Construction and Building Materials 161 (2018) 432–441

Contents lists available at ScienceDirect

Construction and Building Materials

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

New failure criterion models for concrete under multiaxial stress in compression

Chong Rong [a], Qingxuan Shi [a,*], Ting Zhang [a], Hongchao Zhao [b]

[a] School of Civil Engineering, Xi'an University of Architecture and Technology, Shaanxi, Xi'an 710055, China
[b] School of Geology and Mining Engineering, Xinjiang University, Urumqi 830000, China

HIGHLIGHTS

- The main factors that contribute to the failure under multiaxial stress are studied.
- The hydrostatic stress and shear stress are respectively as the main influencing factors to establish equations.
- The accuracy of each failure criterion model is verified.
- The applicability of each failure criterion model is discussed.

ARTICLE INFO

Article history:
Received 13 January 2017
Received in revised form 12 November 2017
Accepted 19 November 2017

Keywords:
Biaxial and triaxial compression tests
Twin shear strength theory
Multiaxial stress
Failure criterion models
Boundary conditions

ABSTRACT

Biaxial and triaxial compression tests were performed on 100 × 100 ×100 mm cubic specimens of concrete under different stress loading rates. All the tests were performed using a true triaxial testing machine. The analysis of the data revealed that the intermediate principal stress, hydrostatic stress and shear stress are the main factors influencing the failure criterion for concrete under multiaxial stress. Based on the twin shear strength theory, three failure criterion models were developed. The five-parameter model A considers the shear strength as the main factor, the five-parameter model B considers hydrostatic strength as the main factor, and the six-parameter model considers both the shear strength and hydrostatic strength. The parameters for these failure criterion models have clear physical significance and form the failure criterion in a theoretical analysis. Models A and B apply to different stress states and show similar results. The six-parameter model can apply to most stress states, but the computed results depend on the boundary conditions. This convenient model can also be extended for nonlinear analyses of concrete under multiaxial stress in compression.

1. Introduction

Concrete composite structures are a widely used structural form and are applied in the construction of high-rise buildings, arch dams, bridges, and other structures. In a composite structure, concrete is the most complicated component. Many researchers [1–6] have studied the behaviour of concrete under multiaxial stress. They found that the compressive strength of the concrete increases with increasing lateral compressive stress. In these previous studies, the strength of concrete under multiaxial stress is related to its uniaxial strength and lateral compressive strength, but the influences of these two strengths are different [7]. This difference is caused by several factors, for example, the strength [8] and material characteristics of the concrete [9,10], initial stress [5,11], and specimen size [12]. Many researchers have studied concrete using different methods and found that the change in the

Abbreviations: σ_1, the maximum principal stress; σ_{1t}, the maximum principal stress of each triaxial compressive ratio; σ_2, the intermediate principal stress; σ_{2b}, the intermediate principal stress of each biaxial compressive ratio; σ_{2t}, the intermediate principal stress of each triaxial compressive ratio; σ_3, the minimum principal stress; σ_{3b}, the minimum principal stress of each biaxial compressive ratio; σ_{3t}, the minimum principal stress of each triaxial compressive ratio; σ_m, the hydrostatic stress; σ_{oct}, the octahedral principle stress; τ_{ij}, the principle shear stress ($i \neq j$); τ_m, the shear stress corresponding to hydrostatic stress; τ_{oct}, the octahedral shear stress; ξ, the height in cylindrical coordinate system; ρ, the radius in cylindrical coordinate system; φ, the angle in cylindrical coordinate system; α, the tension–compression ratio; α_{bc}, the biaxial-axial compression ratio; α_{cc}, the triaxial-axial compression ratio; f_{bc}, the biaxial compress strength; f_{cc}, the triaxial compress strength; f_t, the tense strength; f_{ttt}, the triaxial tense strength; I_1, the first invariants of stress deviator; J_2, the second invariants of stress deviator; J_3, the third invariants of stress deviator.

* Corresponding author.
E-mail address: shiqx@xauat.edu.cn (Q. Shi).

https://doi.org/10.1016/j.conbuildmat.2017.11.106
0950-0618/

behaviour of a composite material is systematic, indicating that different micro-characteristics can be expressed by a similar macroscopic pattern. In the micromechanical research of concrete [13–16], the basic characteristics of concrete under multiaxial stress can be formulated in terms of six mechanical effects: the tensile-compressive strength difference, the hydrostatic stress (σ_m), the shear stress (variation in the minimum stress), the normal stress, the intermediate principal stress (σ_2), and the variation in the intermediate principal stress. In concrete applications, the stress states are complex, and designing complex structures based on only the normal failure mode of concrete is unsafe.

A failure criterion can be described by a mathematical function model to express the damage envelope surface. To quantify the mechanical properties of concrete under complex stress, many failure criteria have been proposed for a variety of concretes and stress states [17–23], such as the Mohr-Coulomb criterion, the Drucker-Prager criterion, the Willam-Warnker criterion, the Ottosen criterion, Asteris and Plevris and criterion, and the Hsieh-Ting-Chen criterion. The original equations of tensile and compressive meridians in each failure criterion employ different stress parameters, such as the principal stress (σ_1, σ_2, σ_3), the stress invariant (I_1, J_2, J_3), the octahedral stress (σ_{oct}, τ_{oct}, θ) and the mean stress (σ_m, τ_m, θ). However, the physical significance of the parameters in these model is ambiguous. There are few criteria that can precisely analyse the failure mechanism of concrete based on mechanical theory. Thus, it is necessary to explore a comprehensive failure criterion that has a clear physical significance for concrete under multiaxial stress.

In this study, a scheme for biaxial and triaxial compression tests is proposed. In this scheme, a large number of stress states are tested. Using a large experimental dataset, the influencing factors of multiaxial strength are analysed, and the main factors are determined. Based on the twin shear strength theory, the concept of a multiparameter double-shear strength failure criterion is developed. Various strength characteristics are studied as boundary conditions. Finally, coordinate system transformations are used to solve the parameters, and a new failure criterion for concrete under multiaxial stress is established.

2. Experimental program

2.1. The concrete mixture ratio

Two kinds of concrete were prepared, one for biaxial compressive specimens (BCS) and another for triaxial compressive specimens (TCS). Table 1 shows the mix proportions of the concrete by weight. Ordinary Portland cement (grade of P.O32.5) with a 28-day compressive strength greater than 32.5 MPa was used. The coarse aggregate consisted of crushed limestone with a maximum size of less than 20 mm. The fine aggregate was medium-grained sand from a natural river and had a fineness modulus of 3.0. Tap water was used to prepare the concrete samples.

2.2. Specimen preparation

Concrete specimens were made in the sizes: 100 × 100 × 100 mm cubes. The aggregate, cement and sand were weighed individually and placed in the mixer in that order, and the mixer was used to agitate the dry mixture until it became homogeneous (approximately 2 min). Then, the predetermined mass of water was slowly poured into the mixer as it was operating (approximately 5 min).

The concrete mixtures were poured into steel formworks, and the formworks were placed on a vibration table. After slight vibration, the concrete mixture filled the formwork with a uniform density. After 24 h, the specimens were removed from the steel formwork and numbered. Next, specimens were immediately placed in standard conditions (temperature of 20 ± 2 °C and humidity >95%) for curing. After 28 days, the specimens were cured in the natural environment. The duration of natural curing exceeded three months, so the influence of different batches on the concrete strength was ignored.

2.3. The test procedure

All specimens were tested in a large concrete triaxial testing machine, which can exert loads independently in three directions. For the multiaxial compressive experiment, the specimen size was 100 × 100 × 100 mm, and the three principal stresses were perpendicular to the specimen surfaces, as shown in Fig. 1(a)–(c). The multiaxial loading state is shown in Fig. 2. In the compressive direction, friction could be eliminated using three layers of plastic membrane with glycerin between each layer.

The loading mode used was proportional monotonic loading, and the loading rate was 0.2–0.4 MPa/s. Different loading mechanisms were used in the biaxial compression tests and triaxial compression tests. In the biaxial compression experiments, five stress ratios were used (σ_2/σ_3 = 0.00, 0.25, 0.50, 0.75 and 1.00). In the triaxial compression experiments, 14 stress ratios were used (σ_1:σ_2:σ_3 = 0:0:1; 0:1:1; 1:1:1; 0.1:0.1:1; 0.1:0.25:1; 0.1:0.3:1; 0.1:0.5:1; 0.1:0.75:1; 0.1:1:1; 0.25:0.25:1; 0.25:0.3:1; 0.25:0.75:1; 0.25:1:1 and 0.3:1:1). All three principal stresses were negative because the concrete specimens were in a compressive stress state, and the principal stresses could be expressed as $\sigma_1 \geq \sigma_2 \geq \sigma_3$. Each stress ratio was tested with three specimens, and the results of similar tests were averaged to yield the experimental data. Discrete results should be removed.

3. Experimental results and discussion

3.1. Results of the experiments

Table 2 shows the biaxial compression experimental results for the five BCS specimens under different stress ratios. Table 3 shows the triaxial compression experimental results for the 14 TCS specimens under different stress ratios and a uniaxial tensile strength (f_t) of 2.07 MPa. Meanwhile, the concrete shows the splitting failure is changing into flow failure with the increasing triaxial compression. It reflects that the shear stress and hydrostatic stress should be seriously considered, they might take important effect on failure form.

Table 1
The concrete mixture ratios.

	Water (kg/m^3)	Cement (kg/m^3)	Sand (kg/m^3)	Aggregate (kg/m^3)	Water cement ratio
TCS	185	330	544	1250	0.56
BCS	185	440	586	1244	0.42

Note: TCS denotes the triaxial compressive strength mixture, and BCS denotes the biaxial compressive strength mixture.