Dynamic strength of concrete under multiaxial compressive loading

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Abstract

The dynamic characteristics of concrete are important for structures subjected to earthquake actions. Now there is much experimental data about this, and most are uniaxial test data. In large concrete structures, such as concrete dams, concrete reactive power, the stress states usually are in multiaxial states; therefore the main objective of this paper is to study the multiaxial compressive characteristics of concrete subjected to high strain rates under multiaxial compressive loading. Cubic specimens (100mm by side) are subjected to quasi-static and dynamic proportional biaxial and triaxial compression tests. The strain rates used are 10^{-5}/s , 10^{-4}/s, 10^{-3}/s, 10^{-2}/s. The stress ratios are for the biaxial compression 1:0.1, 1:0.25, 1:0.5, 1:0.75,1:1; for the triaxial compression the applied constant confining pressures are 4MPa, 8MPa, 12MPA, 16MPa. The tests are carried out on a concrete triaxial dynamic test system designed by the authors. The strength characteristics of the specimens at different strain rates and stress ratios are given. The experiment results indicate that the dynamic strength of concrete under multiaxial compressive stress states is higher than that under the uniaxial compressive stress state. Based on the test data, the failure criterion is established on the octahedral stress space. Its characteristic is that the effect of the similar angle on the dynamic strength is considered to reflect the changes of the dynamic strength between the tensile and compressive meridians.
Keywords: dynamic strength, strain rate, biaxial stress state, triaxial stress state.

WIT Transactions on Engineering Sciences, Vol 72,
www.witpress.com, ISSN 1743-3533 (on-line)
doi:10.2495/MC110261

1 Introduction

Dynamic loading on concrete structures arising from natural hazards such as tornadoes, earthquakes and ocean waves is of great practical significance. Under such dynamic conditions, the loading-rate dependence of material response causes the material behaviour to be significantly different from what is observed under quasi-static conditions. Hence a thorough knowledge of material constitutive relationships and failure criterion, which cover a wide range of strain rates, is very important for the design of structures subjected to all types of loading likely to be encountered during the design lifetime.

Bischoff and Perry [1] reviewed and analyzed the response of concrete under dynamic loads and discussed factors that influence the dynamic compressive behaviour of concrete, such as concrete quality, aggregate type, age, curing, and moisture conditions. Malvar and Ross [2] reviewed the existing data describing the effects of strain rate on the compressive strength of concrete and compared the dynamic increase factor (DIF) formulation recommended by the European CEB Model Code [3]. However; extremely rare dynamic experiments in multiaxial stress states are available among the current documents. For material in multiaxial stress states, cases with biaxial compressive or triaxial compressive loading with the other side keeps constant confining pressure are the two typical loading patterns, which is of great significance for studying the behaviour under arbitrary multiaxial stress states. To improve understanding of the mechanical behaviour of concrete, experiments on the dynamic behaviour of concrete under biaxial and triaxial dynamic compression stress states were conducted in this research corresponding to the range of strain rates and stress states encountered in engineering practice.

2 Experimental program

2.1 Preparation of specimens

Plain concrete cubes with a size of 100×100 ×100 mm were subjected to biaxial or triaxial dynamic compressive loads. Commercially available Portland cement was used. Crushed natural stones were used as coarse aggregate with maximum particle size of 20 mm. River sand was used as the fine aggregates. The concrete mixture proportions by weight are water: cement: fine aggregate: coarse aggregate =1.00:1.02:4.38:5.35. All specimens required for the aforementioned tests were cast on the same day for each mix and covered with a plastic sheet to prevent moisture loss. They were demoulded after 1 day and cured in the fog room at a relative humidity of 95% and temperature of 27±2°C till the age of 7 days. The 28-day compressive strength of concrete obtained by testing standard cube specimens (150mm×150mm×150mm) is 20 MPa. Then, the specimens are dried in air for 8 weeks before testing.

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2.2 Testing of specimens

Dynamic tests were conducted on the servohydraulic multiaxial testing system designed and built at Dalian University of Technology, Dalian, China. The experimental apparatus is detailed in Figure 1 with a test setup in one loading direction illustrated in Figure 2.

Figure 1: Setup of concrete test.

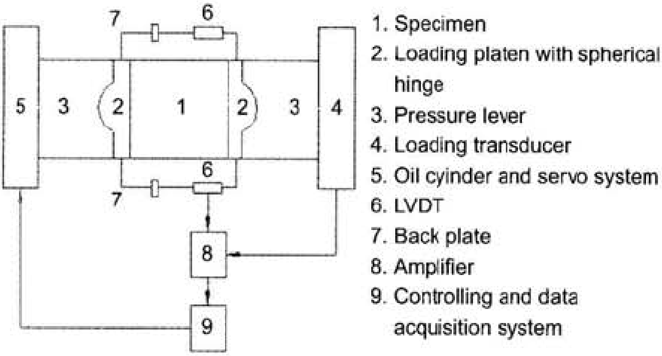

Figure 2: Illustration of testing system in one loading direction.

The testing system allowed free and independent motion in three directions. Along each direction, a pair of pressure levers loaded a test specimen through two platens located on both sides of the specimen. A spherical hinge was installed between a lever and a platen on the same side of the specimen to ensure

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that the load was exerted exactly along the load axis. The two pressure levers were connected with a load transducer and an oil cylinder, respectively. The nominal capacity of the testing system was 2000 kN in each direction. The servo valve can respond to a command signal at a frequency of up to 10 Hz. Each specimen was instrumented with six linear variable differential transformers (LVDTs), two in each loading direction. Each LVDT had a stroke of 7 mm; it was attached to the two platens that were connected in series with the two opposite faces of a cubic specimen. The measured load and deformation were transmitted to the data acquisition and the processing unit of a computer through a specially allocated amplifier. They were then converted to stress and strain, respectively, using the undeformed area and length of the specimen.

The selected loading paths consisted of uniaxial compression, biaxial proportional loading compression and triaxial compression with two constant lateral compressions. The strain rate varied from 10^{-5}/s to 10^{-2}/s. For biaxial proportional compressive loading, the stress ratios of lateral pressure to the axial load are 0:1、0.25:1、0.5:1、0.75:1、1:1. For triaxial compression with constant lateral pressure, the constant pressure is 0, 4, 8, 12, or 16 MPa respectively. To prevent lateral restraint of the loaded specimen, all the loaded surfaces are polished and equipped with three layers of plastic sheet with grease of MoS_2 to reduce the surface friction to a minimum.

3 Experimental results and discussion

Table 1 and Table 2 provide the dynamic strengths under biaxial and triaxial compression stress states. They represent the average value of each group of at least four specimens. Note that compressive stresses in all directions are positive in this paper.

Table 1: Biaxial test results.

Strain rate:/s	Strengths at different stress ratios(σ_2:σ_1)				
	0	0.25	0.5	0.75	1
10^{-5}	9.84	14.86	16.13	16.39	14.00
10^{-4}	10.63	15.48	16.68	16.75	15.32
10^{-3}	11.38	16.17	17.36	17.54	16.66
10^{-2}	12.32	17.15	18.24	18.66	18.01

Table 2: Triaxial test results.

Strain rate:/s	Confinement σ_1/MPa				
	0	4	8	12	16
10^{-5}	9.84	30.05	46.27	61.21	72.14
10^{-4}	10.63	32.11	48.08	61.42	75.34
10^{-3}	11.38	33.70	49.39	61.16	74.08

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3.1 Strength characteristics under biaxial compression

The ultimate strength of concrete in biaxial compression state is higher than the uniaxial strength at any strain rate owing to the effect of lateral confinement. At a specified strain rate, the strength increment depends on the biaxial stress ratio. The maximum biaxial strength occurs at a stress ratio between 0.5 and 0.75 for any strain rate investigated in the present study.

With the increasing strain rate, the ultimate strength at any stress ratio tends to increase. However, the increment at different stress combinations is not identical.

Based on the research cited above, it can be concluded that the strength enhancement of concrete in biaxial stress states is attributed to both the strain rate and the lateral confining pressure. A simple expression for the evaluation of dynamic strength of concrete in biaxial stress state is suggested:

$$\frac{f_{bd}}{f_{us}} = P_1 + P_2 \lg\left(\dot{\varepsilon}\Big/\dot{\varepsilon}_s\right) + \frac{P_3}{(1+\alpha)^2} + \frac{P_4\alpha}{(1+\alpha)^2} \quad (1)$$

where $\dot{\varepsilon}_s$ is the quasi-static strain rate, its value being selected as 10^{-5}/s in this paper; $\dot{\varepsilon}$ is the current strain rate; f_{us} is the uniaxial compressive strength of concrete at quasi-static loading; f_{bd} is the dynamic strength of concrete in biaxial stress state; $\alpha=\sigma_2/\sigma_1$ is the stress ratio; P_1, P_2, P_3 and P_4 represent the parameters associated with material properties. By fitting to the test, data, P_1, P_2, P_3 and P_4 are determined as −0.446, 0.0875, 1.43 and 6.42 respectively. The multiple correlation coefficient being 0.9580, and the mean error being 0.4122 MPa. The suggested relationship in eqn (1) is depicted in Figure 3 and the test results are also shown for comparison. Fairly good agreement is achieved.

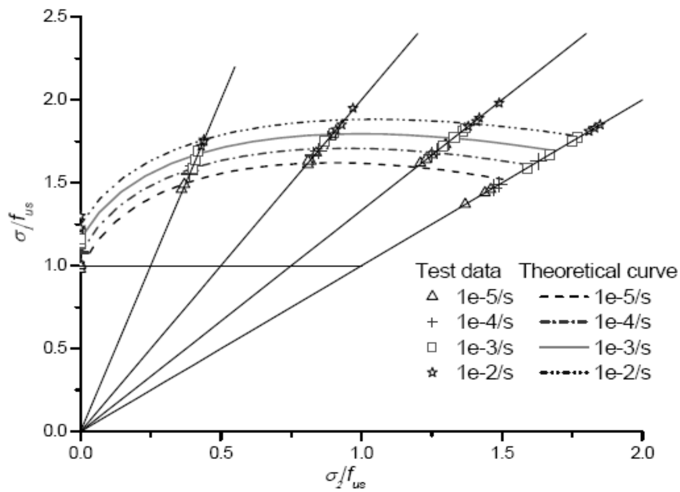

Figure 3: Biaxial strength envelop under biaxial stress obtained from the proposed criterion (c&c region).

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3.2 Strength characteristics under triaxial compression

In general, the strength enhancement of concrete in triaxial stress states is also attributed to both the strain rate and the lateral confining pressure. Newman [4] recommended a nonlinear relation between the ultimate strength and confining pressure. To take into account the effect of strain rates, Newman's equation is modified to

$$\sqrt{A(\dot{\varepsilon})\left(\frac{\sigma_{lat}}{f_{us}}\right)^2 + B(\dot{\varepsilon})\frac{\sigma_{lat}}{f_{us}} + 1} - \frac{f_c}{f_{us}} = 0 \qquad (2)$$

where $A(\dot{\varepsilon}) = a + b\lg(\dot{\varepsilon})$, $B(\dot{\varepsilon}) = c + d\lg(\dot{\varepsilon})$; f_{us} is the uniaxial compressive strength of concrete at quasi-static loading rate ; σ_{lat} is confining pressure; the material constants a, b, c, and d are determined in this study to be 2.22, −1.54, 23.7, and 1.19, respectively. Figure 4 shows the ultimate strengths at various strain rates as a function of the confining pressure. For comparison, eqn (2) was plotted in Figure 4 as well. It can be seen from Figure 4 that eqn (2) is in excellent agreement with the test data. It should be noted that the values predicted by the formula only make sense when confining pressure is smaller than the uniaxial static strength of concrete.

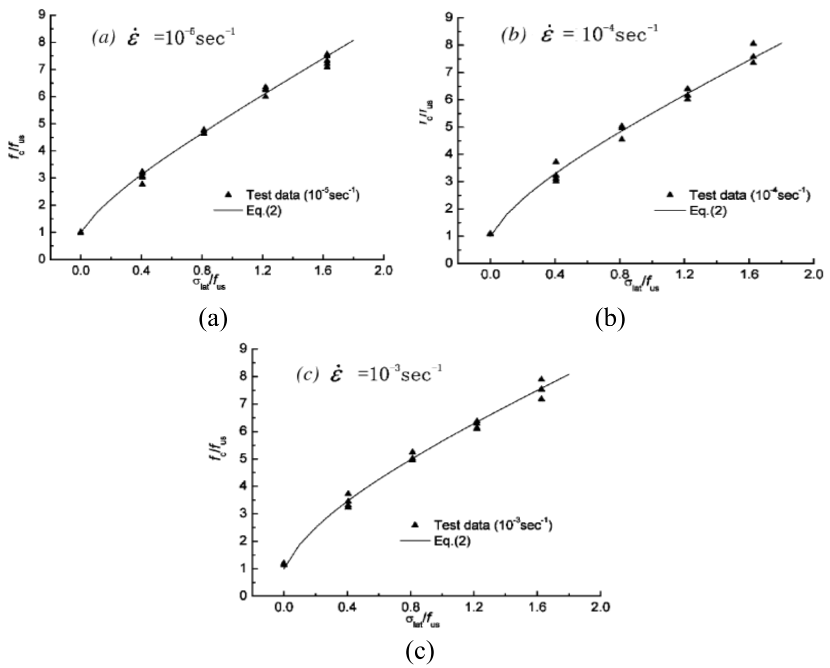

Figure 4: Triaxial strengths of concrete at various strain rates.

4 United failure criteria in octahedral stress space

Based on the strength characteristic of experimental results in Table 1 and Table 2 and theoretical analysis of the failure enveloping plane, the present paper proposes a new failure criterion as the following:

$$\frac{\tau_{oct}}{f_{cs}} = a_1 - b_1\left(\frac{\sigma_{oct}}{f_{cs}}\right) + c_1\left(\frac{\sigma_{oct}}{f_{cs}}\right)^2 \tag{3}$$

where $\sigma_{oct} = \frac{1}{3}(\sigma_1+\sigma_2+\sigma_3)$, $\tau_{oct} = \frac{1}{3}\left[(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2\right]^{1/2}$; a_1, b_1, c_1 are parameters depending on the loading rate, which can be determined by fitting to the test data, as listed in Table 3.

Table 3: Fitting results.

Strain rate/s^{-1}	a_1	b_1	c_1	R^2
10^{-5}	0.2033	−0.9730	−0.4816	0.9547
10^{-4}	0.2865	−0.7384	−0.2948	0.9497
10^{-3}	0.3550	−0.5723	−0.1647	0.9505
10^{-2}	0.4187	−0.4708	−0.0975	0.9407

A total of 236 experimental data points of concrete under dynamic biaxial compressive loads and triaxial compressive loads, were used in the verification of the proposed failure surface for concrete under dynamic loading, as illustrated in Figure 5. Comparisons in Figure 5 indicate that the failure envelope in the octahedral stress space gradually expands with the strain rate.

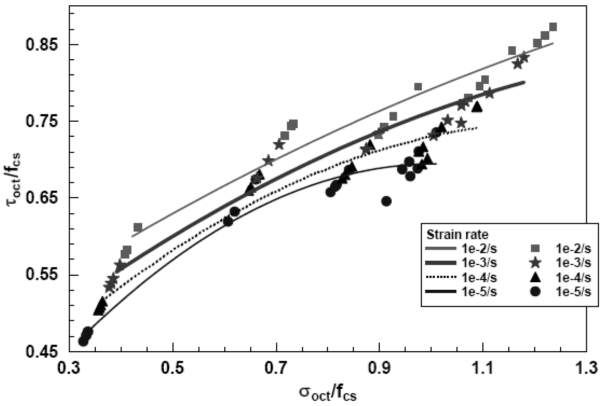

Figure 5: Summary of biaxial and triaxial compressive test data and the proposed envelopes.

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5 Conclusions

The dynamic behavior of concrete in biaxial and triaxial stress state has been experimentally studied under linearly increasing loads of high strain rates. Based on the extensive test data and analyses, the following conclusions can be drawn:

(1) The ultimate strength of plain concrete nonlinearly increases with its confining pressure at all load/strain rates that were considered in this study, but the magnitude of increment depends on the lateral stress ratio.

(2) At low confining pressure, the ultimate strength of concrete increased with the strain rate. When the confining pressure was approximately higher than the uniaxial static strength, the ultimate strength tended to vanish with the strain rate.

(3) Under biaxial and triaxial stress state, the failure envelope in the octahedral stress space gradually expands with the strain rate.

(4) The proposed united strength criterion for concrete under multiaxial stress state reasonably reflects both the effect of strain rate and the effect of lateral confinement. Fairly good agreement with experimental results is achieved.

Acknowledgements

This study was supported by the National Natural Science Foundation of China under Grants 90815026 and 51079019 at Dalian University of Technology, Dalian, China, and Grant 50908026 at Dalian University, Dalian, China.

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