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Compressive behavior of stirrup-confined concrete under dynamic loading

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HIGHLIGHTS

- The new design of the pure stirrup confined specimen without concrete cover.
- The coupling between the strain rate effect and the stirrup confinement effect.
- The newly developed stochastic damage model with considerations of the strain rate effect and the stirrup confinement effect.

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ABSTRACT

Systematic experiments were designed and performed to investigate the compressive behavior of cuboid stirrup confined concrete under dynamic loading. A total of 123 prismatic concrete specimens with four stirrup volume ratios were tested under three levels of strain rates with the help of an electro-hydraulic servo-controlled concrete testing system. Photos of the failed specimens and the complete stress–strain curves were obtained under the strain control loading scheme. The mean values and the standard deviations of stress–strain curves were also obtained and analyzed. The results show that the strength of concrete are enhanced by the stirrups as well as strain rates. The enhancement of stirrup confinement and the enhancement of strain rate are comparable to each other. The stochastic damage model is adopted to describe the nonlinear performance and the randomness of concrete. Based on the experimental data, the model is verified and the parameters are identified. This study provides a foundation for the dynamic analysis of concrete structure.

1. Introduction

Confined concrete is widely used in civil engineering due to its higher compression strength and better ductility than the plain concrete. The studies of compressive behaviors of concrete could be traced to early 1900s. Considere [1] firstly indicated the concept of confinement stress from spirals. Richart et al. [2] reported that the transverse confinement could be converted to the vertical load bearing capacity. Subsequent studies concentrated on exploring the influence of stirrups on concrete based on experiential models until 1980s [3–14]. These works provide a preliminary perspective on the influence of stirrup confinement. Then, Sheikh and Uzumeri [15] proposed the concept of "effective confinement area" to consider the effect of rectangular stirrups. On the basis of effective confinement definition, Mander et al. [16] systematically investigated the behaviors of confined concrete and proposed a unified stress–strain model. This model is currently regarded as the cornerstone for the research of concrete. Later, numbers of models were proposed as the extensions of Mander's model [17–21].

The behaviors of concrete are usually dependent to the loading rate. The higher loading rate usually yields higher apparent strength. The strain rate effect of plain concrete was testified and investigated by many experimental and theoretical works [22–26]. On the other hand, concrete usually works with the steel stirrups for building structures. Therefore, a model considering the enhancements of both the strain rate and the confinement may be developed in the view point of engineering application. And this model should be verified based on the experiments designed for concrete undertaking confinement and dynamic loading. Only numbers of experimental and theoretical works have been done for confined concrete under dynamic loading. Scott et al. [27] performed numbers of tests for stirrups confined concrete specimen under dynamic loading and improved the Kent-Park stress–strain model based on the experimental data. Ahmad and Shah [28] performed systemic experiments for the behavior of hoop confined

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concrete. Totally 94 specimen were tested and the stress–strain curves of the hoop confined concrete under different strain rates were reported. Empirical equations were proposed to predict the effect of strain rate on secant modulus of elasticity, peak stress and strain. In the studies of recent years, the confining stress was also applied by the hydrostatic pressure with the help of hydrostatic loading cell [29]. Under a high level of confinement, the strength enhancement by the strain rate was obviously suppressed.

Furthermore, randomness is an important feature of concrete. The exploration of the randomness can improve the predictions for the behavior of concrete to a certain extent. For example, if the strain at a time point is known, the range of stress could be determined based on the stochastic analysis. The random features of stress–strain curves are also required for the reliability analysis of concrete structure especially for which the structural nonlinearity is considered. However, the randomness of stress–strain curves have not been well investigated in experiments. In the present work, we investigate the random stress–strain curves based on the concept of redundancy tests. That is to say, we suggest that more than twelve specimens should be tested under the same loading condition and at least nine full stress–strain curves should be obtained for each loading condition. Based on a group of stress–strain curves, not only the mean-value curve but also the standard deviation curve could be calculated. The randomness of stress–strain behaviors could then be captured.

This study aimed to experimentally investigate the behavior of concrete under dynamic compression based on the redundancy test protocol. A total of 123 prismatic concrete specimens were divided into 12 groups. In total, four levels of stirrup ratios and three levels of loading rates were considered. The mean value and standard deviation stress–strain curves were obtained based on the tested stress–strain curves. The stochastic damage theory was developed to model the stochastic damage behaviors of concrete under the dynamic compression with stirrup confinement. Model parameters were identified based on the experimental mean value and standard deviation stress–strain curves. Model results agree well with the experimental results, which demonstrated that the proposed model was reasonable.

2. Experimental program

2.1. Materials

The concrete used in the experiment was designed and produced by a commercial concrete company. The fine aggregate was yellow and medium sand. The coarse aggregate was gravel with particle size of 5–25 mm. Slag and fly ash were added to improve the workability and strength of concrete. The admixture was entraining superplasticizer. Table 1 shows the detailed mixture ratio of concrete. Stirrups were hot-rolled ribbed bars with designed yield strengths of 400 MPa. The diameter of the stirrups was 6 mm. The tested mechanical properties of the plain concrete and the steel reinforcing bars are listed in Table 2.

Table 1
Mixture ratio of concrete.

Constituent	Weight, kg/m^3
Water	122
Portland cement	255
Sand	822
Gravel	998
Fly ash	72
Entraining superplasticizer	6.16
Slag	98

Water/cementitious material = 0.48; fine aggregate ratio = 45.2%.

Table 2
Mechanical properties of plain concrete and steel reinforcing bars.

		Mean value	Standard deviation
Plain concrete	Young's modulus (MPa)	45.7	5.0
	Uniaxial compressive strength (MPa)	36631	2266
Steel reinforcing bar	Young's modulus (MPa)	185769	10036
	Yielding stress (MPa)	629	65

2.2. Specimens

The cage of steel reinforcing bars was fabricated beforehand and placed into the mold. Then concrete was casted into the mold. The prepared specimen was in the form of RC short column with the dimensions of 150 × 150 × 400 mm.

The design and preparation of the specimen are more or less different from the regular RC column due to the objective of the research. Our research is concentrated on the confined concrete. Thus the unconfined concrete within the specimen should be as less as possible to reduce its influence to the experimental results. But in the real engineering structures, the concrete covers are required to protect the steel bars from environmental attacks even though they are not undertaken any confinements. To evaluate the possible influence of concrete cover to the experimental results, simple calculations were performed in the present work. Consider the regular section of RC column shown in Fig. 1. It is easy to see that the cover concrete occupies more than 40% of the sectional area. As we know, the failure pattern of cover concrete is usually more complicated than plain concrete due to the disturbance of stress from the inside steel bars. Moreover, the behaviors of cover concrete is out of scope of the present work and also play insignificant role in structural design and analysis.

The cage of steel reinforcing bars is shown in Fig. 2. The steel wires with the diameter of 3 mm are adopted as the longitude reinforcement. Thus the axial load carried by the longitude bars could be neglected because their sectional areas are too small. The hoops of lateral bars are as large as possible. They actually contact the inner face of mold so that the thickness of cover concrete should be nearly zero. The volumetric ratio of stirrup was determined by the spacing, which had four levels: plain (0%), low (0.95%), middle (1.66%), and high (2.61%). After careful makeups, the specimens were cured with proper humidity and temperature for at least 28 days. The upper and lower faces of the demolded specimen were smooth and parallel to each other.

As the strain rate of the structure under seismic action was approximately 10^{-3}–10^{-2}/s [23], the strain rates considered in this study had three levels including 10^{-5}/s (quasi-static), 10^{-3}/s (low rate), and 10^{-2}/s (high rate). Each of the stirrup ratio corresponded to three levels of strain rates.

2.3. Test machine system

The stiffness of the test machine and the accuracy of the data collection were crucial to obtain the complete stress–strain curves. The test machine was an electro-hydraulic servo-controlled concrete testing system. The spherical hinge in the upper platen relieves the possible bending of the specimen. And the scale marks on the bottom platen are used to guarantee the accurate centration of the specimen. The stiffness of the machine reached