Construction and Building Materials 160 (2018) 440–449

Contents lists available at ScienceDirect

Construction and Building Materials

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

Study of concrete damage mechanism under hydrostatic pressure by numerical simulations

Jian Cui, Hong Hao *, Yanchao Shi

[a] Tianjin University-Curtin University Joint Research Centre of Structure Monitoring and Protection, School of Civil Engineering, Tianjin University, China
[b] School of Civil and Mechanical Engineering, Curtin University, Australia

HIGHLIGHTS

- Concrete will suffer damage when the applied hydrostatic pressure is high.
- Deviatoric stresses are obvious inside the specimen under hydrostatic loadings.
- Deviatoric stresses are the primary cause of the concrete damage.
- ITZ and zones around pores are the most vulnerable zones.

ARTICLE INFO

Article history:
Received 16 April 2017
Received in revised form 3 October 2017
Accepted 16 November 2017

Keywords:
EOS of concrete
Hydrostatic pressure
Mesoscale model
Damage
True tri-axial test

ABSTRACT

Current material models commonly assume concrete does not suffer damage under hydrostatic pressure. However concrete damages were observed in recent true tri-axial tests. Hydrostatic pressures varying from 30 MPa to 500 MPa were applied on the 50 mm cubic concrete specimens in the tests. Uniaxial compressive tests and microscopic observations on the hydrostatic tested specimens indicated that concrete suffered obvious damage if the applied hydrostatic pressure was higher than the uniaxial compressive strength of concrete specimen. This study aims to examine damage mechanism of concrete under hydrostatic pressures through numerical simulations. A mesoscale concrete model with the consideration of randomly distributed aggregates and pores is developed and verified against the testing data, and then used to simulate the responses of concrete specimens subjected to different levels of hydrostatic pressures. The simulation results show that under hydrostatic pressure there are significant deviatoric stresses distributed inside the specimen especially in the zones around the pores and between aggregates and mortar because of the inhomogeneous and anisotropic characteristics of the concrete material. The mortar paste matrix in these zones is seriously damaged leading to concrete damage associated with significant stiffness and strength losses. More accurate concrete material models need be developed to take into consideration the damages that could be induced by hydrostatic stress.

1. Introduction

This study focuses on the behavior of concrete subjected to hydrostatic pressures (equation of state, EOS). When a concrete structure subjects to extreme loading conditions such as near-field detonations and projectile penetrations, the material experiences a complex stress state, e.g. very high confining pressure or very high hydro pressure caused by the lateral inertial confinement. Therefore material models able to capture the behavior of concrete under complex stress-states are needed for reliable predictions of concrete structure responses to these extreme loadings. Current material models commonly assume concrete material does not suffer damage under hydrostatic pressures. In other words, no matter how high is the hydrostatic pressure applied to concrete material, it does not experience stiffness and strength loss although it suffers plastic deformation, i.e., compaction of the pores. This assumption could be true if concrete material is homogeneous and isotropic. In reality, concrete is a composite material, consisting of randomly distributed aggregates and pores in mortar matrix, and therefore is neither homogeneous nor isotropic. The assumption that hydrostatic pressure does not damage concrete material is thus not necessarily valid. To model the multiphase property of concrete material, Karinski et al. [1] developed a

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* Corresponding author at: Tianjin University and Curtin University Joint Research Centre of Structural Monitoring and Protection, School of Civil Engineering, Tianjin University, China.

E-mail address: hong.hao@curtin.edu.au (H. Hao).

https://doi.org/10.1016/j.conbuildmat.2017.11.083
0950-0618/

multi-scale mix based equation of state for cementitious materials that considers the microstructure of cement paste and concrete. In the model, cement paste represents the non-linear elastic-plastic behavior while fine and coarse aggregates are assumed to be linear elastic. The model validation shows good agreement with available test results.

Concrete is one of the most widely used construction materials in the field of civil engineering and military engineering. Thus concrete structures might be exposed to extreme dynamic loading conditions. Understanding its material behavior under complex stress-states is essential for reliable predictions of the responses of concrete structures. Most experimental results available in the literature only address the damage and destruction of concrete material under deviatoric stress [2–6], usually obtained with a cylindrical specimen subjected to an axial loading with confining pressure. Because of the lack of understanding and data to characterize the performance under hydrostatic pressures, the commonly used concrete material models in hydrocodes such as KCC model [7] and RHT model [8] in LSDYNA [9] do not consider the damage of material in hydrostatic pressure. The study of concrete under high hydrostatic pressure is limited owing to the difficulty in applying the very high true tri-axial pressures in tests. However, the damage of concrete under high hydrostatic pressure influences the failure surface, damage evolution algorithm and equation of state (EOS) of the concrete constitutive model under the complex stress states [10]. Poinard, et al. [11] did a series of pseudo tri-axial tests using cylindrical concrete specimens which have a 29 MPa uniaxial compressive strength. In their research it was observed that the bulk modulus of the concrete decreased substantially after the specimen having been subjected to a hydrostatic pressure higher than 60 MPa. The authors attributed this drop to cement matrix damage. Pham et al. [12] found that in their FRP-confined concrete tests, the core concrete has suffered serious damage although the FRP-confinement could significantly increase the concrete strength. Karinski et al. [13] developed an experimental setup to perform confined compression tests of cementitious material specimens at high pressures. They found that cracks occurred in specimens with W/C = 0.50 (water/cement ratio). In the other specimens made with a lower w/c ratio, no crack was observed. The authors attributed this observation to the fact that cement paste with W/C = 0.50 has higher porosity and larger maximum capillary pore size as compared to lower w/c ratios, which made the specimen more vulnerable to confined compressive loadings.

There are several approaches in numerical simulation to study concrete material behavior, i.e., macro-level, meso-level and micro-level. At macro-level, the concrete is regarded as a homogeneous material, therefore the model at this level cannot considerate the influences of individual components in concrete material on its mechanical properties. At mesoscale, the coarse aggregates, mortar matrix, pores and the interfacial transition zone (ITZ) can be modelled in detail. The computational effort of meso-level modelling is substantially higher than the macro-level model, but the influences of each component on concrete material performance can be captured. At micro-level, the mortar matrix of the previous level is further subdivided into fine aggregates and hardened cement paste. Among these levels, mesoscopic level analysis is the most practicable and it can provide more insights to the mechanical response of concrete because the volume fractions and distributions of multiple phases such as aggregates, mortar and pores can be explicitly modelled in detail. Many mesoscale concrete models [14–18] have been developed to study the anisotropic and heterogeneous behavior of concrete under different stress states. In a mesoscale model, the influence of important parameters, such as the shape, distribution and size of course aggregates within the mortar matrix are studied by different researchers [19–22]. In the study by Kim et al. [20], it was concluded that aggregate shape had a weak effect on the ultimate tensile strength of concrete and on the tensile stress-strain curve. However, due to the stress concentration at the sharp edges of polygonal aggregate shape, the ultimate tensile strength of the circular shaped aggregate model was a little higher than those of the other aggregate shapes. Some previous numerical studies proved that models with circular or spherical aggregates yield reliable predictions of response of concrete specimens under different loadings [23,24]. It should be noted that most previous studies do not consider pores although concrete material usually has an approximately 10% porosity depending on the W/C ratio [11,25,26].

The present study develops a three-dimensional mesoscale model of concrete with consideration of mortar matrix and randomly distributed course aggregates and pores to investigate the stress distribution inside the concrete specimen and the damage evolution due to deviatoric stresses. The commercial software LS-DYNA is employed to perform the numerical simulations. The accuracy of the numerical model is verified by testing data. The numerical model is then used to simulate concrete material responses under different levels of hydrostatic pressures to examine the behavior and the damage mechanism of concrete under high hydrostatic pressures. The results are used to analyze and explain the observed concrete material damage under hydrostatic pressures.

2. Experimental study of concrete damage under hydrostatic pressure

A series of true tri-axial tests were carried out to study the damage of concrete under high hydrostatic pressures [27]. Some representative testing data are used to verify the numerical model developed in the present study. For completeness the tests are briefly described here.

2.1. Test set-up

The experiments were conducted by a true tri-axial hydraulic servo-controlled test system developed by Central South University in China [28,29]. The machine could apply quasi-static loads along the three principal stress directions through hydraulically driven pistons, independently. In this test, the cross section of steel load transfer block is 47 mm × 47 mm, 3 mm shorter than the 50 mm cubic specimen to avoid the collision of the load transfer bars along different directions when the specimen experiences a large strain during the loading process, as illustrated in Fig. 1. The axial loads was recorded by the load cell sandwiched between the actuator of the machine and the spherical hinge (Fig. 1(a)), and the deformation of the specimen was measured by LVDT sensors. The elastic deformation of the load transfer bar was measured by strain gauges and removed from the record of LVDT in the subsequent data analyses to obtain the strain of the tested specimen, as detailed in Fig. 1(b). At the time of hydrostatic testing, the uniaxial compressive strength of concrete was also tested as 35.2 MPa on average.

2.2. Test procedure and results

One loading-unloading cycle was applied on the cubic specimen during the hydrostatic test. To ensure $\sigma_1 = \sigma_2 = \sigma_3$ (σ_1, σ_2, and σ_3 are major, intermediate, and minor principal stresses, respectively) during the loading–unloading process, the forces of X, Y and Z axes were applied by the force control mode at a rate of 1 kN/s (0.4 MPa/s) until reaching the desired stress level. Before unloading, the desired stress level was maintained for about 6 min. To inves-