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True-triaxial compressive behaviour of concrete under passive confinement

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HIGHLIGHTS

- True-triaxial compression tests associated with passive confinement were successfully conducted on concrete cubes.
- The tests firstly extended the database for concrete with non-uniform passive confinement field and explicit stress ratio.
- The models for failure strength and corresponding axial strain were proposed.
- True-triaxial failure performance associated with passive confinement was different from that with active confinement.

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ABSTRACT

With the new triaxial testing system developed to generate passive confinement, 117 normal-weight concrete cubes were tested under 13 loading schemes, including biaxial compression and triaxial compression with both uniform and non-uniform passive confinement. The distinct failure patterns were observed under different monotonic loading schemes. The characteristics of peak strength and corresponding axial strain were investigated and compared with data for concrete under traditional triaxial testing. The peak strength and corresponding axial strain have been observed to be related to the confinement stiffness, non-uniform stiffness ratio and the maximum lateral strain. On comparison, it revealed that the models calibrated from the traditional triaxial testing could predict the peak strength with an error within ±10% but cannot well predict the corresponding axial strain.

1. Introduction

A multiaxial stress state is common for concrete material in structures. When the concrete is associated with fibre reinforced polymer (FRP) confinement, the triaxial stressing of concrete is characterized by passive confinement. Due to the linear elasticity of FRP wrapped around the concrete structural members, the lateral confinement will be generated and increased linearly with the development of lateral expansion, which is designated passive confinement. For circular cross sections, concrete is subject to uniform confinement pressure across the section, i.e., two equal principal stresses. The pressure is to be calculated explicitly. Such a multiaxial stress condition can be well simulated by the FRP-confined cylinder to investigate the mechanical behaviour. Since the 1990s, normal-weight concrete [1–3] to high-strength concrete [4,5], and static loading [1–7] to cyclic loading [8,9] have been thoroughly studied. However, in the real structures, more complicated multiaxial stress appears in the concrete structural members such as square and rectangular columns. For non-circular sections within FRP wraps, the confinement field is non-uniform and implicit in the column testing. To predict the mechanical behaviour for concrete under non-uniform passive confinement, the confinement efficiency factor was introduced for the column subject to the equivalent uninform confinement [10,11], but such methods cannot be used for three-dimensional structural analysis. The constitutive model is needed.

To date, numerous constitutive models have been proposed by researchers [12–16]. The development required vast databases of concrete under triaxial testing. The true-triaxial testing equipment is essential for the calibration of the model. Generation of three principal stresses independently and actively is versatile, while it cannot generate passive confinement. A majority of numerical analyses adopted these constitutive models to study the behaviour of concrete structural members subject to steel confinement [17–19] or FRP confinement [20–22]. Recent experimental investigation

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has found path-dependence between active and passive confinement in the case of uniform confinement [4,23,24]. The efficiency and accuracy of these simulations is questionable in the case of the FRP application because the existing true-triaxial testing data that the models were based on were limited to the case of active confinement. Up to now, no attempt has been made to investigate the true-triaxial compression behavior of concrete under passive confinement.

A new true-triaxial test system was developed by the authors at Tongji University [25]. This system can exert passive loads in two perpendicular directions independently and simultaneously with the axial loading. In this paper, an experimental study on concrete cubes was conducted using the new system. The cubes with three different concrete strengths and a total of 117 pieces were tested under 13 different monotonic loading schemes, including the biaxial and triaxial compression. Generation of the first database for true-triaxial compressive behaviour of concrete under passive confinement is helpful. The failure pattern and mechanical behaviour were investigated and compared with the traditional triaxial testing. Besides the explicit model for peak strength and deformation, the failure surface in the octahedral stress space considering the typical feature of FRP confinement was developed in this paper. The former one can benefit the quick calculation at ultimate state design for engineers. The latter is the key component of a concrete plasticity model.

2. Test program

2.1. Specimens

Normal weight concrete cubes (117 pieces) with the dimensions of 100 mm × 100 mm × 100 mm were cast for the triaxial compression test. The cubes were divided into three batches by their designed 150 mm cubic 28-day strength, that is, 20 MPa, 30 MPa, and 40 MPa. All of the cubes were cured in the standard curing room for 28 days. Then, the casting surface of each cube was ground using a grinding machine and smoothed with mortar of the same water-cement ratio. All of the cubes were tested after 90 days to minimize the age effect.

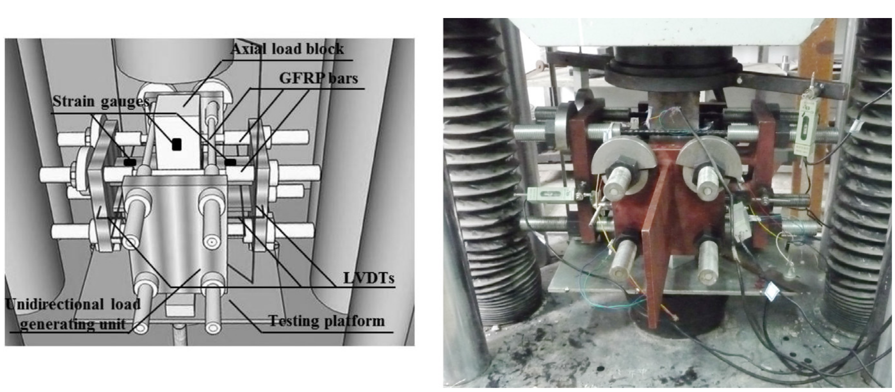
2.2. Test equipment and setup

The new true-triaxial test was conducted using a uniaxial compression test machine (2000 kN/SHT4206 Servo hydraulic testing machine) associated with a biaxial loading apparatus designed by the authors (Fig. 1) [25]. The biaxial loading apparatus was assembled with two unidirectional load-generating units. Each unit was designed to exert the passive confinement, where the stiffness was controlled by the diameter of four embedded Glass FRP (GFRP) bars with the same Young's modulus. In the current testing program, four different diameters (i.e., 8 mm, 10 mm, 14 mm, 16 mm) were adopted with the Young's modulus (E_r) of 45 GPa. For each load-generating unit, pairs of Linear Variable Differential Transformers (LVDTs) and strain gauges were set for acquiring the deformation and pressure in one lateral direction. The axial deformation and load were obtained from the vertical LVDT and the load cell in the compression machine. Six two-ply greased Teflon sheets were used as the friction reduction pad. The configuration was determined by the parametric study through uniaxial compression test on concrete cubes with the change of ply number of Teflon sheets and interlayer grease [25]. As the friction is proportional to the normal stress and the lateral passive pressure is usually lower than unconfined concrete strength, the determined configuration was also efficient for reducing the friction on side surface. Before testing, first two friction reduction pads were placed on the upper and lower surfaces of concrete along the axial direction. When two unidirectional load-generating units encased the cube before tighten the anchorage, the remaining four pads were inserted into each gap beside the cube side.

When the setup was prepared, the test was initiated by exerting an axial load from the compression machine by the displacement control at a constant loading rate of 0.1 mm/s. The load would be terminated once the deformation in one lateral deformation reached 2 mm, which was the deformation limit of the biaxial loading apparatus to maintain its elastic behaviour.

2.3. Test program

Two categories of monotonic test programs were designed: biaxial compression (C/C, where C for compression) and triaxial compression (C/C/C). The mechanical behavior of concrete under biaxial and triaxial tension-compression is not in the current investigation scope, as passive confinement cannot be generated in TTC and TC, where T for tension, or takes minor effect in C/C/T. The passive confinement will not be generated until concrete dilation happens, and the dilatation needs to be initiated by the active compression in another perpendicular axis from the Poisson ratio effect. The active compression was generated by the uniaxial compression test machine in the new system. Therefore, both active compression and passive confinement pressure need coexist in the same load scheme. The load schemes TTC and TC can only have active confinement. In the scheme of C/C/T, the compact component in the axis of passive pressure due to the tension will counteract part of dilation component due to active compression. Based on



a. Illustration[25] b. Photo

Fig. 1. Sketch of triaxial loading system [25].