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Dimensionless number for dynamic response analysis of box-shaped structures under internal blast loading

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ABSTRACT

Based on the governing equations of a fully clamped plate, a new dimensionless number for the dynamic response of box-shaped structures subjected to internal blast loading was suggested in this paper. The dimensionless number considered the influence of blast load, the strength of material and the structural dimensions. The parameters in the proposed dimensionless number can be easily obtained in practice. The dimensionless number has clear physical meaning and leads to good correlation between the response of box-shaped structures and the blast energy. It was also found that the structural response is inversely proportional to the material strength and the volume of the structure. The dimensionless number was applied to analyze the experimental data of box-shaped structures under internal explosion. The validity and efficiency of the dimensionless number were discussed, and an empirical expression was obtained which can be applied to the prediction of dynamic response of similar box-shaped structure under different internal explosive loads.

1. Introduction

In recent years, terrorist attack and accidental explosion have increased worldwide [1–3]. Box-shaped structures are facing the threat of internal explosion, and box-shaped structures widely exist in containers, freight cars and apartments of ships. Because of the confinement of the bulkhead or the wallboard of the box-shaped structure, internal blast load is comprised of not only several short duration shock loads but also a long duration gas pressure load [4,5]. Studies in Refs. [5–7] indicate that internal explosions are more complicated and more destructive than external explosions. Thus, practical methods for dynamic analysis of structural response under internal blast loading, which are concerned by the area of explosion result analysis, damage prediction and blast-resistant design, are badly needed.

The elastic–plastic response of spherical vessels under internal blast has been investigated by many scholars [8–11]. Ma et al. [12] studied the different modes of both ductile and brittle failures of containment vessels subjected to internal blast loading. The radial deformation of cylinder-shaped pipes subjected to internal blast loading has also been studied analytically by Duffey and Mitchell [13] and Benham and Duffey [14]. Wang [15] investigated the damage and response processes of a rectangular steel tube subjected to internal explosion through numerical simulations. However, the internal blast loading within the fully confined cuboid structure is less investigated. Hou et al. [16] and Kong et al. [17] both reported an experimental and numerical study of steel chambers with different sizes and shapes subjected to internal blast loading, where the pressure–time curves and the damage shape were presented. Geretto et al. [18] conducted a series of experiments of steel cuboidal containers subjected to fully confined blast, and the effect of explosive mass and plate thickness on the final plate deformation was investigated.

The issues with regard to dynamic response of structures under internal blast are very complicated and related to many influencing factors. Dimensional analysis is an effective method to create dimensionless terms. Through dimensional analysis, the influencing factors could be combined in a particular way, simplifying the problem [19,20]. Numerous scholars have presented dimensional analysis on the dynamic response of structures under dynamic loads [21–29]. In 1973, Baker and Westine [30] advised that dimensional analysis method should be applied to every experimental study.

Johnson [21,22] suggested a dimensionless damage number in the study of the dynamic plastic response of materials,

$$Dn = \frac{I^2}{\rho \sigma_0 H^2} \tag{1}$$

where I is the impulse, σ_0 is the yield stress. ρ and H are density and thickness of the material, respectively.

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Nomenclature

C_0	sound velocity of environment
Dn	Johnson damage number
D_{in}	dimensionless number suggested in this paper
E_e	explosive energy per unit volume
H	plate thickness
H_n, H_m	nominal plate thickness and measured plate thickness
I	impulse
L	plate length
M_x, M_y	bending moment per unit length
M_{xy}	torsion moment per unit length
m_X, m_Y	dimensionless bending moment
m_{XY}	dimensionless torsion moment
M_0	fully plastic bending moment per unit length $M_0 = \sigma_0 H^2/4$
p	pressure
Q	total explosive energy
Q_x, Q_y	transverse shear per unit length
t	time
T	dimensionless time
u	transverse deflection
U	dimensionless transverse deflection
V	explosive volume
V_0	initial velocity
W	explosive mass
x, y	coordinate
X, Y	dimensionless coordinate
μ	mass per unit area
τ	duration of the impulse
σ_0	yield stress
ϕ_q	dimensionless number suggested by Nurick and Martin
ρ_s	density of structure
δ	midpoint deflection of plate
δ_n	normalized midpoint deflection of plate
δ_m	measured midpoint deflection of plate

Nurick and Martin [28,29] improved the Johnson's damage number by bringing in the width (b) and length (l) of the plate in the study of quadrangular plates subjected to uniform loads, noted as ϕ_q.

$$\phi_q = \frac{I}{2H^2(bl\rho\sigma_0)^{1/2}} \tag{2}$$

And then, they investigated the relationship between the midpoint deflection–thickness ratio (δ/H) and the dimensionless damage number φ_q. And an empirical equation was proposed as follows,

$$\frac{\delta}{H} = 0.48\phi_q + 0.277 \tag{3}$$

In the current study, experimental data of box-shaped containers under internal blast loads were introduced. In order to analyze the experimental data of internal blast, a new dimensionless number for the dynamic response of box-shaped structures was suggested. In the latter part of this study, the suggested dimensionless number was adopted to analyze the experimental data. In addition, comparison study between the newly suggested dimensionless number and the damage number proposed by Nurick and Martin [28] was conducted. Through that, the validity and efficiency of the newly suggested dimensionless number were discussed, and an empirical expression was obtained which can be applied to the prediction of dynamic response of similar box-shaped structure under different explosive loads.

1.1. Experiment setup and results of box-shaped containers under internal blast loads

Three series of tests of fully confined containers subjected to internal blast loading were reported by Geretto et al. [18]. In their study, three different plate thicknesses (3 mm, 4 mm and 5 mm) were tested. The quasi-static yield strengths of the different thickness plates were obtained via uniaxial tensile tests. The yield strengths of the steel plates with thicknesses of 3 mm, 4 mm and 5 mm were found to be nominally 233 MPa, 222 MPa and 263 MPa, respectively. The test container is fixed in a heavy base as illustrated in Fig. 1. The inner dimensions of the containers were all 200 mm × 200 mm × 200 mm constructed with six deformable sides. The sides and bottom plates were welded together with fillet welds to form the body of the container. The top plate was bolted to the container. The blast loads were generated by detonating different masses of spherically shaped plastic explosive (PE4) which had a density of 1.35 g/cm^3, and a detonation energy per unit volume of 9.0×10^9 J/m^3. The explosive was accurately placed in the center of the container to provide a standoff distance of 100 mm from each surface.

The cross-sectional deformation profiles of the 3 mm thickness top plate of the containers subjected to internal blast loading are pictured in Fig. 2, and the cross-sectional deformation views of different plate thicknesses of the container body are shown in Fig. 3. It shows that the deformation increases with an increase in the mass of explosive in the case of fully confined containers subjected to internal blast loading.

The experiment program and the results of measured midpoint deflection of the top plate are listed in Table 1, in which σ_0 is the static yield stress of the specimens, W is noted as the explosive mass, the final measured midpoint deflection of top plates is noted with δ_m, the inner dimension of container is noted with L and measured plate thickness noted with H_m. In addition, numerical values listed in the last row are for the dimensionless number D_{in}, which will be proposed in the next section.

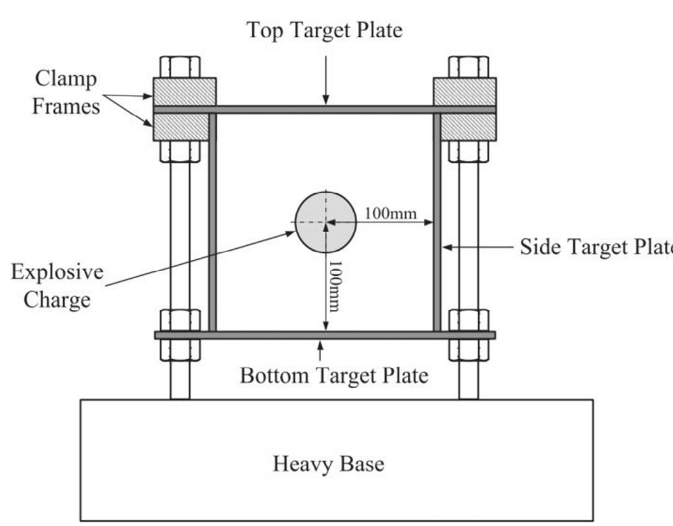

Fig. 1. Illustration of test device of fully confined blast [18].