assumed to be equivalent to the 4340 STEEL with the Johnson-Cook constitutive law [4]. The Johnson-Cook equation and parameters are as shown in Eq. 1 and Table 1, respectively. Here, Y is yield stress, ε is strain, $\dot{\varepsilon}$ is strain rate and T is temperature.

$$Y = (A + B * \varepsilon^n)(1 + C * \ln\dot{\varepsilon})(1 - T^m) \tag{1}$$

Table 1 Johnson-Cook parameters for STEEL 4340.

Density ρ[kg/m^3]	Shear modulus G_0 [GPa]	A [GPa]	B [GPa]	n	C	m
7830	77.0	0.792	0.51	0.26	0.014	1.03

TNT explosive had an initial density of 1630 kg/m^3 and a detonation speed of 6930 m/s. The JWL equation of state [5] applied for TNT are shown in Eq. 2

$$P = A\left(1 - \frac{\omega\eta}{R_1}\right)\exp\left(-\frac{R_1}{\eta}\right) + B\left(1 - \frac{\omega\eta}{R_2}\right)\exp\left(-\frac{R_2}{\eta}\right) + \omega\eta\rho_0 e \tag{2}$$

where P is pressure, ρ is density, e is specific internal energy, $\eta = \rho / \rho_0$ (ρ_0 is unburned initial density) and JWL parameters of A, B, R_1, R_2, ω are shown in Table 2.

Table 2 JWL parameters for TNT.

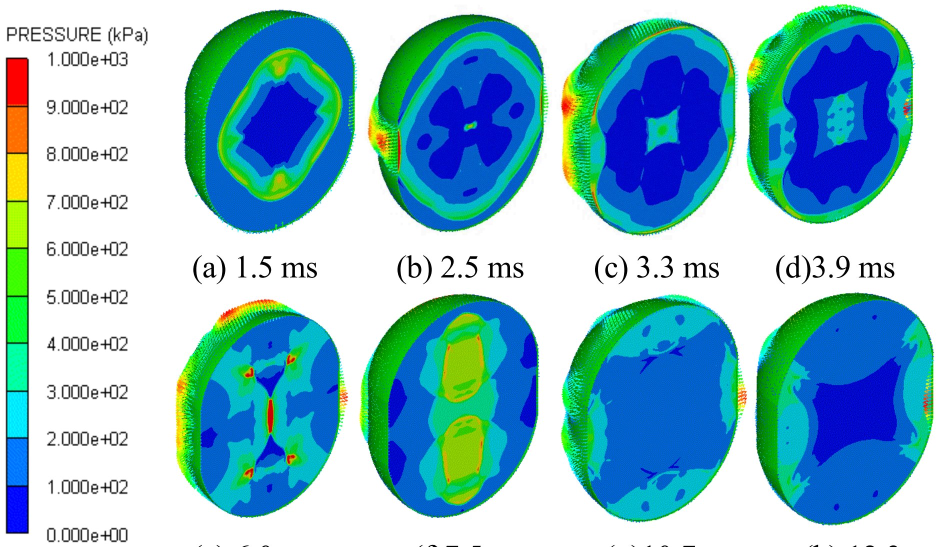
A [GPa]	B [GPa]	R_1	R_2	ω
371.2	3.231	4.15	0.95	0.3

Air is assumed to conform to the ideal gas law with the ratio of specific heat γ of 1.4.

Results and Discussion about the Actual Egg-Type Form Model

Propagation of blast wave and velocity vector of inner steel liner. Figure 3 depicts the sequence of the pressure distributions in the gas region and velocity vector distributions in the inner steel liner. Concrete part is not displayed, but is displayed a square opening area (door) on the right-hand side of the pit.

It can be recognized that the blast wave propagates concentrically as observed in Fig. 3 (a). In Fig. 3 (b), the blast wave impacts on the steel wall in the middle of cylindrical structure, consequently the velocity vectors of the inner wall in the vicinity of the impact surface proceed outward significantly. The blast wave reached the top and bottom of the pit as seen in Fig. 3 (c) around 3 ms. The velocity vector near the door shown in Fig. 3 (d) and (e) reverses direction in alternate shifts, accordingly it can be understood that expansion and contraction of the structure is invited around the door. The similar phenomena with different cycles are also confirmed around the wide range of the inner wall, especially around the top area of the pit where the boundary conditions are free, while those at the bottom of the pit are constrained.

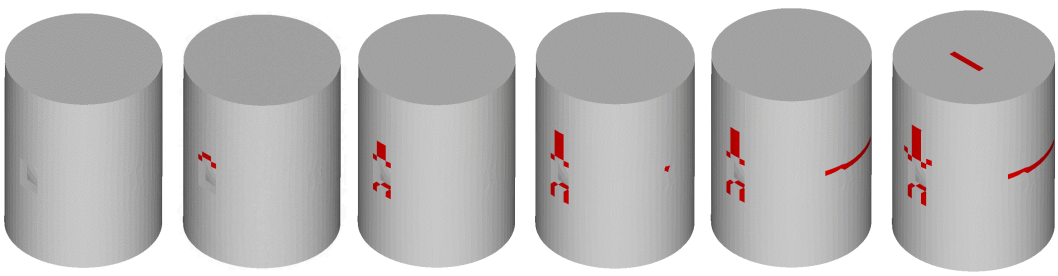


(a) 1.5 ms (b) 2.5 ms (c) 3.3 ms (d)3.9 ms

(e) 6.0 ms (f)7.5 ms (g)10.7 ms (h) 12.3 ms

Figure 3 Propagation process of blast wave and velocity vector of inner wall of egg form model.

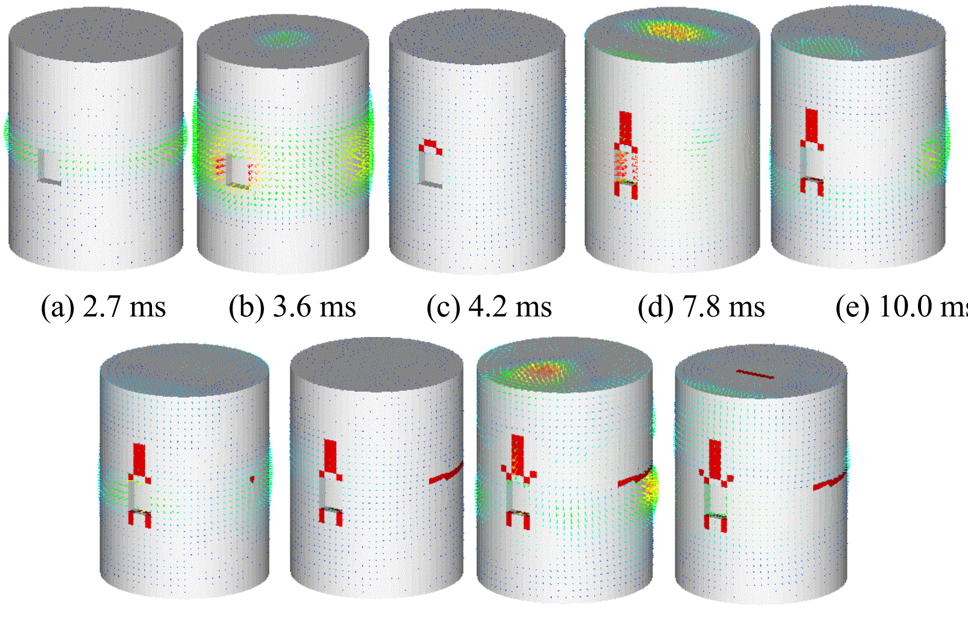
Concrete damage. Figure 4 shows the sequence of the concrete damage profile in the actual egg-type form model, where the door is located on the left-hand side of the pit. Any concrete damage is not observed at 2.4 ms in Fig. 4 (a), although slight elastic deformation can be seen, in spite of the blast wave impact on the inner wall and velocity vector generation in the structure at 2.5 ms in Fig. 3 (b). The plastic deformation in the concrete can be confirmed for the first time over the door at about 4ms as shown in Fig. 4 (b). After that, the plastic damage matures as failure damage, and then the failure damage around the door is gradually spreading as seen in Fig. 4 (c) and (d). The damage in the circumferential direction which is confirmed in Fig. 4 (d) is progressing in Fig. 4 (e). The damage in the upper part can be seen to be generated in Fig.4 (f), too. It should be noted here that those simulated results are substantially the same as the actual location of the damage observed on the inner wall, the upper part and the door, as reported earlier [2].



(a) 2.4 ms (b) 4.2 ms (c) 4.8 ms (d) 10.9 ms (e) 11.4 ms (f) 21.1 ms

Figure 4 Concrete damage about the egg-type form model (Damaged parts are shown by red color).

Velocity vector of concrete. Figure 5 shows the velocity vector and damage distribution of the concrete. The velocity vectors of the door become larger in Fig. 5 (b), and then some damage on the door is generated in Fig. 5 (c). At this time, the velocity vectors reverse their directions inward, although it is not displayed in this figure. The outward-directed velocity vectors at the surface on circumferential direction was comformed in Fig. 5 (b) and 5 (e), after that, the some damage shown in Fig. 5 (f) is generated. The damage on the upper part displayed in Fig. 5 (i) occured due to the repeated expansion and contraction caused by blast wave at the upper part.



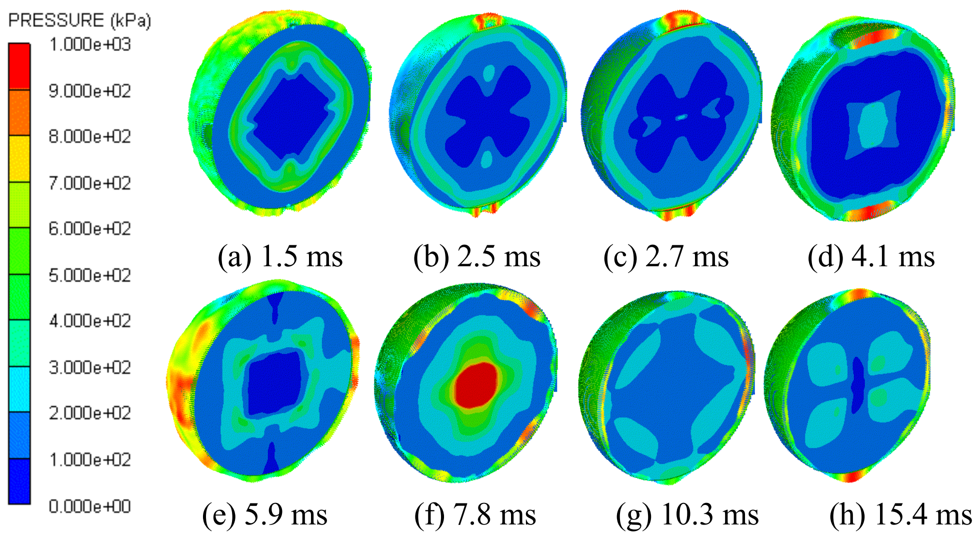
(a) 2.7 ms (b) 3.6 ms (c) 4.2 ms (d) 7.8 ms (e) 10.0 ms

(f) 10.9 ms (g) 13.0 ms (h) 19.2 ms (i) 21.1 ms

Figure 5 Velocity vector and damage of the actual egg-type form model.

Results and Discussion about the Spherical Form Model

Propagation of blast wave and velocity vector of inner steel liner. Figure 6 shows sequence of the blast wave propagation and the velocity vector distribution of the inner wall. As well as the case of the actual egg-type form model, the propagation of the blast wave is spread concentrically as found in Fig. 6 (a) and 6 (b). The blast wave generated by TNT impacted against the upper, bottom and middle area of the steel inner liner and the velocity vector is generated in the outward direction in Fig. 6 (b), 6 (c). The velocity vector reversed direction in Fig. 6 (d), that is, the inner steel liner contracts after expansion. The velocity is generated in the wide range of the inner steel liner in Fig. 6 (e).

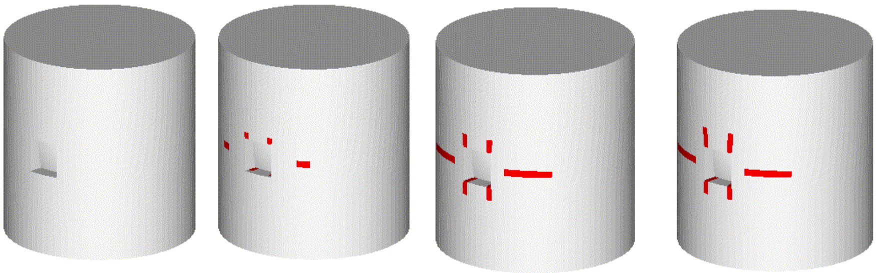


(a) 1.5 ms (b) 2.5 ms (c) 2.7 ms (d) 4.1 ms

(e) 5.9 ms (f) 7.8 ms (g) 10.3 ms (h) 15.4 ms

Figure 6 Propagation of blast wave and velocity vector of inner steel plate.

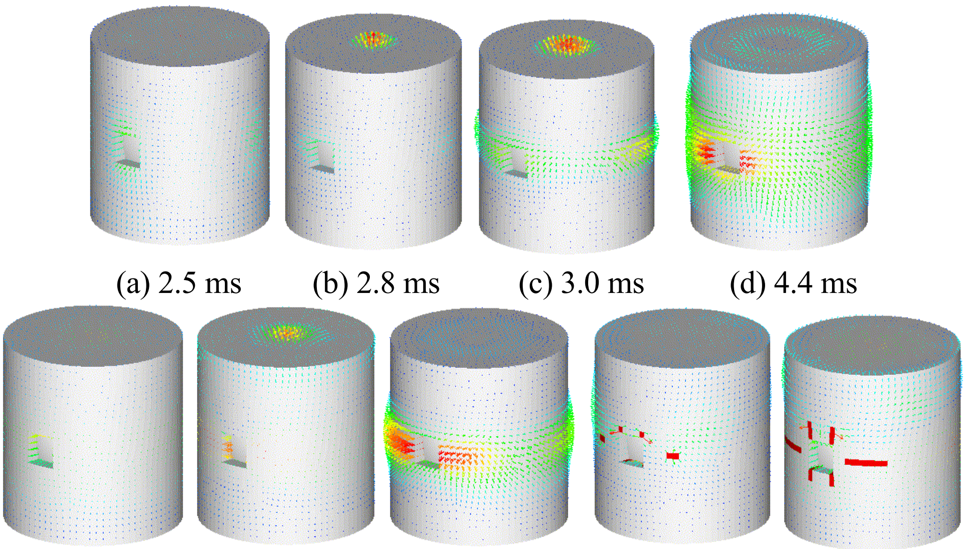
Concrete damage. Figure 7 shows the concrete damage of the spherical form model. In the simulated results of the actual egg-type form model, the concrete damage around the door seems to come up, when the inner wall backs and moves to the internal side as seen in Fig. 3 (d) and Fig. 4 (b). On the other hand, the damage of the spherical form model is not apparently observed in Fig. 7 (a) . The first failure damage of this model may come up at 12.0 ms in Fig. 7 (b), and then the damage of concrete is initiated around the door and propagates in the circumferential direction in the middle of the cylinder. This progressive damage or crack terminates before 12.4 ms as depicted in Fig. 7 (c) and 7 (d). In fact, any additional damages were not estimated after more calculations.



(a) 4.4 ms (b) 12.0 ms (c) 12.4 ms (d) 13.4 ms

Figure 7 Concrete damage to the spherical form model.

Velocity vector of concrete. Figure 8 showed the sequence of the velocity vector and damage distibutions on the external surface of the cylindrical concrete structure. The influence of the blast wave shown in Fig. 6 (b) appeared at the top of the pit with a slight delay as found in Fig. 8 (b) and (c) caused by the inertia of the concrete. The velocity vectors on the middle area of the cylinder are also generated in Fig. 8 (c). The repeated expansion and contraction caused by blast wave was confirmed at the top part and the middle of cylindrical structure in Figures 8, there is no damage at those areas. On the other hand, the larger velocity vectors genelated outward direction around door was confimed in Fig. 8 (d) and (g), after that, the concrete damage are observed in Fig. 8 (h) and (i).



(a) 2.5 ms (b) 2.8 ms (c) 3.0 ms (d) 4.4 ms

(e) 6.2 ms (f) 8.1 ms (g) 10.6 ms (h) 12.0 ms (i) 13.4 ms

Figure 8 Velocity vector and damage of the spherical form model.

Discussion about Two Models

The results obtained by these numerical simulations were listed as follows:

I. The simulated results of the actual egg-type model were substantially the same as the location of damage observed in the pit at the inner wall, the upper part and door.

II. The concrete damage was caused by the repeated expansion and contraction of the inner steel plate.

III. The actual egg-type form model got damages around the door part, the upper part and the circumferential direction. On the other hand, the spherical form model got damage only around the door part.

IV. The reason of result III was that expansion and contraction at the entire inner steel liner at the same time can be reduce the influence of the impact. On the contrary, in the actual egg-type model, the expansion and contraction point on inner steel plate changed the upper parts & inner steel wall in alternate shifts and changing the point caused great damage on pit.

V. There are some damages around the door in both models. Additional reinforcements around the door are required.

Summary

The authors have been studied on optimizing the design of an explosion pit made by reinforced concrete structure covered with a steel liner. Three-dimensional numerical simulations were carried out by using ANSYS AUTODYN against TNT detonation loading in the pit. The numerical simulation with the actual egg-type form model revealed that the expansion and contraction of concrete caused by impulsive pressure result in the damage at the inner wall, top part and square opening (door). The result implies that firstly the cracks were occurred at the corners of the door and were grown larger. The numerical result is in a good agreement with the distribution of the cracks on the pit. In addition, the numerically simulated results for a spherical form model are also demonstrated and it resulted in less concrete damage than the actual egg-type form model.

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