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Seismic performance of reinforced concrete columns after freeze–thaw cycles

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HIGHLIGHTS

- Eight RC columns subjected to freeze–thaw cycles under low cyclic loading were tested.
- Effect of freeze–thaw cycles and axial compression ratios on the seismic performance of RC columns were investigated.

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ABSTRACT

The purpose of this study is to investigate the seismic performance of reinforced concrete columns after freeze–thaw cycles. Based on low cyclic loading tests of eight column specimens, the failure patterns, hysteresis loops, load carrying capacity, displacement and ductility factor, skeleton curves, stiffness degradation and energy dissipation capacity of frost-damaged concrete columns were analyzed. The effect of freeze–thaw cycles and axial compression ratios were investigated in detail. Test results show that for the column specimens under the same level of axial compression, with the number of freeze–thaw cycles increasing from 0 to 300, the plastic deformation capacity decreased whereas the rate of stiffness degeneration and strength decay increased continuously. The coupling effect of the deterioration of material and loosening of bond induced the value of equivalent viscous damping coefficients to decrease at first then increase, however, the cumulative energy dissipation decreased continuously. Test results also indicate that for the column specimens with the same level of frost damage, with the increase of axial compression ratio, the load carrying capacity and initial stiffness increased, whereas the deformability capacity, the equivalent viscous damping coefficients and the cumulative energy dissipation decreased obviously, respectively.

1. Introduction

Freezing and thawing damage has became a primary problem of durability for hydraulic concrete structures in the northern part of China [1]. Freeze–thaw induced degradation, which include the deterioration of material and loosening of bond, caused a change of these structures' mechanical property. Meanwhile, these structures are also probably subjected to earthquake excitation according to Seismic Ground Motion Parameter Zonation Map of China [2]. Therefore, the seismic performance assessing of these deteriorated concrete structures is becoming more and more urgent and important.

Several researches have been primarily concerned with the effect of freeze–thaw cycles on the material property of concrete. Shi [3] showed that the freeze–thaw-induced deteriorations of mechanical properties for normal strength concrete would be more serious than that for high-strength concrete. With the number of freezing and thawing cycles (*FTC*) increasing, the elastic modulus and compressive strength of concrete decreased whereas the strain at peak compressive stress increased [4–7], the fracture energy of concrete initially increased and then decreased [8–10]. Hasan [11] and Zou [12] have experimented the stress–strain response of frost-damaged concrete subjected to fatigue loading. It showed that the fatigue deformation modulus of concrete decreased as the number of freezing and thawing cycles increased [11], and the reduction of fatigue strength as increasing the number of loading cycles to failure for frost-damaged concrete is faster than that for undamaged concrete [12]. Xu et al. [13] experimented the dynamic constitutive relation of concrete with freeze–thaw damage under repeated loading, it showed that the hysteresis of strain recovery during unloading process for frost-damaged concrete is

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Notation

FTC	freezing and thawing cycles
CA	coarse aggregate
TA	thin aggregate
WRA	water reducing agent
AEA	air-entraining agent
v	axial compression ratio
RCS	relative compressive strength
C.V	coefficient of variation
P_y, Δ_y	yield load and corresponding displacement, respectively
P_m, Δ_m	maximum load and corresponding displacement, respectively
P_u, Δ_u	ultimate load and corresponding displacement, respectively
u	ductility factors
h_{ey}, h_{em}, h_{eu}	equivalent viscous damping coefficients corresponding to the yield load, the maximum load and the ultimate load, respectively
E_p, E_{pi}	cumulative energy dissipation and the area of one single hysteresis loop, respectively

more obvious than that for undamaged concrete. Several kinds of stress–strain models of frost-damaged concrete have been proposed, see [4,6,7,13]. Another group of studies have investigated the effects of freeze–thaw cycles on the bond property of concrete, and some kinds of bond stress–slip relationships of frost-damaged concrete have been proposed, see [14–17]. Shih et al. [14] showed that cyclic temperature changes appear to have a decisive influence on the maximum bond resistance and the shape of the bond stress–slip relationships of concrete subjected to monotonic and reversed loading. Frost damage even need not to reach the reinforcement layer to have significant influence on the bond behavior, even slight damage in the structure of concrete cover can reduce the maximum bond tension considerably [16].

Conclusively, material and bond properties of frost-damaged concrete have been fully studied. While relatively little attention has been paid to the macroscopic change of mechanical properties of structures subjected to freeze–thaw cycles. A few studies involving the load-carrying capacity, which include flexural behavior [16,18–20], shear behavior [21] and eccentric compression behavior [22] of frost-damaged concrete structural components under monotonic loading, have been reported. In an experimental study carried out by Petersen et al. [16], the moment–curvature relations of slightly damaged beams and intensively damaged beams were compared with that of undamaged beams, respectively. It was found that even with very small freezing and thawing damage the decrease in stiffness before and after cracking is apparent, and the tension-stiffening effect is less for the damaged beam. Hanjari et al. [23] devised a method to quantify the effect of freeze–thaw cycles on the load-carrying capacity in ultimate limit state by finite element analysis. The previous research were primarily concerned with the influence of freeze–thaw cycles on the load-carrying capacity of concrete structural components under monotonic loading, however, to the authors' knowledge, there have been no tests made to experimentally investigate the seismic behavior of frost-damaged concrete structures under low cyclic loading.

The main purpose of this study is to investigate the effect of freeze–thaw cycles on the seismic performance of reinforced concrete columns. Therefore, eight reinforced concrete columns with four kinds of damage states and two kinds of axial compression ratio were made, and then the low cyclic loading tests were carried out. The failure modes, hysteresis loops, load carrying capacity, displacement and ductility factor, skeleton curves, stiffness degradation and energy dissipation of frost-damaged concrete columns were analyzed, in addition, the number of *FTC* and axial compression ratios (v) were the main factors to be considered. The outcome of the tests can provide meaningful references for the seismic performance assessing of the deteriorated concrete structures.

2. Experimental program

2.1. Materials

The early strength Portland cement (*C*) with a 28-day nominal compressive strength of 42.5 MPa was used in this research. The practical compressive strength of the cement at 3-day and 28-day were 22.0 MPa and 47.2 MPa, respectively. The man made stone with a particle size of 5–20 mm and the nature sand with a modulus of fineness above 2.6 were adopted as the coarse aggregate (*CA*) and thin aggregate (*TA*), respectively. Water reducing agent (*WRA*) and air-entraining agent (*AEA*) were also added into the concrete meeting the regulation of Chinese code GB50119-2003 [24]. The concrete used in this study was of grade C30, with a water cement ratio of 0.5, see Table 1 for mix composition. Two kinds of steel reinforcing bars with different specification were used in the specimens. The mechanical properties of steel bars are listed in Table 2.

2.2. Design and fabrication of specimens

Eight rectangular RC columns with cross-section of 200 × 200 mm^2 and height of 1100 mm were fabricated in this experiment, forty concrete cubes of 100 mm were cast as the reference specimens. A summary of column specimens parameters is presented in Table 3. Cantilever-type specimens fixed at a concrete base were adopted, and the dimensions of the base was 900 × 500 × 400 mm^3. The longitudinal reinforcement of the specimens is symmetrically arranged and well distributed around the cross-section, and the percentage of longitudinal reinforcement and transverse stirrups for all of the columns were 2.308% and 0.942%, respectively. The thicknesses of concrete cover of the stirrups was 20 mm. The geometry and reinforcement details for the specimens are shown in Fig. 1. It should be pointed out that secondary concreting was adopted during the fabrication process for avoiding the frost damage of column-base joint, i.e. the columns with a dimensions of 200 × 200 × 1180 mm^3 were fabricated at first, of which the anchor bars in the concrete base was reserved, see Fig. 2, when the freeze–thaw exposure of all columns were finished, fabrication of formboard and secondary concreting were carried out for all the column specimens, see Fig. 3.

2.3. Freeze–thaw exposure

The fast freeze–thaw tests were carried out in the Large-scale Climate Simulation Laboratory at Xi'an University of Architecture and Technology, see Fig. 2. After 24-day curing, all of the columns were submerged in tap water at 29 ± 5 °C for 4 days. Then they were stored in the freezing chamber to reach the desired levels of frost damage, i.e. number of *FTC* = 100, 200 and 300, respectively. Temperature variation in one *FTC* in this test is determined by Chinese code GB/T50082-2009 [25] and is shown in Fig. 4, wherein the maximum temperature is 10 °C maintained for 65 min and minimum temperature is −17 °C maintained for 60 min. The temperature change to reach the maximum and minimum temperature are 0.90 °C per minute and 0.257 °C per minute, respectively. There was a spray phase maintained 5 min at the end of the maximum temperature phase. One *FTC* consumed 260 min in total.

Table 1
Concrete mix composition.

Concrete strength	*W/C*	Mix (kg/m^3)					
		W	*C*	*TA*	*CA*	*WRA*	*AEA*
C30	0.5	190	380	769	1061	2.667	0.076