Dynamic response of fiber-composite-reinforced shell structure subjected to internal blast loading

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Abstract. In this study, we report the analysis of a dynamic response process of a fiber-composite-reinforced shell when subjected to internal blast loading of different TNT equivalent by using a three-dimensional digital image correlation method. And it was compared with the dynamic response of the metal shell with the same TNT equivalent and the same surface density. We received the relationship between dynamic deformations and the sizes of the two shells under different TNT equivalence. Through comparison of the results, it was shown that the response process of the fiber-composite-reinforced shell was much more complex than that of the metal shell. Our experimental results suggest that the shock wave intensity, the material mechanical properties and the structure symmetry had important influences at different stages of the structural dynamic response. Fiber composites with high strength restricted the structural deformation extent and deformation rate. In addition, the interaction between fiber composite and metal liner reduced the probability of structural damage caused by the energy concentration. This work provides important insights for the design of cylindrical explosion vessels.

1. Introduction

An explosion vessel can not only effectively limit the action sphere of the shock wave, but also seal in the harmful gases produced by an explosion, providing security for surrounding environments, personnel and equipment. Therefore, explosion vessels are widely used in detonation, explosion processing, explosion synthesis and weapon destruction [1,2]. Traditional explosion vessels are mainly made of metals with good malleability and high strength. Because of developments in the defense industry, the working pressure of explosion vessels needs to be improved. However, the strength of metal is low, and only by increasing the thickness of the vessel can the explosion vessel satisfy the required high work pressure, which will increase manufacturing difficulty and bring more processing defects [3]. To overcome the shortage of an acceptable metal explosion vessel, Fedorenko et al. used a lightweight, high-strength fiber-composite-reinforced metal shell (FCRS) instead of a metal shell (MS) to make an explosion vessel [4–6]. They regarded a fiber-composite-reinforced cylindrical shell as a simplified cylindrical explosion vessel, obtaining valuable research results. For example, the FCRS structure was insensitive to internal defects and micro cracks of material, with higher carrying capacity and less influence from size effects. Syrunin et al. studied how different winding modes of the fiber composite affected the structural antiknock ability [7,8]. The result indicated that the antiknock performance was best when the fiber composite was an interlaced helical winding combined with hoop...
winding with a thickness ratio of 1:1. The angle between the helical winding direction and the axis was , while the angle between the hoop winding direction and the axis was 90°. Kim et al. used a probability analysis method to describe the effect of mechanical properties of fiber composites on structural failure under internal explosion pressure [9]. Clayton et al. used an analytical method to calculate analytical values of metal liner surface strain of the FCRS under an internal explosion. The results were in good agreement with the experimental results [10]. Dong et al. made a comparison of antiknock ability between carbon-fiber-reinforced shell and glass-fiber-reinforced shell, and analyzed structural destruction forms resulting from different fiber styles [11–13]. The above researches mostly focused on the characteristics of the deformation and failure of FCRS subjected to internal explosion. However, little research has been done into the dynamic response process. In this paper, we studied the response processes of FCRS and MS subjected to internal explosions, with the same surface density, then made a comparison between them.

2. Experimental procedure
The three-dimensional (3-D) digital image correlation method is a method using two cameras to form a binocular observation system, like the human eyes system. The 3-D information on the surface of the object can be obtained by analyzing the parallax of the same image point from different images [14–17]. O-xyz, O-x1y1z1, and O-x2y2z2 are global coordinate systems on the surface of the object and the coordinate systems of high-speed cameras 1 and 2, respectively. The measuring point P(x, y) on the surface of the object is imaged on points P1(x1, y1) and P2(x2, y2) in the local coordinate systems of the two high-speed cameras. The intersection of the extension of O1P1 and O2P2 determines the coordinates of point P. Calibrations of the high-speed cameras were needed before the experiments by placing a calibration plate on the surface of the object. A series of pairs of images taken by the two cameras can determine the space coordinates of the camera. A cylindrical charge was used in the experiments. The explosive was put at the geometric center of the shell. Table 1 shows the geometry size of different equivalent explosives. The experimental principle and testing arrangement are shown in figure 1. To ensure synchronous image acquisition of the two high-speed cameras, a probe was used to trigger the cameras. Before the explosion, the probe was in an open circuit. When exploded, the circuit was connected by the charged particles. The electric current triggered the two cameras, which started to collect images at the same time. The shooting speed of the high-speed cameras was set to 100000 frames per second, and the speckle area of the shell was 200 × 150 (mm²). In the global coordinate system, the speckle coordinates and the displacement component were (x, y, z) and (u, v, w), respectively. Strain information was obtained by differentially computing the displacement, which can be expressed as [18,19].

\[
\begin{align*}
\varepsilon_x &= \frac{\partial u}{\partial x} + \frac{1}{2} \left[ \left( \frac{\partial u}{\partial x} \right)^2 + \left( \frac{\partial v}{\partial x} \right)^2 + \left( \frac{\partial w}{\partial x} \right)^2 \right] \\
\varepsilon_y &= \frac{\partial v}{\partial y} + \frac{1}{2} \left[ \left( \frac{\partial u}{\partial y} \right)^2 + \left( \frac{\partial v}{\partial y} \right)^2 + \left( \frac{\partial w}{\partial y} \right)^2 \right] \\
\varepsilon_z &= \frac{1}{2} \left( \frac{\partial u}{\partial z} + \frac{\partial v}{\partial z} + \frac{\partial w}{\partial z} \right) + \frac{1}{2} \left[ \left( \frac{\partial u}{\partial z} \right)^2 + \left( \frac{\partial v}{\partial z} \right)^2 + \left( \frac{\partial w}{\partial z} \right)^2 \right]
\end{align*}
\]

Table 1. Geometry size of different equivalent explosive.

| The mass of TNT (g) | The size of TNT (D × L mm) |
|---------------------|----------------------------|
| 20                  | 25 × 25                    |
| 30                  | 30 × 26                    |
| 60                  | 35 × 38                    |
| 80                  | 40 × 40                    |
The composite contained glass fiber and epoxy resin. The fiber composite wound on the metal liner and constituted FCMS. The winding mode of fiber and the winding angle along the thickness direction were shown in figure 2. The surface density of FCRS was the same as that of MS. Stainless steel was used for two shells. The geometrical dimensions of the shells are in table 2.

3. The structure dynamic response

| Shell type               | Length (mm) | Inner diameter(mm) | Thickness(mm) | Mass (Kg) |
|--------------------------|-------------|--------------------|---------------|-----------|
| MS                       | 500         | 210                | 3             | 7.73      |
| FRCS(composite + inner)  | 500         | 210                | 1.5+12        | 7.83      |
3.1. Dynamic deformation of the two shells under different TNT equivalent

Figure 3a shows the surface speckle area of the shell. The scale in figure 3a is a generatrix on the surface of the cylindrical shell. Point A, which is the midpoint of the generatrix, is chosen as the origin. Then, from the origin, every 5 mm along the generatrix one point is chosen as the monitoring point, which is used to reflect dynamic responses at different locations on the outer surface. Point A is the main monitoring point. The hoop strain–time curves of midpoint A on the two shells are shown in figure 3. Under the action of the shock wave produced by an explosion, the MS showed obvious plastic deformation. However, the deformation of FCRS is still in the elastic range. Under the same explosion loading, the maximum deformation of FCRS is lower than the maximum deformation of MS. The relationship between hoop deformations of the shells and the mass of TNT was fitted. The results are shown in figure 3d and the relationship formulas as follows.

\[
\begin{align*}
    y_{MS} &= 5807.55 \cdot l \cdot z^{4.295} \\
    y_{FCRS} &= -77685 \cdot l \cdot z + 48843 \\
    (l &= \frac{h}{r}, z = \frac{r}{w^{\frac{5}{3}}})
\end{align*}
\]  

Among these: \(y_{MS}\) and \(y_{FCRS}\) are the maximum hoop deformation of MS and FCRS, respectively. \(r\) is the inner radius of the shell. \(h\) is the thickness of shell. \(z\) is the proportion distance. \(w\) is the mass of the TNT.

\[\text{Figure 3. Deformation of MS and FCRS.}\]

(a) The coordinates of monitoring points. (b) Hoop strain–time curve of MS. (c) Hoop strain–time curve of FCRS. (d) Data fitting for the largest hoop deformation of MS and FCRS.

The maximal displacements of monitoring points at different positions on the two shells with different TNT equivalent during and after the load process are shown in shown in figure 4a and figure 4b. The final deformation of the two shells with different TNT equivalent is shown in figure 4c. It can be seen that under the same explosion loading, the maximum deformation and final deformation of FCRS are lower than that of MS.
Figure 4. Plastic deformation of MS and FCRS after TNT explosion. (a) The maximum deformation and final deformation of MS. (b) The maximum deformation and final deformation of FCRS. (c) The final deformations of the two shells.

Figure 5 shows the radial velocity–time curve of the midpoint A. Under the action of the four kinds of TNT equivalent explosions, the maximum radial expansion speeds of MS are 21.72 m/s, 38.05 m/s, 71.60 m/s, and 103.37 m/s. Conversely, the maximum radial expansion speeds of FCRS are 10.98 m/s, 17.46 m/s, 36.40 m/s, and 50.12 m/s. After 400 μs, the vibration of the MS almost attenuated to zero. FCRS experienced two stages in its deformation, rapid expansion and rapid contraction. The radial vibration duration of FCRS is longer than MS. The compare result of the loading rates of the two shells (radial velocity/shell inner diameter) show that, the deformation rate of MS is almost twice that of FCRS under the same TNT equivalent. As stainless steel is a kind of strain rate reinforced material [20], the effect of deformation rate on strength of stainless steel can be decreased by using FCRS.

Figure 5. (a) The time curve of radial expansion velocity of midpoint A under the action of 20–30 g TNT. (b) The time curve of radial expansion velocity of midpoint A under the action of 60–80 g TNT.
3.2. Dynamic response at different time

Under different TNT equivalents, the same type of shells showed different sizes of radial displacement but similar dynamic deformation processes. Therefore, we take 80 g TNT as an example to compare the dynamic response characteristics of MS and FCRS at different times. The deformation characteristics of MS subjected to an internal explosion during different times are shown in figure 6. At the initial time, the radial displacement of the shell was zero. At 60 μs after blasting, the shock wave started to act on the shell, causing radial expansion. At 310 μs the radial displacement became a maximum (7.20 mm). Then the MS rebounded and the radial displacement decreased. After 480 μs, the radial displacement tended to be stable at 6.40 mm. The deformation of the shell was plastic deformation. The whole dynamic response process was very simple.

![Figure 6](image)

**Figure 6.** Deformation characteristics at different times of MS subjected to 80 g TNT explosion. (a) 0 μs, (b) 60 μs, (c) 160 μs, (d) 310 μs, (e) 330 μs, (f) 480 μs.

The deformation characteristics of FCRS subjected to an internal explosion during different times are shown in figure 7. The surface of FCRS was not as smooth as that of MS. However, this did not affect the response process. At the initial time, the radial displacement of the FCRS was zero. At 120 μs the radial displacement became a maximum (2.06 mm). Then, the FCRS began to rebound. At 140 μs the radial displacement reduced to 1.62 mm. At 200 μs, the shell center shrank dramatically, while the edge speckle areas expanded along the radial direction. At 240 μs, the shrinkage of the shell center was a maximum (−1.24 mm), and the radial expansion of the edge speckle areas were also maxima. Then, the shell center expanded again, meanwhile the edge speckle areas shrank. The shell center radially expanded because it was compressed by the two ends of the shell along the axial direction toward the center. After 460 μs, the radial displacement tended to be stable at 0.162 mm. In this case, the deformation of the FCRS was plastic deformation. However, the radial expansion and shrinkage and the compression from the ends of the shells along the axial direction made the dynamic response process of FCRS complicated.
Figure 7. Deformation characteristics at different times of FCRS subjected to 80 g TNT explosion. (a) 0 μs, (b) 120 μs, (c) 140 μs, (d) 200 μs, (e) 240 μs, (f) 290 μs, (g) 340 μs, (e) 360 μs, (f) 460 μs.

Through comparison between figure 6 and figure 7, it was found that the deformation of MS during the whole response process was symmetric. However, for FCRS, the deformation was symmetric before 140 μs and asymmetric after 140 μs. As the explosion shock wave affected the shell symmetrically, the MS was an axially symmetric structure and the material was isotropic, the symmetry of the deformation of MS was very good. In contrast, fiber composite is an anisotropic material. Winding angles at different directions changed FCRS into an asymmetric structure. At the initial time, the energy of the explosion shock wave was huge. The symmetry of the structure and the anisotropy of the material were hardly enough to have an impact on the deformation of the structure. Then the shock wave attenuated, and shell deformation absorbed energy, so the energy of the shock wave decreased rapidly. The asymmetry of the structure and the anisotropy of the material gradually played a leading role in deformation of the structure. After 140 μs, deformation of the structure gradually became asymmetric. The interaction between fiber composite and metal liner made the radial force of FCRS more evenly distributed than the radial force of MS. The two shells with the same surface density showed different response characteristics under the same explosion loading.

3.3. Dynamic response of the frequency domain
To reflect accurately the response characteristics of the two kinds of shell under different TNT equivalents, the velocity–time curve of midpoint A on the surface of the two shells was analyzed by an empirical mode decomposition, the Hilbert–Huang transform (EMD-HHT), according to the literature [21]. The empirical mode decomposition was used for preprocessing and an intrinsic mode function (c_i) with different scales was obtained. Then the Hilbert–Huang transform was applied to the IMF and the distribution of vibrational energy in the frequency domain of the two shells under different TNT equivalents was obtained, The process is as follows:
\[ v(t) = \sum_{i=1}^{n} c_i + r_i(t) \]  \hspace{1cm} (3)

\[ H[c(t)] = \frac{1}{\pi} PV \int_{-\infty}^{\infty} \frac{c(t')}{t-t'} dt' \]  \hspace{1cm} (4)

\[ z(t) = c(t) + jH[c(t)] = a(t)e^{j\Phi(t)} \]  \hspace{1cm} (5)

\[ f(t) = \frac{1}{2\pi} \omega(t) = \frac{d\Phi(t)}{dt} \]  \hspace{1cm} (6)

\[ H(\omega, t) = \text{Re} \sum_{i=1}^{n} a_i(t)e^{j\omega(t)\phi} \]  \hspace{1cm} (7)

\[ E(\omega) = \int_{0}^{r} [H^2(\omega, t)dt] \]  \hspace{1cm} (8)

Among these: \( v(t) \) is signal of radial velocity of the midpoint A. \( \sum_{i=1}^{n} c_i \) is the sum of \( c_i \), \( r_i(t) \) is the residual, \( PV \) is Cauchy principal value; \( a(t) = \sqrt{c^2(t) + H^2[c(t)]} \) is amplitude function; \( H(v, t) \) is Hilbert spectrum; \( f(t) \) is instantaneous frequency; \( \Phi(t) = \tan^{-1} \frac{H[c(t)]}{c(t)} \) is phase function; \( E(\omega) \) is energy spectrum in the frequency domain of speed signals, \( T \) is signal cycle.

The energy of the vibrational signal below 2000 Hz and above 10000 Hz is very small, so it can be ignored. The energy in the frequency range 2000–10000 Hz was used as the total energy of the vibrational signals. The percentage of the energy in the frequency range 4000–6000 Hz in the total energy was calculated and the results are shown in figure 8. The vibrational energy of MS was concentrated in the range 4000–6000 Hz and accounted for 80–90% of the total energy. The vibrational energy of FCRS was very dispersive in the frequency domain. The energy in the range 4000–6000 Hz only accounted for 35–40% of the total energy, thus reducing the probability of damage by energy concentration.

**Figure 8.** The frequency distribution of vibration of two shells. (a) The frequency distribution of vibration energy of midpoint A on MS under different TNT equivalence. (b) The frequency distribution of vibration energy of midpoint A on FCRS under different TNT equivalence.
4. Conclusion

In summary, this study reproduced the dynamic response characteristics of MS and FCRS with the same surface density subjected to an internal explosion using the 3-D digital image correlation method. The strength of MS was low, thus the plastic deformation occurred in the center of the MS under internal explosion loading and the dynamic response of the MS was very simple. However, under the same explosion loading, FCRS remained well in the elastic range. An explosion vessel made of FCRS can not only reduce deformation rate and deformation degree, but also reduce the probability of damage by energy concentration. Therefore, an explosion vessel made of FCRS has a very good antiknock performance.

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