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Further research on mechanism of strain growth caused by superposition of different vibration modes

Wenxiang Liu[a,b], Qingming Zhang[a,*], Fangping Zhong[b], Shuai Cheng[b], Dezhi Zhang[b], Li Yang[c]

[a] State Key Laboratory of Explosion Science and Technology, Beijing Institute of Technology, Beijing 100081, China
[b] Northwest Institute of Nuclear Technology, Xi'an 710024, China
[c] China Research and Development Academy of Machinery Equipment, Beijing 100089, China

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ABSTRACT

Strain growth threatens the safety of explosion containment vessels and the superposition of different vibration modes is an important cause of strain growth. In this study, the response of a 2D axisymmetric spherical shell with a fully constrained perturbation is investigated through numerical simulation. The substrains induced by membrane and bending modes are extracted to reveal the mechanism of strain growth. The main conclusions are as follows. (1)The strain growth mainly results from the superposition of the breathing mode and the bending mode with close frequency. (2) The interaction between membrane vibrations and bending waves influences the amplitudes and the periods of the substrain curves. (3) The strain growth factor along the spherical shell is cyclic. (4) With the cyclic feature neglected, the strain growth factor has an inverse relationship with the distance from the symmetric axis.

1. Introduction

Strain growth is a phenomenon that the local response of the shell of an explosion containment vessel subjected to internal blast loading becomes larger at a later stage than its breathing mode response during the initial stage [1]. Strain growth threatens the safety of explosion containment vessels.

The strain growth was discovered in 1976 [2] and since then the mechanism of strain growth has been widely concerned. In addition to the resonance created by reflected shock waves [3,4], the superposition of different vibration modes is another important cause of strain growth. Buzukov [2] conducted experiments on cylindrical chambers subjected to internal blast loading from linear explosives and considered the strain growth to be associated with the initiation and participation of multiple vibration modes of the structure. Zhu [5] investigated the mechanism of strain growth by conducting experiments on two cylindrical explosion chambers and proposed that the development of bending modes might cause strain growth. Belov [6,7] compared the 1D (spherically symmetric) calculations with experimental results and attributed strain growth in a spherical shell to the excitation and interaction of various vibration modes with close frequencies. Abakumov [8] investigated the response of an imperfect spherical shell by the Timoshenko shell theory, which considered both the rotatory inertia and the transverse shear, and proposed that the strain growth might be caused by various bending responses, which were excited by the imperfections and the adjoined mass. Karpp [9] studied the response of an axisymmetric spherical shell with relatively large flanges around the equator and proposed that the disturbance from the flanges propagated to the strain-gauge area and caused strain growth. Duffey [10] observed the strain growth in spherical containment vessels, in which modal beating appeared, and proposed that strain growth was primarily caused due to the beating of vibration modes with close frequencies. Li [11] investigated the in-plane response of an elastic cylindrical shell subjected to an blast loading by theoretical analysis and numerical simulation using LS-DYNA,and concluded that the coupling between the membrane breathing mode and flexural bending modes is the primary cause of strain growth. Dong [1] studied the dynamic elastic responses of a spherical containment vessels subjected to internal blast loading and concluded that the nonlinear modal coupling between the membrane modes and unstable bending modes controlled by the Mathieu equation caused the strain growth.

All of the aforementioned studies investigated the strain growth caused by the superposition of different modes based on total strains rather than the substrains induced by different modes. A more detailed and systematic understanding of the strain growth may be obtained by analyzing the substrains. In this paper, the response of a 2D axisymmetric spherical shell with a fully constrained perturbation is investigated through numerical simulation, and the

* Corresponding author.
E-mail address: qmzhang@bit.edu.cn (Q. Zhang).

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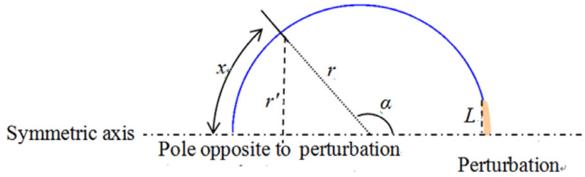

Fig 1. Numerical model of spherical shell.

substrains induced by membrane and bending modes are extracted to reveal the mechanism of the strain growth.

In the second section of this paper, the method of extracting the substrains is presented, and membrane vibrations, bending waves and strain growth of the spherical shell are studied by using the substrains. The third section introduces the strain growth observed in the experiment.

2. Mechanism of strain growth caused by superposition of vibration modes

2.1. Methodology

The 2D axisymmetric numerical model of the spherical shell, which has a radius of 261.5 mm and a thickness of 3 mm, is established using Autodyn, as shown in Fig. 1. Transient impulse acts on the inner surface of the spherical shell instead of internal blast loading, and the first strain peak of the shell is set to approximately 740 $\mu\varepsilon$ by adjusting the impulse. An elastic model is used for the material Q345R of the spherical shell. The simple response of the 2D axisymmetric spherical shell, without bending deformation in the rotatory direction, facilitates the analysis.

The opening, flange, and supporting structure of the spherical shell, which cause bending waves, are known as the perturbations. The radius of the spherical shell is denoted as r, the radius of the perturbation as L, the distance from the symmetric axis as r', the angle of the shell element down from the symmetric axis as α, and the arc length from the shell element to the pole as x, as shown in Fig. 1.

The spherical shells with $L = 10$ mm are used to study the strain growth under three types of perturbations, namely, force perturbation (the perturbation on which the force acting is different from that of the spherical shell), fully constrained perturbation (the perturbation whose velocity is zero), and mass perturbation (the perturbation whose mass is different from that of the spherical shell), as shown in Fig. 2. A mass perturbation is designed to be the one whose thickness is the same as that of the shell, but the density is 2; 20; 40; 1000; 100,000; and 10,000,000 times that of the shell.

Strain growth factor, which is the ratio of maximum strain to the first strain peak, can be used to characterize the severity of strain growth phenomenon. The maximum strain growth factors of the spherical shells under the three types of perturbations are compared as shown in Fig. 3. The strain growth factor with the force perturbation is the smallest, and the strain growth factor with the fully constrained perturbation is the largest. For the mass perturbation, the greater the mass is, the larger the strain growth factor is, and the strain growth factor with the infinite mass perturbation is almost equal to the factor with the fully constrained perturbation.

The motion of the fully constrained perturbation is the simplest and the strain growth factor is the largest, thereby facilitating the analysis. Thus, the following analysis of the strain growth mechanism has been conducted on the spherical shell with the fully constrained perturbation.

2.2. Extracting substrains

Based on the deformation mechanism of thin shell, the strains of outer surface, middle surface, and inner surface of the shell with membrane deformation are the same, while the strain of the outer surface of the shell with bending deformation is opposite to that of the inner surface and the strain of the middle surface is zero. The deformation mechanism of thin shell is shown in Fig. 4.

The total strain is formed by the superposition of the substrains, including the substrain induced by membrane deformation (called membrane strain) and the one induced by bending deformation (called bending strain). The substrains can be extracted from the total strains.

The membrane strain is calculated by

$$\varepsilon_m = \frac{\varepsilon_{outer} + \varepsilon_{inner}}{2} \tag{1}$$

and the bending strain is calculated by

$$\varepsilon_b = \frac{\varepsilon_{outer} - \varepsilon_{inner}}{2} \tag{2}$$

where ε_{outer} and ε_{inner} indicate the total strains of the outer and inner surfaces respectively.

The substrain curves of the spherical shell with the fully constrained perturbation of $L = 10$ mm are extracted by using the formulas (1) and (2). Fig. 5 shows the total strain and substrain curves.

2.3. Mechanism of strain growth

2.3.1. Membrane vibrations

An ideal spherical shell subjected to internal blast loading undergoes the breathing mode response, consisting of membrane vibrations that have the same amplitude and period. However, the spherical shell with the perturbation forms membrane vibrations that deviate from those of the ideal spherical shell.

Fig. 6 compares the membrane strain curves of the ideal spherical shell and the imperfect spherical shell with $L = 10$ mm. When $\alpha = 4.6°$, the amplitude of the membrane strain curve of the

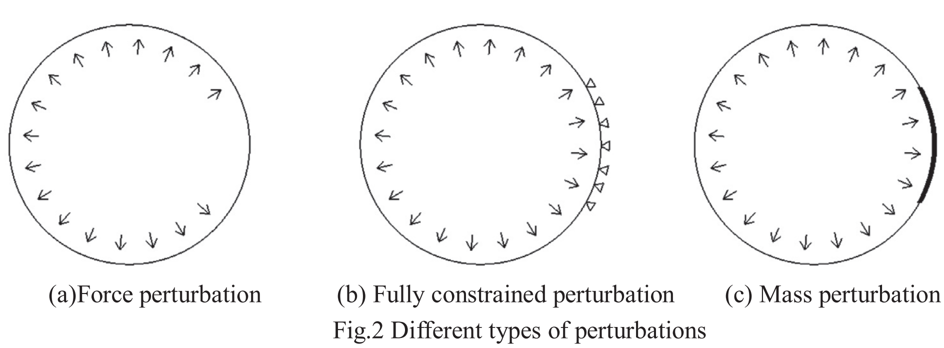

Fig. 2. Different types of perturbations.