International Journal of Solids and Structures 96 (2016) 173–180

Contents lists available at ScienceDirect

International Journal of Solids and Structures

journal homepage: www.elsevier.com/locate/ijsolstr

Scale effect of explosive destruction of spherical vessels: Dynamic crack propagation and branching

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ARTICLE INFO

Article history:
Received 6 January 2016
Revised 5 April 2016
Available online 8 June 2016

Keywords:
Scale effect
Explosive destruction
Rate dependent
Crack propagation and branching

ABSTRACT

Scale effect was repeatedly founded in Explosion containment vessels (ECVs) that with an increment of scale factor, the relative weight (the ratio of explosive destruction charge to the weight of vessel) decreased drastically. Also a reduction of the amount of deformation before failure and an increase in the tendency to the brittle failure were observed in large size structures. Though the scale effect was believed relevant with crack propagation energy and is decisive to the ultimate strength of explosively loaded structures, there's still no satisfying mechanism had been obtained in the past decades. In this paper, a numerical method combining with a phenomenological failure criterion was presented to re-examine the scale effect problems, where a failure criterion fully considering strain rate softening was implanted into the finite element code to account for the explosive destruction of the vessel. FSI (Fluid Structure Interaction) simulation and crack analysis covering the different scale factor from 1 to 10 were conducted, and the dynamical crack propagation and branching process was clearly revealed, which illuminates the cause of fracture and fragments of vessels, as well as the scale law of destruction charge. It was concluded that strain rate softening becomes more significant with an increase of strain rate, which leads to a rapid destruction in a very narrow region even the plastic deformation is too late to occur in the rest parts of the material, thus the brittle fracture mode was presented. The approach illustrated in this paper also provides an effective way to assessment the limit load of ECVs, which is helpful to prevent catastrophic brittle and quasi-brittle failure of the vessels.

1. Introduction

The conception of explosion containment vessels (ECVs) was firstly proposed for the use of nuclear test in 1960 s, afterwards, its function enlarged on destruction chemical weapons, storage and transportation of hazardous materials, etc. When a larger size and volume of vessel was to be required to contain much more explosive energy, the scale effect became extremely important in determine the actual strength and limit load of large structure. Some Geometric similar vessels with different scale factors were investigated by Soviet Union scientists group. Ivanov et al. (1972, 1974) studied similar closed steel vessels loaded by the explosion of an internal charge. It followed from their experiments that reducing the size of vessel by a factor of 15 led to an increase in the relative weightξ by a factor of 15∼16. Here the relative weightξ is the ratio of the explosively destroying charge to the weight of the vessel. Ivanov et al. (1981) tested a full sized specimen and a geometrically similar model with a scale factor of 10. The results showed that with similar ξ under otherwise equal conditions, when the model remained undamaged, the full sized vessel broke into five fragments roughly equal in size. Measurements on the fragments showed no residual strain. The other examples of scale effect were provided by Tsypkin et al. (1975) and Tsypkin and Ivanov (1981), where a reduction of the amount of deformation before failure and an increase in the tendency toward brittle failure was found in structures, with an increase in their size. In addition, the scale effect widely existed in explosive forming (Ezra and Penning, 1962), double-layered cylindrical shell (Bondar' et al., 1996) and in the first-cycle elastic strain response of a spherical ECV (White and Trott, 1980). Since the scale effect origin in a brittle failure of a vessel made of plastic steel, it is highly necessary to study the dynamic response of material that beyond the limits of elastic deformation, not only for the fuller utilization of the strength reserves, but also for the prevention of the catastrophic brittle and quasibrittle failures.

A possible reason that an increase in strain rate causes a change in properties for vessel steel particularly increases in the yield

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http://dx.doi.org/10.1016/j.ijsolstr.2016.06.010
0020-7683/

strength. However, this strength hardening by increasing strain rate by 10 times should not exceed 5% for vessel steels.

One cannot exclude the possibility of the accumulation of irreversible change in the vessel material, since the vessels were destroyed by progressively increasing the weight of the exploded charge. However, the fact that the vessel with least numbers of charges was destroyed at a ξ less than that otherwise similar conditions vessels, which indicated that the scale effect must be important in the case of a single explosion.

Ivanov et al. (1972), Tsypkin and Ivanov (1981) and Golubev et al. (1981) concluded that the scale effect is of energy character. It may be a promising direction to consider the crack propagation energy to reveal the mechanism of scale effect, however, the research along this direction is not well developed, the research literatures on the topic of scale effect became scarcely after 1990 s, just as figured out by Ivanov et al. (1972), the detailed mechanism of the effect still remains unclear.

In this paper, we re-examine the experimental description and data of scale effect. Firstly, a finite element model considering fluid-structure interaction (FSI) was used to accurately calculate the loading and response of the vessel, including peak pressure and impulse by detonation, the strain histories and strain rates. Secondly, a more elaborate finite element model with an initial crack was employed. Combining with a proposed phenomenological failure criterion, the crack growth and branching and how they cause the fragments of the vessel are clearly revealed by numerical simulation. The simulated fracture and fragments show a good agreement with experiments. The results indicated that scale effect indeed originate in strain rate softening rather than hardening and is strongly depend upon dynamic crack propagation process. The approach illustrated in this paper also provides a way to determine the limit loads of ECVs, as well as to prevent catastrophic brittle failures.

2. Experiments

2.1. Experimental description

Series experiments on the freely suspended spherical vessels filled with water were performed by Ivanov et al. (1972, 1981). A full sized specimen and a geometrically similar model with a scale factor of 10 were used. The explosive charge was made of a mixture of trotyl and hexogene, 50% of each. The full sized vessel was made of grade 22 K thick sheet boiler steel, while the model was made from a fragment of a shell of a nature specimen that failed under elastic strain in one of the experiments. The mechanical properties of vessel were: $R_{\mathrm{m}}=490$ MPa and $R_{\mathrm{e}}=274$ MPa, while the model made from fragments was heat treated and their mechanical properties are $R_{\mathrm{m}}=529$ MPa and $R_{\mathrm{e}}=265$ MPa, which was close to the raw vessels.

The failure in the full-size vessel was catastrophic, with complete separation of the body into five fragments, which arising from the rapidly propagation and branching of cracks. However, the failure in the model was local, without complete separation of the body into parts under series given charges from2.16 g to 4.54 g. The cracks are formed at plastic strains of 0.6–0.8%. Fig. 1 shows the two failure modes.

Table 1 gives the descriptions of different failure modes of full sized vessel and small models in experiments (Ivanov et al., 1981).

2.2. Non-dimensional analysis

Two similar elements of the wall of vessels differing in linear dimensions by a factor n and loaded by the explosion of charges at $\xi=$const were considered in non-dimensional analysis. Followed the method used by Ivanov et al. (1972), some essential assumption was listed:

(1) The specific energy of crack formation per unit square q_c is a constant and to be a part of specific elastokinetic energy q_k .
(2) The total energies expended on the propagation of the cracks through similar elements of the vessels will differ by a factor n^2.
(3) The reserves of elastokinetic energy Q_k, from which the crack propagation energy is drawn, differ in these elements by a factor n^3.

Based on above assumptions, we have:

$$\frac{Q_k}{Q_c}=R\frac{q_k}{q_c}=const \tag{1}$$

where R is the characteristic dimension of structures, Q_c is the energy expended on crack propagation, q_k is the specific elastokinetic energy. Since q_k is only a part of the specific total specific energy q, ($q_k=\eta q$), Eq. (1) can be re-expressed as:

$$\frac{q}{q_c}=\frac{const}{\eta R} \tag{2}$$

the value η can be determined by dynamic stress-strain curve for the vessel steel as the ratio of the elastic strain energy to the total energy. For the duplex-linear hardening,

$$\eta=\lambda+(1-\lambda)\frac{q_s}{q} \tag{3}$$

where $\lambda=E_2/E_1$, E_1 is the Young's modulus, E_2 is Hardening tangential modulus. $q_s$is the elastic strain energy at the yield point.

Eq. (3) can be rewritten in terms of maximum strain,ε, and strain at the yield point, ε_0. Considering the maximum tangential stress$\sigma$to the yield stressσ_s:

$$\frac{\sigma}{\sigma_s}=1-\lambda+\lambda\frac{\varepsilon}{\varepsilon_0}=\sqrt{\frac{q_k}{q_s}} \tag{4}$$

or

$$\frac{\eta q}{q_s}=\left(1-\lambda+\lambda\frac{\varepsilon}{\varepsilon_0}\right)^2 \tag{5}$$

from Eqs. (3) and (4), we can obtain:

$$q_s=q\lambda\left[\left(1-\lambda+\lambda\frac{\varepsilon}{\varepsilon_0}\right)^3-(1-\lambda)\right]^{-1} \tag{6}$$

$$\eta=\lambda\left(1-\lambda+\lambda\frac{\varepsilon}{\varepsilon_0}\right)^2\left[\left(1-\lambda+\lambda\frac{\varepsilon}{\varepsilon_0}\right)^2-(1-\lambda)\right]^{-1} \tag{7}$$

For given steel, q can be written in the form:

$$q=\kappa\xi^2 \tag{8}$$

where κ is a material constants relating with density and sound speed of material.

Therefore the relative weight of the destroying charge and the parameters of the vessel can be expressed:

$$\xi^2+\frac{1-\lambda}{\lambda}\cdot\frac{q_0}{\kappa}=\frac{C_1}{R\lambda} \tag{9}$$

where $C_1=\frac{const}{\kappa}q_c$

From , (7) and (8), the expression relating the radius of the vessel and the maximum strain at fracture can be obtained:

$$\frac{\varepsilon}{\varepsilon_0}=\frac{1}{\lambda}\sqrt{\frac{R_0}{R}}-\frac{1-\lambda}{\lambda} \tag{10}$$