Theoretical and Applied Fracture Mechanics 52 (2009) 111–116

Contents lists available at ScienceDirect

Theoretical and Applied Fracture Mechanics

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

Elastic–plastic-hydrodynamic analysis of crater blasting in steel fiber reinforced concrete

Z.L. Wang [a,b,*], H. Konietzky [c], R.Y. Huang [b]

[a] *Department of Geotechnical Engineering, Tongji University, Shanghai 200092, China*
[b] *Department of Modern Mechanics, University of Science and Technology of China, Hefei 230027, China*
[c] *Institut für Geotechnik, Technische Universität Bergakademie Freiberg, Freiberg 09596, Germany*

ARTICLE INFO

Article history:
Available online 8 August 2009

Keywords:
Steel fiber reinforced concrete
Volume fraction
Constitutive model
Erosion criterion
Crater blasting

ABSTRACT

This paper presents a numerical analysis of crater blasting in steel fiber reinforced concrete (SFRC). In order to model the nonlinear damage-softening behavior of SFRC, the effective stress and effective plastic strain curve is tabulated and used as input for the material Type10 (MAT_ELASTIC_PLASTIC_HYDRO) available in LS-DYNA. The Gruneisen equation of state (EOS) is used to model the pressure volume relationship. With the two erosion criteria namely tensile cut-off and failure strain incorporated, the crater blasting in SFRC is simulated. Numerical results show that the adopted model and high-pressure EOS can well capture the main characteristics and failure process of SFRC under blast loading, and the related parameters can be determined conveniently. In addition, the volume fraction of fibers exerts a significant influence on the dimension of blast-induced crater.

1. Introduction

Concrete has been widely used in the construction practice around the world despite the fact that it has a relatively low tensile strength and weak deformation capability, also known as brittleness. However, it is generally accepted that the toughness, compressive strength and other mechanical properties of plain concrete can be improved with the addition of various ingredients to the concrete batch such as carbon fibers, glass fibers, and steel fibers. The steel fibers are being enjoyed high favour in real-life applications. [1–4].

SFRC has been used in a wide range of fields such as airport runways, mine and tunnel linings, rock slope stabilizations, shell domes, dam constructions, seismic retrofitting of all sorts of reinforced concrete buildings, repair and rehabilitation of marine structures, fire protection coatings, and even in conventional reinforced concrete frames. A main advantage of SFRC is the high energy absorption capacity and high toughness due to its high ductility [5]. As shown in Fig. 1, by comparing the striking craters from penetration experiments with the same testing conditions but on two different targets made of plain concrete and SRFC, respectively, it is clear that SFRC has better capacity to resist the impact of projectile [4].

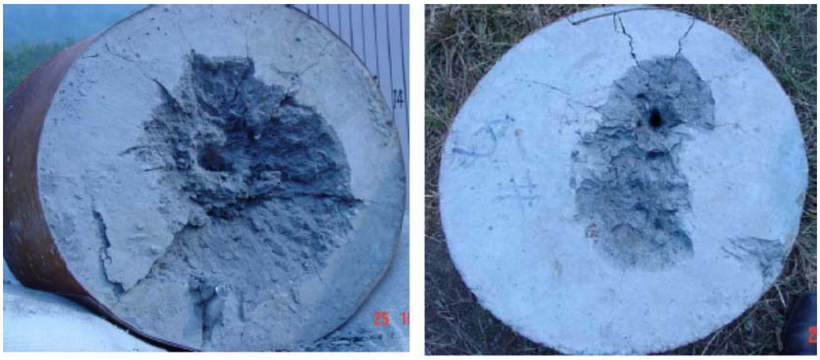
A good understanding of the response of SFRC to impact or blast loading is essential to the design and protection of fortifications [6]. However, evaluating the performance of concrete structures to dynamic loading through full-scale tests is often beyond affordability. With the rapid development of computer technology and the advancement of software techniques, numerical simulation of structural response to static or dynamic loading has become doable [7–9]. A wave propagation code, or hydrocode (see for example, LS-DYNA [7] and ABAQUS [10]), is the most popular method used to simulate this kind of problem. It has been recognized that the constitutive model of SFRC plays a vital role for reliable predication of material structural response to external loading. Various damage mechanics based methods for investigating the response of SFRC have been developed and many material models have also been proposed, such as TCK [11], HJC [12] and RHT [13] models. For all these models, either many parameters need to be determined or the material parameters are very difficult to determine because the experimental test in the extreme condition (for example, ultra-high strain-rate) is not easy to perform due to the limitations of measurement methods [2,14]. Therefore, a valid constitutive equation that scientifically and reasonably reflects the characteristics of SFRC material behavior is highly expected, especially the parameters should be fewer and can be established readily.

Although a lot of research work has been carried out on the SFRC related topic, the effect of the nonlinear softening behavior and the effect of steel fiber reinforcement on the failure of SFRC under blast loading have not been well addressed [3,4,6,14]. The present study is centered on development of a practical constitutive

---

* Corresponding author. Address: Department of Geotechnical Engineering, Tongji University, Shanghai 200092, China. Fax: +86 21 65985210.
E-mail address: GeowzL@yahoo.com.cn (Z.L. Wang).

0167-8442/$ - see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.tafmec.2009.08.005



(a) Plain concrete (b) SFRC

Fig. 1. Comparison of craters in penetration test.

model for characterizing the damage-softening behavior of SFRC and analyzing the effect of fiber volume fraction on crater blasting.

2. Constitutive model and EOS for materials

The hydrocode, LS-DYNA [7,8] is adopted herein, which treats stresses and strains separately in volumetric and deviatoric portions. The deviatoric portion is governed by a strength model. For the volumetric portion, the equation of state (EOS) is always used to determine the relationship between the hydrostatic pressure, the local density and the local energy.

2.1. Material model for SFRC

Fig. 2 shows the average stress–strain plots obtained from tests [14]. It is easy to see that on increasing the volume fraction of fibers the peak strain as well as the compressive strength (peak stress) increases. Both ascending and descending branches of the stress–strain curves are affected by the addition of steel fibers. However, the effect is noted to be more significant in the descending branch of the stress–strain curves. In general, the area under the stress–strain curve is considered as a measure of material toughness [4,15]. Clearly, the toughness of SFRC also increases with the content of steel fibers (see Fig. 2).

The compressive stress–strain curves of SFRC can generally be fitted using the following formula [6,15]:

$$\frac{\sigma}{\sigma_c} = \frac{\frac{\varepsilon}{\varepsilon_c}}{k\left(\frac{\varepsilon}{\varepsilon_c} - 1\right)^2 + \frac{\varepsilon}{\varepsilon_c}} \tag{1}$$

where k is material constant, σ_c and ε_c are peak stress and peak strain, respectively.

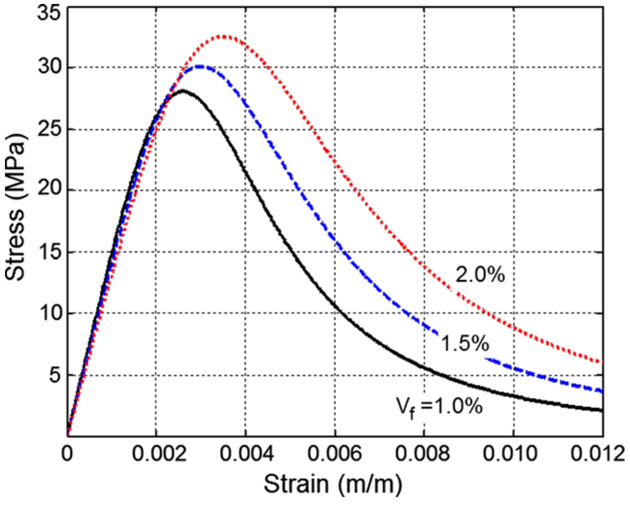


Fig. 2. Macroscopic stress–strain curves of SFRC.

Eq. (1) may be regarded as a simple constitutive equation of SFRC in compression, whereas it is based on one-dimensional test and not easy to be extended to three-dimensional complex state of stress. It is thus inconvenient to incorporate such material behavior into the common commercial code. As well known, LS-DYNA has several built-in concrete models designed for special purposes such as "*Concrete Damage Model*", "*Johnson–Holmquist-Concrete Mode*" and "*Brittle Damage Model*", etc. [7]. These models are beneficial to explore mechanical behavior of concrete, but the damage-softening behavior of SFRC is not well understood. Besides, those models involve too many parameters which cannot be determined by simple material tests. Remarkably, the material Type 10 (MAT_ELASTIC_PLASTIC_HYDRO) is applicable to a wide range of materials, including those with pressure dependent behavior.

The main formulations of this constitutive model are given as below based on radial return plasticity. The effective trial stress is defined by:

$$^{*}\bar{\sigma}^{n+1} = \left(\frac{3}{2}\ {}^{*}s_{ij}^{n+1}\ {}^{*}s_{ij}^{n+1}\right)^{1/2} \tag{2}$$

where the left superscript, *, denotes a trial stress value, s_{ij} is the deviatoric stress, and n is the number of calculation cycles.

If the effective trial stress $^{*}\bar{\sigma}^{n+1}$ exceeds yield stress σ_y, the Von Mises flow rule

$$\phi = \frac{1}{2}s_{ij}s_{ij} - \frac{\sigma_y^2}{3} \leqslant 0 \tag{3}$$

is violated and the trial stresses will be scaled back to the yield surface, i.e., a radial return.

$$s_{ij}^{n+1} = m\ {}^{*}s_{ij}^{n+1} \tag{4}$$

If the effective trial stress is less than the yield stress, the material falls into elastic state and thus the scale factor m in Eq. (4) equals to 1.0.

The algorithm for material in plastic loading stage can be outlined as five steps:

(i) Solve for the plastic strain increment

$$\Delta\varepsilon^p = \frac{({}^{*}\bar{\sigma}^{n+1} - \sigma_y^n)}{(3G + E_h)} \tag{5}$$

where G and E_h represent the shear modulus and plastic hardening parameter, respectively.