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A study of tensile damage and attenuation effect of perforated concrete defense layer on stress waves

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Abstract

Civil defense shelters are often constructed beneath the ground to provide protection against blast loadings. Concrete is widely used as the material for the defense layer of the shelters. This paper adopts a continuum damage model of brittle media to numerically investigate the dynamic fracture and attenuation effect of perforated concrete defense layer on stress waves from planar charge. The model includes damage accumulation and loading rate-dependence, and has been succinctly implemented into the dynamic finite element code, LS-DYNA, via its user defined subroutine. The numerical results reveal that the adopted model can well predict the tensile damage owing to the reflection of pressure waves from cavities and free boundaries. Again, the elastoplastic properties of concrete play significant roles in the stress-wave attenuation and the peak values of hydrostatic pressure beneath a circular cavity are largely reduced. One empirical formula is finally proposed to relate the decay factor of peak hydrostatic pressure to the cavity dimensions and relative position.

Keywords: Concrete defense layer; Cavity; Stress waves; Tensile damage; Attenuation effect; Decay factor; Empirical formula

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1. Introduction

The diffraction and attenuation of stress-waves are important aspects in the design of civil defense shelters [18,4,22,16]. The development of modern military technology greatly enhances the destructive power and hit rate of new weapons, thus posing great challenges to defense engineering nowadays. Civil defense shelters are widely constructed beneath the ground to provide protection against blast loadings [18,1]. Blast waves due to planar charge detonation evolve into the propagation of stress-waves in underground media. Such waves will be diffracted when hitting obstacles such as cavity, crevice or other media. The wave stress intensity may be greatly reduced beneath these obstacles. This reduction of stress from the peak value is often termed as attenuation or insulation of stress-waves [16].

Civil defense shields are widely used to reduce or even prevent the damage and destruction of underground structures from blast or impact loading [17,9,11,22,3]. When designing a civil defense work, the attenuation of and screening against stress-waves must be considered and new stress-wave migration systems are expected. Some experimental tests related to this problem have been performed by the authors, and some field observations have been conducted. Fig. 1 is the full-scale test appearance, and Fig. 2 depicts the configuration of the experimental defense structure. It clearly shows that a layered defense structure typically consists of three layers [18,12]: a soil cover layer, a protection layer and a support layer. Furthermore, the protection layer has two sub-layers: a projectile shelter layer and a stress distribution layer. Generally speaking, the stress distribution layer is made of perforated concrete or buffer materials such as sand and geofoam. Its major function is to redistribute the blast loading over a larger area. However, studies on the function of the stress distribution layer are limited so far.

Artificial cavities are normally incorporated into the stress distribution layer to dissipate the energy of stress waves. The stress-wave attenuation due to the dynamic fracture and plastic deformation of the perforated concrete is far from well

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Fig. 1. Appearance of the field test for defense structure under planar charge.

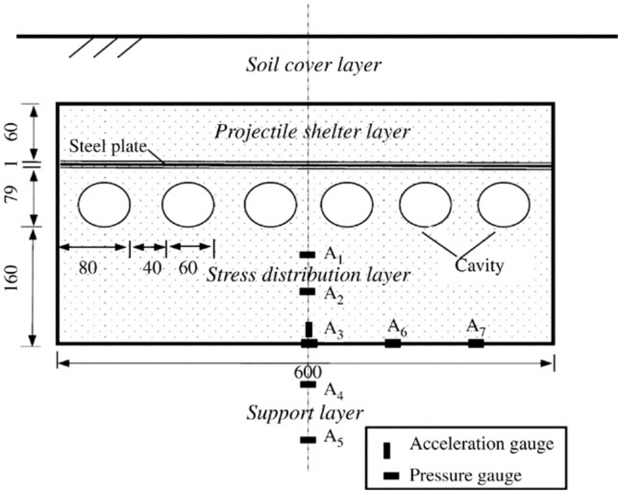

Fig. 2. Schematic of the defense structure in the test (unit in cm).

understood [19,20]. What is more, the existence of cavities in a perforated defense layer may create great potential of tensile damage above cavities due to the lower wave impedance of air inside the cavities. Besides, the potential damages due to reflected tensile waves near free boundaries (non-transmissive) should also receive attention. So far, studies on such phenomena are rarely found in literature.

In the present study, a continuum damage model for brittle media [21,13] is adopted and successfully implemented into the finite element software, LS-DYNA, through its user subroutine capability [14]. The numerical scheme with the model parameters are then calibrated against limited field test data. The tensile damage owing to the cavity and free boundary reflection is investigated subsequently. The attenuation effect of a single circular cavity on peak hydrostatic pressure is also explored in detail based on the damage model. Finally, an empirical formula is proposed to relate the decay factor for peak hydrostatic pressure to the cavity parameters.

2. Continuum damage model for concrete medium

Within a concrete mass, flaws and cracks exist even prior to any loading. Under externally tensile stresses, these flaws or cracks will grow in size and number, causing the deterioration of concrete stiffness and strength. In this section, a continuum damage model for brittle concrete was adopted and a software subroutine was specially developed for the study of the tensile damage and attenuation effects of perforated concrete defense layer on stress waves.

To make a complex problem more tractable, it is assumed that the concrete is an isotropic, homogeneous, continuous and brittle material with pre-existing micro cracks. The finite element program coupled with the defined model captures the general effects of the microcrack system on material stiffness, instead of treating individual cracks which are direction-sensitive. As for the damage process, it is assumed that damage is caused by the activation and growth of pre-existing microcracks. It is accumulated over time and is irreversible.

According to the concepts of continuum mechanics, for isotropic materials, when a material point is subjected to stresses, it changes in volume due to the volumetric parts of the stresses and in shape due to its deviatoric parts. The volumetric strain ε_v is regarded as a time-dependent variable, which determines whether the microcracks will be activated and will evolve.

Under external loadings, the dynamic fracture of concrete does not occur unless the stress is larger than its tensile strength. This is accounted for by setting a critical value ε_c for the volumetric strain ε_v [15,13]:

$$\varepsilon_c = \frac{1-2v}{E}\sigma_s \tag{1}$$

where E is the Young's modulus, v is the Poisson's ratio and σ_s represents the tensile strength of concrete.

Obviously, microcracks will be activated when ε_v exceeds ε_c, whereas the microcrack system remains stable when ε_v is less than ε_c. On the other hand, the concrete material will not fail if the duration of an applied stress whose value is well above the tensile strength is too short. In this regard, a crack density C_d is defined as [21,13]:

$$C_d = \alpha(\varepsilon_v - \varepsilon_c)^\beta t \tag{2}$$

where α and β are material constants, t is time.

The differential form for the crack density is written as:

$$\mathrm{d}C_d = \alpha\beta(\varepsilon - \varepsilon_c)^{\beta-1} t\,\mathrm{d}\varepsilon_v + \alpha(\varepsilon_v - \varepsilon_c)^\beta \mathrm{d}t. \tag{3}$$

In the present model, the damage scalar D is assumed to take the following form:

$$D = 1 - \exp(-C_d^2). \tag{4}$$

The degraded Young's modulus E_d for the damaged concrete is computed as:

$$E_d = E \cdot (1 - D). \tag{5}$$

According to Jaeger and Cook [8], if a brittle body (rock, concrete) contains closed cracks, the effective Poisson's ratio is greater than its intrinsic Poisson's ratio. However, when the body contains very flat, open cracks or equidimensional cavities, the effective Poisson's ratio is smaller than its intrinsic Poisson's ratio. By assuming that all types of cracks are