Numerical simulation study on the effect of different mass flanges on strain growth of cylindrical shell

Y M Han¹, W B Gu¹,², Y H Hu¹, J Q Liu¹ and Z Wang¹
¹College of Field Engineering, Army Engineering University of PLA, Nanjing, 210007, China
E-mail: guwenbin1@aliyun.com

Abstract. LS-DYNA software was used to establish the three-dimensional finite element simulation calculation model of cylindrical shell, and the effect of different mass flanges on the strain growth within the elastic response range of shell was analyzed and compared. The research found that: when the flange mass was changed, the radial and circumferential strain first peak value of shell basically did not change, while the axial first peak value changed greatly. The variation trend of strain growth response in radial direction and axial direction is basically the same, but the influence of axial strain growth is larger. Compared with the larger mass flange, the smaller mass flange may cause larger strain growth of the shell. Different flange mass only affects the time of strain growth and different frequency parts of excitation strain response, but hardly affects the appearance time of the "dangerous time domain". The longer the dangerous time domain is, the smaller the strain growth factor is.

1. Introduction
Explosive containers are special devices that limit explosive products and explosive energy in a certain confined space, and are widely used in civil and military fields. When the inside of the container is subjected to an impact load, a complex dynamic response is generated. Strain growth is a dynamic response of the vessel wall. It means that the maximum value of the strain does not appear at the first peak, but at the peak of the subsequent response. There are many factors that cause strain growth, which can be summarized into three aspects: a) resonance caused by explosive load [1-3]; b) disturbance caused by structure [4-6]; c) disturbance caused by modal superposition [7-15]. When the strain increases beyond the design allowable stress of the explosive container, the tank may be invalid, damaged, leaked, etc., posing a great threat to the safe use of the container. Therefore, the phenomenon of strain growth is the focus of the explosion container designer.

Since Buzukov [16] observed the cyclical growth of the strain of cylindrical explosive vessels in experiments in 1976, the strain growth phenomenon of explosive vessels has attracted the interest of many scholars. Karpp [4] once again observed the strain growth of the spherical container in the experiment, and established a two-dimensional axi-symmetric spherical shell model, which simplified the flange into a mass, and verified that the flange will cause a spherical container large axial symmetric disturbance, this kind of disturbance that can cause severe strain growth, but did not give a more in-depth theoretical analysis; Li et al [11] simplified the explosion vessel into a two-dimensional ring for numerical simulation. By changing the partial mass of the ring, the effect of small structure disturbance on the ring strain growth was simulated. The results show that the perturbation of the small structure can accelerate the energy transformation from the breathing mode to the bending
mode, thus aggravating the strain growth. In fact, these small structures can be nozzles, small openings, etc., but the effect of large structures (flanges, large openings, etc.) has not been studied in this paper. Hu et al [17] simplified the explosion vessel into a cylindrical shell, and analyzed the influence of flange radial length on strain growth through numerical simulation. It is believed that as the radial length of the flange increases, the bending disturbance of the various frequencies of the cylindrical shell is excited. This enhances the linear modal coupling response of the cylindrical shell, resulting in an increase in the strain growth factor. When more high frequency parts are introduced into the strain response, the strain growth time will also shorten.

As a necessary structure of the cylindrical container (as shown in figure 1), flanges play a safe role in confining explosive containers through bolt connections to prevent separation of tank body and end cover, leakage of toxic gases such as explosion products, etc. However, because flanges generally have a large mass, their different length, mass, position and thickness will greatly affect the dynamic response characteristics of the container after the impact of the explosion [17], which has the potential danger of inducing strain growth. However, there are currently few articles that systematically analyze the effect of flange on strain growth. Therefore, this paper will study the effects of different mass flanges on strain growth in terms of head peak, strain growth time and strain growth rate and so on.

![Image](image.png)

**Figure 1.** Cylindrical explosive container with flange structure.

In this paper, the three-dimensional finite element model of the sliding-sliding boundary cylindrical shell is established and solved by LS-DYNA software. The influence of different mass flanges on the strain growth of the shell is analyzed. This can lay a foundation for the safe design of the explosion vessel, avoiding the dramatic impact of the flange on the tank strain growth, thereby enhancing the safety of the use of the explosion vessel.

2. **Models and parameters**

2.1. **Finite element model**

In order to investigate the effect of flange mass on the strain growth of cylindrical shells, under the premise of the same boundary conditions, this section designs four numerical simulations of different mass flanges, as shown in Table 1, and the model is shown in figure 2. The difference in flange mass is expressed in terms of different material densities.

In order to eliminate the adverse effects of the radial elongation of the flange, the following four sets of numerical models concentrate the mass of the flange on the cylindrical housing unit, and four models with four end flange thicknesses of 4.26 cm are provided. The four material densities are converted by the volume ratio of flanges with a material density of 7.83 g/cm³ and the radial length of 1 cm, 3 cm, 5 cm and 7 cm, respectively.
Table 1. Numerical simulation of four different working conditions.

| Variable       | Condition 1 | Condition 2 | Condition 3 | Condition 4 |
|----------------|-------------|-------------|-------------|-------------|
| Density (g/cm³) | 16.18       | 33.99       | 53.27       | 74.01       |

Figure 2. One of the cylindrical shell models with different mass flanges.

2.2. Material parameters
This paper is based on Dong's numerical model [15] and Zhu's experimental container [10] for numerical calculation. Referring to the modeling method of Hu [17], a cylindrical shell with an inner diameter of 21.28 cm, a thickness of 0.98 cm and a length of 85.2 cm was designed and divided into grids of approximately 0.16 cm, 1.45 cm and 2.13 cm in the radial, circumferential and axial directions, as shown in figure 2. Using the *MAT_ELASTIC material model, the parameters are shown in Table 2. Set the axial motion constraints at both ends of the housing.

Table 2. Material parameters of cylindrical housing.

| Parameter       | Young’s modulus | Poisson’s ratio | Density (g/cm³) |
|-----------------|-----------------|----------------|-----------------|
| Size            | 210 GPa         | 0.333          | 7.83            |

The impact load on the container is reduced to a transient triangular wave pulse $P(t)$, where $P_0$ is the peak pressure and $t_1$ is the positive pressure action time:

$$P(t) = \begin{cases} \frac{t}{t_1} & (0 \leq t \leq t_1) \\ 0 & (t > t_1) \end{cases}$$

When the positive pressure action time of impact load is very small, the response of tank mainly depends on the impulse of load, and the waveform of load has little influence on it [3]. So set the pulse's positive pressure time to 50 microns, which controls the amount of the impulse by changing the peak size. The impulse of the load is half of the product of the peak value and the time of action, in Pa·S. The impulse acting on the inner surface of the cylindrical shell is set to be 300 Pa·S.

3. Effects of flange mass on strain growth of cylindrical shell

3.1. Strain head peak
It can be seen from Table 3 and Figure 3 that, under impact load, flanges of different mass have almost no effect on radial and circumferential strain head peak of shell centre torus, especially the circumferential strain head peak, whose variation range is only a few micro strains, but has a great effect on the axial strain head peak. It can be seen from Figure 3 that the axial strain head peak
increases with the increase of flange mass. The reason is that: the flange is at both ends of the shell, when subjected to the impact load, the radial and circumferential elastic response of the flange initially affects only the two ends of the shell, while the axial tensile stress and compressive stress act on the axial direction of the entire shell, directly affecting the axial strain response of the shell, and this effect is proportional to the flange mass. Therefore, when considering the axial strain response, the effect of different flange mass is particularly important.

**Table 3.** Strain response characteristics of shells under different mass flanges.

| Density of flange g/cm³ | First peak compressive strain /µε | Maximum compressive strain /µε | Compressive strain growth factor | Compressive strain growth time |
|-------------------------|-----------------------------------|---------------------------------|-------------------------------|-------------------------------|
| Radial                  |                                   |                                 |                               |                               |
| 16.18                   | 326.3                             | 569.1                           | 1.744                         | 3860.9                       |
| 33.99                   | 325.7                             | 424.3                           | 1.303                         | 8656.5                       |
| 53.27                   | 325.3                             | 482.4                           | 1.483                         | 4101.5                       |
| 74.01                   | 325.3                             | 585.3                           | 1.799                         | 4364.0                       |
| Circumference           |                                   |                                 |                               |                               |
| 16.18                   | 661.3                             | 1048.0                          | 1.585                         | 3986.4                       |
| 33.99                   | 659.2                             | 791.0                           | 1.200                         | 7519.5                       |
| 53.27                   | 656.5                             | 904.8                           | 1.378                         | 3979.4                       |
| 74.01                   | 653.9                             | 1086.7                          | 1.662                         | 4240.0                       |
| Axial                   |                                   |                                 |                               |                               |
| 16.18                   | 37.4                              | 184.1                           | 4.925                         | 590.5                        |
| 33.99                   | 64.4                              | 120.0                           | 1.863                         | 5811.9                       |
| 53.27                   | 72.8                              | 158.4                           | 2.174                         | 4182.4                       |
| 74.01                   | 83.9                              | 189.4                           | 2.257                         | 1707.0                       |

| Density of flange g/cm³ | First peak tensile strain /µε | Maximum tensile strain /µε | Tensile strain growth factor | Tensile strain growth time |
|-------------------------|-------------------------------|----------------------------|-------------------------------|----------------------------|
| Radial                  |                               |                             |                               |                             |
| 16.18                   | 299.9                         | 559.6                       | 1.866                         | 4236.5                      |
| 33.99                   | 287.7                         | 423.6                       | 1.472                         | 8278.5                      |
| 53.27                   | 283.6                         | 462.2                       | 1.630                         | 8525.4                      |
| 74.01                   | 280.4                         | 609.7                       | 2.174                         | 4240.0                      |
| Circumference           |                               |                             |                               |                             |
| 16.18                   | 655.7                         | 1047.2                      | 1.597                         | 3859.5                      |
| 33.99                   | 655.7                         | 789.4                       | 1.204                         | 7393.8                      |
| 53.27                   | 655.7                         | 914.4                       | 1.395                         | 4105.0                      |
| 74.01                   | 655.7                         | 1071.7                      | 1.634                         | 4366.5                      |
| Axial                   |                               |                             |                               |                             |
| 16.18                   | 78.4                          | 192.2                       | 2.452                         | 2627.9                      |
| 33.99                   | 114.2                         | 117.9                       | 1.033                         | 6188.0                      |
| 53.27                   | 130.2                         | 173.4                       | 1.331                         | 1775.5                      |
| 74.01                   | 146.2                         | 250.1                       | 1.710                         | 1810.4                      |

**Figure 3.** First peak of the strain response of the shell under different mass flanges.

**Figure 4.** Strain growth factors of radial strain response at the middle section of the cylindrical shell with different mass of flanges.
3.2. Strain growth factor
As shown in figure 4, the strain growth factor shows the characteristics of high at both ends and low in the middle, and the change trend of radial and circumferential direction is basically the same, and the two circumferential lines basically overlap. For the axial direction, although the overall change trend is the same as the other two directions, the change range is large. This further confirms the point in 3.1. When the flange density is $16.18 \, \text{g/cm}^3$, the axial tensile strain of the shell center torus is 2.5 times of the first peak value, and the compressive strain is up to 4.9 times, which is dangerous for the container, and may even cause the container failure or damage. It is indicated that the small mass flange may cause the larger strain increase of the shell. Therefore, when designing an explosive container, a reasonable selection of the mass of the structure can enhance the service life of the container.

3.3. Dangerous time domain
As can be seen from Table 3, the maximum radial and circumaxial strain values mainly concentrated around 4000 microseconds and 8500 microseconds, while the growth time of axial strain was distributed throughout the time domain. The maximum strain of the compressive strain and tensile strain of the middle section of the cylindrical shell with a flange density of $33.99 \, \text{g/cm}^3$ and the tensile strain of the middle section of the cylindrical shell with a flange density of $53.27 \, \text{g/cm}^3$ appears around 8500 $\mu$s. As can be seen from figure 5, a peak close to the maximum strain has appeared in the strain response curve of about 3000 $\mu$s. If the time period in which there are several strain peaks $\geq 90\%$ of the maximum strain value is defined as the ‘dangerous time domain’ of the strain response (as shown in the dashed box in Figure 5(a)-5(d) of the four models), it can be considered that the mass of the flange has almost no influence on the starting time of the dangerous time domain. That is to say, the middle section of cylindrical shell with any flange mass appears higher radial strain growth at about 3000 $\mu$s in the condition. If the structure under high stress and strain will produce plastic deformation or damage, it has reached the relatively dangerous state about 3000 $\mu$s.
Figure 5. Radial strain response at the middle section of the cylindrical shell with different mass of flanges under 300 Pa·S transient impact load.

In the research process, it is found that both radial and circumferential directions have dangerous time domain, while axial direction has no such rule, so the radial direction is taken as an example to carry out the analysis. Table 4 lists the response time of the dangerous time domain caused by flanges of different mass. It can be obtained from the table that the dangerous time domain is the longest under the action of flange with a density of 33.99 g/cm³. Although its strain growth factor is the smallest, it still cannot indicate that the effect of flange on shell under this mass is safe. The definition of fatigue damage is given in reference [18]: "the development process of local and permanent structural changes of materials that are subjected to disturbance load at a certain point and undergo crack or complete fracture after sufficient cyclic loading". The dangerous time domain with a long duration can also be regarded as a process of repeated loading with high stress, which may also lead to fatigue damage of the shell, which is unfavorable to the service life of the container. By comparing Table 3 and Table 4 and Figure 5, it can be concluded that, under the same impulse, the longer the continuous response time of the shell with high strain is, the smaller the maximum strain is. In other words, the longer the dangerous time domain is, the smaller the strain growth factor is.

Table 4. Dangerous time domain of radial strain.

| Density of the flange (g/cm³) | 16.18 | 33.99 | 53.27 | 74.01 |
|-----------------------------|-------|-------|-------|-------|
| Dangerous time domain (μs)  | 2018.0| 11093.9| 6087.1| 1278.0|

3.4. Frequency characteristics

The flanges of the four shells are of different mass, but the spectrum diagram of their strain curves shows similar amplitudes and frequencies, that is, they all have the main peak of 4 kHz, but the flanges with a smaller mass will cause a small peak at about 6.5 kHz, and the flanges with a larger mass will cause a small peak at about 3.7 kHz. In the study or daily detection of explosion containment vessels, sensors or other devices need to be installed on them. If the vessels resonate with instruments, it is not conducive to measurement and detection. Therefore, when designing explosion containment vessels, the position of small frequency peak can be changed by adjusting the mass of flange to avoid resonance with the sensor or other instruments.

4. Conclusions

In this paper, the numerical calculation model of cylindrical shells is established to study the effect of different mass flanges on the strain growth of explosive vessels. The main conclusions are as follows:

- Under the same impact load, changing the mass of the flange has little effect on the radial and circumferential strain peaks of the central torus of the shell, but has a greater influence on the axial first strain peak, it increases with the increase of flange mass, so we must pay attention to it.
- When the mass of the flange is changed, the strain growth coefficient curves of the radial and circumferential directions of the shell center torus are very similar, and the circumferential
direction is basically identical, while the axial direction changes greatly. The effect of flange with different mass on axial strain growth reaches the maximum when the mass of four flanges is the smallest, which indicates that the flange with small mass may cause larger strain growth of shell.

- Flanges of different mass can affect the time of strain growth, but hardly affect the moment of occurrence of the dangerous time domain. The longer the danger time domain is, the smaller the strain growth factor is, and vice versa. For material fatigue damage, the continuous loading of high stress should not be ignored.

- Smaller flanges excite the high frequency portion of the strain response, while larger flanges excite the low frequency portion of the strain response. The mass of the flanges should be selected reasonably to avoid resonance between the response of different frequencies and other instruments on the vessels.

References

[1] Buzukov A A 1980 Forces produced by an explosion in an air-filled explosion chamber Fiz Goreniya Vzryva 16 87-93

[2] Zhdan S A 1981 Dynamic load acting on the wall of an explosion chamber Fiz Goreniya Vzryva 17 142-6

[3] Dong Q, Li Q M and Zheng J Y 2010 Interactive mechanisms between the internal blast loading and the dynamic elastic response of spherical containment vessels Int. J. Impact Eng. 37 349-58

[4] Karpp R R, Duffey T A and Neal T R 1983 Response of containment vessels to explosive blast loading J. Pressure Vessel Technol. 105 23-7

[5] Abakumov A I, Egunov V V, Ivanov A G et al 1984 Calculation and experiments on the deformation of explosion-chamber shells Zh Prikl Mekh Tekh Fiz 3 127-30

[6] Dong Q, Li Q M, Zheng J Y et al 2010 Effects of structural perturbations on strain growth in containment vessels J. Pressure Vessel Technol. 132(1) DOI:10.1115/1.4000372

[7] Duffey T A and Romero C 2003 Strain growth in spherical explosive chambers subjected to internal blast loading Int. J. Impact Eng. 28 967-83

[8] Kornev V M et al 1979 Experimental investigation and analysis of the vibrations of the shell of an explosion chamber Fiz Goreniya Vzryva 15 155-7

[9] Belov A I, Klapovskii V E, Kornilo V A et al 1984 Dynamics of a spherical shell under a nonsymmetric internal pulse loading Fiz Goreniya Vzryva 20 71-4

[10] Zhu W H, Xue H L, Zhou G Q et al 1997 Dynamic response of cylindrical explosive chambers to internal blast loading produced by a concentrated charge Int. J. Impact Eng. 19 831-45

[11] Li Q M, Dong Q and Zheng J Y 2008 Strain growth of the in-plane response in an elastic cylindrical shell Int. J. Impact Eng. 35 1130-53

[12] Dong Q, Li Q M and Zheng J Y 2009 Investigation on the mechanisms of strain growth in cylindrical containment vessels subjected to internal blast loading ASME PVP 2008 (Chicago,USA) 5 pp 211-20

[13] Liu W X, Zhang Q M et al 2017 Further research on mechanism of strain growth caused by superposition of different vibration modes Int. J. Impact Eng. 104 1-12

[14] Dong Q, Li Q M and Zheng J Y 2010 Further study on strain growth in spherical containment vessels subjected to internal blast loading Int. J. Impact Eng. 37 196-206

[15] Dong Q, Li Q M and Zheng J Y 2017 Strain growth in a finite-length cylindrical shell under internal pressure pulse J. Pressure Vessel Technol. 139(2) DOI:10.1115/1.4035696

[16] Buzukov A A 1976 Characteristics of the behavior of the walls of explosion chambers under the action of pulsed loading Fiz. Goreniya Vzryva 12 605-10

[17] Hu Y H, Gu W B, Liu J Q et al 2019 Numerical simulation of the effect of flange radial length on strain growth of cylindrical containment vessels Vibroeng. Procedia 25 182-7

[18] ASTM 1979 American National Standard. ANSI/ASTM, E206-72