The dynamic response of cylindrical shell and square plate with pre-formed holes under blast loading

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Abstract. The dynamic response of cylindrical shells and square plate with pre-formed holes under blast loading was studied by numerical simulation. The numerical model was calibrated by the experimental data of square plates with pre-formed holes. The dynamic responses and deformation of cylindrical shells with pre-formed holes subjected to blast loading was investigated by the same numerical model. The structure response process has been divided into four specific stages which has been discussed systematically. According to the comparison of structure response process, stress concentration between these two structures under blast loading, it is concluded that the square plates have a better performance than that of cylindrical shell with or without pre-formed holes and the influence of pre-formed holes on blast-resisting of square plate is bigger than that of cylindrical shell. In addition, the global and local deformation characteristics are mainly result from the space configuration and pre-formed holes, respectively.

1. Introduction

For the conventional warhead or the metal container storing flammable explosive gas, fragments and blast loading will be incurred under initiation or accident stimuli. Under the combined action of these two kinds of loading, what the shell structures such as vehicles, airplanes, buildings, cabins of ship and a large number of potentially containers subjected to is not the accumulation of effects of fragments and blast loading separately, but the damage effect of blast loading applied on the perforated structures or on the contrary. According to Forsén [1], the mechanism and the degree of damage of the coupled effect will be more complicated and serious, respectively.

The coupled effect of fragments and blast loading has been studied in some structures by experiments and numerical simulations. He et al. [2] carried out a blast experiment to study the coupled effect of protective door under the combined loading of fragments and blast wave. Nyström et al [3] investigated the combined effects of blast and fragment loading on the reinforced concrete wall through numerical simulation method. The damage effect of the wall subjected to blast loading, fragment loading, and combined blast and fragment loading were compared, which indicates that the coupled effect has a larger damage than others. Zhang [4] et al investigated the deformation failure modes and damage mechanisms of sandwich plates with core of steel-GFRP-steel under blast waves with high-velocity fragments and found that the damage degree under the combined action of these two loadings is much higher than that under blast waves only.

Because of the complexity on the response process and mechanism of the combined action, it is difficult to control the influent factors in experiment. Considering the fragments arriving the structures
earlier than blast loading at relatively farther distance [5-6] in according to the attenuation rules of blast wave and fragments velocity in air, the approach of structures with pre-formed holes under blast loading is widely adopted to decoupled the complex coupled effect. Con plastic hinge formation and extensional effects, Schleyer [7] applied an energy approach to solve the large deformation problem of square plates with either square or circular holes under transverse pulse pressure loading and conducted experiments to validate this approach. Assuming that the fragments perforate the square plates before the pressure load arrives, Rakvåg [8] carried out experiments that plates with pre-formed holes are subjected to controlled pressure pulses and analyzed deformation modes. In addition, the difference of deformation around the pre-formed holes between standard Lagrangian and Fully coupled FSI simulations is discussed. Hou et al [9-10] studies the deformation rules with change of the number and diameter of holes and proposed a formula to calculate the midpoint deformation of plate with holes.

In order to obtain the deformation mechanism of cylindrical shells under the influence of pre-formed holes, the present research is concerned with the distribution of stress concentration, local and global deformation generated on cylindrical shells and square plates with pre-formed holes under blast loading, representing an extension of the previous works on the perforated structures. The commercial software Ls-Dyna 971 was applied to investigate the dynamic responses and deformation of cylindrical shells with pre-formed holes under blast loading. To calibrate the accuracy of the numerical model, the numerical results of a series of square plates with pre-formed holes were compared with the experimental results recorded by Li et al [11]. The calibrated models were then employed to perform the simulations of the cylindrical shells with pre-formed holes. The comparison of structure response process, stress concentration between cylindrical shell and square plate with pre-formed circular holes under blast loading have been discussed in this study. In addition, the stages of stress concentration are classified and the deformation mechanism are analyzed. Details are presented in the following sections.

2. Numerical model calibrations
To validate the accuracy and reliability of the numerical model in the study reported in this paper, a square plate with pre-formed circular holes tested by Li et al [11] was used to calibrate the model. A total of nine explosion tests were conducted in the experiments, three of them were related to circular holes under different charges of 550g, 650g and 750g, respectively. The same structural parameters were adopted in these three tests including a square plate with the length of 1000mm and the thicknesses of 4mm, the core loading area of 600mm×600mm, nine holes with the diameter of 80mm and the distance of 150mm between centers of two adjacent holes. Selected test data were used to calibrate the numerical model established in this study.

2.1. Element, mesh, boundary conditions and contact modeling
A quarter of the plates and frames were modeled, as shown Figure. The numerical models have been established by the commercial software Ansys 17.0. A feature element size of 5mm was selected to be optimal for the square and solid elements, which balanced the numerical element sensitivity requirement and the computational efficiency. The square plate with pre-formed circular holes was modeled by shell elements [12] , while the supporting frame and the cover plate were modeled by solid elements.
To simulate the action of bolts used in the experiments to fix the square plate, the nodal constraints were used as boundary conditions at positions of bolts in the square plate, the supporting frame and the cover plate.

The *CONTACT_AUTOMATIC_SINGLE_SURFACE model was adopted to prevent the penetration between the square plate, the supporting frame and the cover plate.

2.2. Material model

According to the experiments of Li et al [11], Q345 steel was adopted as material of square plates. With quite well describing of the hardening effect, strain rate effect and temperature softening effect of metallic materials [13], the Johnson-Cook strength model of Ls-Dyna 971 named *MAT_JOHNSON_COOK was used to represent the mechanical behavior of Q345 and to model the dynamic response of square plate with pre-formed circular holes under blast loading. The model is expressed as equation (1):

$$
\sigma_E = \left( A + B (\varepsilon_E)^n \right) \left[ 1 + C \ln \left( \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right) \right] \left[ 1 - \left( \frac{T - T_r}{T_m - T_r} \right)^m \right]
$$

(1)

where A, B, C, n and m are the constants of the material and are given in Table 1, $\sigma_E$ is the equivalent stress, $\varepsilon_E$ is the effective plastic strain, $\dot{\varepsilon}$ is the strain rate, $\dot{\varepsilon}_0$ is the reference strain rate in quasi-static experiment, T is the current temperament, $T_r$ is the room temperature and the $T_m$ is the melting temperature of the material.

The keyword *EOS_GRUNEISEN was adopted as the equation of state of Q345 steel and the pressure for compressed materials as equation (2):

$$
P = \rho_0 C^2 \mu \left[ 1 + \left( 1 - \frac{\gamma_0}{2} \right) \mu - \frac{\mu^2}{2} \right] \left[ 1 - \left( S_1 - 1 \right) \mu - S_2 \frac{\mu^2}{\mu + 1} - S_3 \frac{\mu^3}{(\mu + 1)^2} \right] + (\gamma_0 + a \mu) E
$$

(2)

| A (MPa) | B (MPa) | n    | C   | m   | $T_m$ (K) | $D_1$ | $D_2$ | $D_3$ | $D_4$ | $D_5$ |
|---------|---------|------|-----|-----|-----------|-------|-------|-------|-------|-------|
| 356     | 760     | 0.62 | 0.056 | 0.94 | 1798      | 0.296 | 1.184 | -1.465 | 0.005 | 8.07  |
where \( C \) is the intercept of the \( v_s-v_p \) curve; \( S_1, S_2 \) and \( S_3 \) are the coefficients of the slope of the \( v_s-v_p \) curve; \( \gamma_0 \) is the Gruneisen gamma; \( a \) is the first order volume correction to \( \gamma_0 \) and \( \mu = \rho / \rho_0 -1 \).

### 2.3. Blast load modeling

In this study, blast loading was generated by the CONWEP(Conventional Weapons Effects Program) empirical model in Ls-Dyna 971, which is a quite accurate method to load air-blast free-field blast wave. The pressure can be calculated by equation (3):

\[
P_{\text{load}} = P_{\text{reflected}} \cdot \cos^2 \theta + P_{\text{incident}} \cdot (1 + \cos^2 \theta - 2 \cos \theta)
\]

where \( \theta \) is the angle of incidence; \( P_{\text{incident}} \) is the incident pressure; \( P_{\text{reflected}} \) is the reflected pressure.

According to the experiments of Li et al [11], the mass of charge are 550g, 650g and 750g with the standoff distance 250mm, respectively.

### 2.4. Result and discussions

![Figure 3](image_url)

**Figure 3.** Comparison of permanent displacement of max-deformation point between the experimental data and the numerical results.

In order to validate the agreement between the numerical results and experimental data reported [11] of the square plate with pre-formed circular holes under blast loading, the permanent displacements of max-deformation point are compared for three cases with different weight charge (550g, 650g and 750g) with the standoff distance 250mm. As shown in figure 3, the numerical results of permanent displacement of max-deformation point agree with the experimental data of that and the maximum errors were all less than 5%.

The comparison above indicates that the numerical model established in this study gives reliable predictions of square plates with pre-formed circular holes under blast loads and can be applied in subsequent calculation and analysis.

### 3. Numerical simulation

The calibrated numerical model above was adopted to carry out the simulation of dynamic response and damage of cylindrical shell with pre-formed circular holes under external blast load. The response and damage quantities such as the permanent displacement, the displacement of the center locus and 1/4 locus as shown in Fig, the degree of damage and the coefficient of stress concentration around the pre-formed circular holes and plastic energy were analyzed and compared with that of the square plate with pre-formed circular holes to examine the capacities of blast-resistance.

In this study, the comparison is further performed by considering the deformation curves of the plate center locus and 1/4 locus which is shown in figure 4.
3.1. The configurations of cylindrical shell with pre-formed circular holes

In order to compare the capacities of blast-resistance between cylindrical shell and square plate with pre-formed circular holes, keeping the same size of holes, the number of holes, the hole-spacing, the loading area and the thickness of shell/plate, the equivalent cylindrical shell with pre-formed circular holes were considered in this study. The schematic diagram of equivalent structure were shown in figure 5.

3.2. Modeling

The 750g TNT charge was ignited with the standoff distance 250mm above the cylindrical shell as shown in figure 6. Blast load was modeled by adopting the CONWEP empirical model implemented in Ls-Dyna. The cylindrical shell with pre-formed circular was modeled with Belyschko-Tasy four-node shell elements of 5mm size, while the supporting frame and the cover plate were modeled by eight-node solid elements of 5mm size. The material properties, type of elements, mesh method, blast load modeling, boundary conditions and contact modeling are same as the calibration simulation.
4. Numerical simulation

The simulation results presented and discussed about the comparison between cylindrical shell and square plate with pre-formed circular holes in two sections include: the structure response process and the deformation mechanism; and the deformation curves. These were individually described in Section 4.1-4.2.

4.1. The structure response process and the deformation mechanism

Figure 7 show the structure response process and stress field of square plate and cylindrical shell with pre-formed circular holes under blast loading. The operating condition of them in the simulation were that 750g TNT charge and 250mm standoff distance above. According to the characteristic of the structural response of cylindrical shell with pre-formed circular holes, the process is divided into four specific stages, that is, First stage-In control of circumferential tensile stress field; Second stage-The transition of tensile stress field; Third stage-In control of axial tensile stress field; Fourth stage-Becoming uniform stress field.
4.1.1. First stage (60μs-150μs). 750g TNT charge is ignited at t=0μs. Because of the same standoff distance, the blast loading begins to interact with the square plate and cylindrical shell on material around the center hole at the same time t=60μs. As shown at t=110μs, before the blast loading arriving at the cover plate, the stress-zones generated by the blast loading occur on the square plate with a circular shape while on the cylindrical shell with a shape similar to rectangle, which is due to the difference of cylindrical shell between axial and circumferential direction. As shown at t=150μs, with the blast loading acting on these two structures progressively after arriving at the cover plate, the stress-zone on the square plate is represented as a shape similar to rectangle surrounding all holes exactly, at the same time, the zones reflected stress appear near the cover plate. There is a significant stress concentration zone around the center hole. For cylindrical shell, there are two stress concentration bands along circumferential direction between the rows of holes, the circumferential tensile stress field is generated and broken off by holes.

4.1.2. Second stage (150μs-290μs). From t=150μs to t=210μs, the stress concentration zone of square plate is changing to the region between the center hole and the outer holes. However, with the deforming downwards, the intensity of the axial tensile stress field increases much quicker and the global tensile stress filed comes into the stage of transition. Accordingly, the stress concentration zones of cylindrical shell are distributed between holes and between holes and the cover plate along axial direction, at the same time, stress on the region of non-holes along axial direction begins to dissipate, as shown at t=210μs. As a result, there are three stress concentration bands along axial direction and broken by holes. As demonstrated at t=290μs, the stress concentration zones of square plate change to the nine regions around nine hole, respectively. However, with cylindrical shell deforming downwards progressively, the circumferential tensile stress field is being translating to the axial tensile stress field, consequently, the middle stress concentration band along axial direction is becoming to extent along circumferential direction until intersecting with the other two stress concentration bands along axial direction.

4.1.3. Third stage (290μs-840μs). From t=290μs to t=840μs, a global sunken deformation with a circular shape tending to square shape is generated for the square plate, while that with an elliptical shape tending to square shape is generated for the cylindrical shell. This is an interesting trend because of the existence of pre-formed holes. As shown at t=840μs, the stress concentration zone of square plate is located at the region between the adjacent holes and the intensity of the stress concentration zone between outer holes is bigger relatively. The stress concentration zone of cylindrical shell is only located between holes along circumferential direction, which indicates that this stage has been in control of axial tensile stress field.

4.1.4. Third stage (290μs-840μs). From t=840μs to t=1600μs, with the global sunken deformation increasing rapidly, the intensity of stress concentration is dissipating due to the energy of blast loading translating to the energy of plastic deformation. The stress concentration zone is only around the hole in a small range at t=1600μs and disappears completely at t=4000μs, which indicates that this stage has been in control of uniform stress field.

4.2. The comparison of deformation curves between cylindrical shell and square plate with pre-formed circular holes

A typical displacement time histories at the max-deformation point of the square plate and cylindrical shell are given in Fig 8. The permanent and peak displacement of the cylindrical shell is 119.76% and 120.65% more than that of the square plate, which indicates that the reduction of blast-resistant capability resulting from pre-formed holes for the cylindrical shell is more than that for the square plate. This is caused by being in control of single direction tensile stress field for the cylindrical shell, while all direction tensile stress field for the square plate, as described at the section 4.1.
Figure 9 shows the permanent local deformation at the center locus and 1/4 locus of the square plate and cylindrical shell. As shown in figure 9 for the center zone of these two structures, the maximum and minimum local deformation at the center locus are belong to cylindrical shell along axial direction and square plate, respectively, however, that at the 1/4 locus are belong to cylindrical shell along circumferential direction and square plate, respectively. For the zone near the cover plate, the maximum and minimum local deformation at the center locus or at the 1/4 locus are belong to cylindrical shell along axial direction and cylindrical shell along circumferential direction, respectively. This phenomenon of local deformation indicates that the local deformation of cylindrical shell is bigger than that of square plate for a majority of zones besides the zone along the axial direction near the cover plate.

Comparing figure 9(a) and figure 9(b), the deformation of square plate at the center locus is bigger than that at the 1/4 locus, which indicates that a local sunken with an approximate spherical surface has been generated and the center hole keeps a circular shape. In addition, the deformation of cylindrical shell along axial direction at the center locus is bigger than that at the 1/4 locus, however, there is almost no difference between the deformation of cylindrical shell along circumferential direction at the center locus and the 1/4 locus, which indicates that the shape of the center hole is similar to a space shape of saddle.
In order to explore the reason leading to the phenomena above, the existence of pre-formed holes and the different configuration of cylindrical shell between the axial direction and the circumferential direction are presented in this study as two viewpoints. The same configuration, parameters, blast loading, boundary and mesh method as figure 1 and figure 9 but without the pre-formed holes are adopted as the control experiment performed by the method of numerical simulation. The local deformation between the square plate and cylindrical shell with pre-formed holes is shown in figure 14, which has the same phenomena as the cylindrical shell and square plate with pre-formed holes and indicates that the different configuration of cylindrical shell between the axial direction and the circumferential direction is key leading to the phenomena mentioned above and the existence of pre-formed holes just has an effect to increase the global and local deformation. Besides, the comparison of the phenomena between figure 13 and figure 14 also indicates the smoothness of space surface of cylindrical shell and square plate after permanent deformation, otherwise the shape of wave would appear on them. Comparing the figure 13(a) and figure 14(a), there is an interesting phenomenon that the shape of the curve between the center hole and the adjacent holes at the center locus along axial or circumferential direction is raised towards the source of TNT charge for cylindrical shell with pre-formed holes, however this phenomenon is not existent for cylindrical shell without preformed holes and for square with or without preformed holes, which may result from the combination of the local effect of pre-formed holes and the different configuration of cylindrical shell between the axial direction and the circumferential direction. In addition, the peak deformation of cylindrical shell and square plate with pre-formed holes are 70.5mm and 58.7mm, while that without pre-formed holes are 61.9mm and 47.8mm, which indicates that the square plates have a better performance than that of cylindrical shell with or without pre-formed holes and the influence of pre-formed holes on blast-resisting of square plate is bigger than that of cylindrical shell.

![Figure 10](image.png)

**Figure 10.** The local deformation between the square plate and cylindrical shell without pre-formed holes.

5. Conclusion

This study presents the deformation mechanism of cylindrical shells under the influence of pre-formed holes under blast loading by employing a numerical model validated. The structure response process has been divided into four specific stages and has been discussed systematically. The structure response process, stress concentration between cylindrical shell and square plate with pre-formed circular holes under blast loading are obtained and analyzed, it is concluded that the square plates have a better performance than that of cylindrical shell with or without pre-formed holes and the influence of pre-formed holes on blast-resisting of square plate is bigger than that of cylindrical shell. In addition, the global and local deformation characteristics are obtained in this study, which indicates that the space configuration and pre-formed holes are the dominant factors.
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