Engineering Structures 124 (2016) 49–63

Contents lists available at ScienceDirect

Engineering Structures

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

Seismic behaviors of squat reinforced concrete shear walls under freeze-thaw cycles: A pilot experimental study

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ARTICLE INFO

Article history:
Received 26 November 2015
Revised 7 June 2016
Accepted 8 June 2016

Keywords:
Freeze-thaw cycles
Squat reinforced concrete shear wall
Seismic performance

ABSTRACT

An experimental study was undertaken to investigate the influence of freeze-thaw cycles (FTCs) on the seismic performance of shear wall specimens. Four identical squat reinforced concrete (RC) shear wall specimens were tested; three were subjected to 100, 200 and 300 FTCs, and the other one was left undisturbed and used as a control specimen. The shear wall specimens were loaded in a reverse cyclic manner, and the principal damage states were investigated throughout the testing process. The responses of the wall specimens were initially dominated by flexural cracking but gradually changed to shear cracking; the damage patterns of the wall specimens gradually changed from diagonal tensile failure to compressive failure, as the number of FTCs increased. Based on the test results of this study, the effects of FTCs on the damage characteristics, hysteretic behavior, ductility, secant stiffness degradation, strength degradation and energy dissipation capacity of the samples were analyzed. The test results indicate that FTCs have significant effects on the seismic performances of shear walls. As the number of FTCs increases, the load-carrying capacity decreases significantly, and the contribution of shear deformation increases significantly. Specimens experiencing more FTCs tend to have larger ductility coefficients and plastic rotation magnitudes. Note that the energy dissipation coefficient and cumulative hysteretic dissipation energy are more sensitive to changes in the number of FTCs than the work index.

1. Introduction

It is known that frost action in cold climates is one of the major causes of concrete deterioration [1]. The physical damage of concrete caused by freeze-thaw cycles (FTCs) is usually considered to be a durability issue of concrete surface only, and the FTC influence on concrete mechanical behavior is often not considered [2]. However, for existing buildings, frost action is a long-term process that cannot be observed within a short period until the concrete cover begins to spall. As the number of FTCs increases, buildings become more structurally fragile; thus, a procedure to evaluate the performance of existing buildings under FTCs shall be developed.

In cold regions, such as Northeastern China and Xinjiang Province, Reinforced Concrete (RC) structures experience frost action for long periods each year; the temperature during these periods varies significantly between day and night, providing a natural condition for frost action. In middle and northern Europe, as well as North America, Canada, Japan and Russia, RC structures damages caused by FTCs received significant attention for several decades [3]. For instance, in United States, many RC structures are constructed in extreme cold regions like North Dakota, where the freeze and thaw process becomes a key influence on the mechanical behavior of concrete [4]. In Canada, the infrastructure is deteriorating rapidly because of exposure to cold-climate conditions such as freeze–thaw action, deicing salts and sustained low temperatures [5].

Water is typically splashed onto bridge piers and shear walls and columns of underground parking structures, making the concrete surfaces wet; when temperatures drop below 0 °C, the water freezes. Powers [6,7] reported that as the water in moist concrete freezes, it causes pressure to increase in the pores of the concrete. If this pressure exceeds the tensile strength of the concrete, the cavity will dilate and rupture. The cumulative effect of successive FTCs and the disruption of the concrete's paste and aggregate can eventually cause expansion, cracking, scaling, and crumbling of the concrete.

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http://dx.doi.org/10.1016/j.engstruct.2016.06.013
0141-0296/

To determine the frost resistance of plain concrete, concrete specimens that are shaped as cylinders, prisms and cubes are often tested with a standard freeze-thaw test (e.g., ASTM C666-92 [8], RILEM TC176-IDC2002 [9] and GB/T50082-2009 [10]). For a reinforced concrete (RC) building, the reinforcement bars meshes and stirrups in the RC components could restrict the propagation of the freeze-thaw cracks and improve the compression and tension strengths of the section core concrete as well as the ductilities of the RC components. However, the freeze-thaw testing method used by the current standards [8–10] does not consider this advantageous confinement effect.

Studies of FTCs have primarily focused on material-level behavior, such as concrete strength and stiffness, stress-strain relationships of concrete, and bond strength [2,11–15], and have not considered the confined concrete strength. Duan [16–18] investigated the stress-strain relationship for stirrup-confined concrete after FTCs by testing two series of concrete specimens. Analytical models for the stress-strain relationship of freeze-thaw unconfined and confined concrete were empirically developed; however, the scope of this study was limited to the material level. The deterioration models for concrete elastic modulus and bond strength subjected to FTCs were adopted to compute the moment-curvature relation of RC beams damaged by FTCs, while the cyclic degradation behavior of strength and stiffness of the specimens damaged by FTCs was not yet investigated [19].

RC buildings are subjected to mechanical loads and environmental effects. However, studies of the cyclic material behavior of concrete damaged by FTCs have been limited to date [2,20], and the cyclic material behavior of confined concrete damaged by FTCs has never been described.

In addition, the deterioration of seismic performance due to cyclic load reversals and frost action is not reported for RC structures in the above analyses. Therefore, this study presents a pilot experimental study of the seismic behaviors of RC shear walls that experience FTCs. This study aims to experimentally investigate the influence of FTCs on the seismic behaviors of RC members and describe the related physical mechanisms behind the experimental phenomena. In this experiment, four identical squat reinforced concrete shear walls were tested at FTCs ranging from 0 times to 300 times under cyclic reversal of loads.

2. Experimental program

2.1. Description of test specimens

Considering the limitation of the dimensions of the environmental chamber used in this study, four identical RC shear wall specimens were designed for testing with various numbers of FTCs and the design parameters of wall specimens were shown in Table 1. The walls constructed were 0.7 m long, 0.7 m high, and 0.1 m thick. The aspect ratio and moment-to-shear ratio of the walls were 1.0 and 1.14, respectively. Boundary elements in the form of beams were set for the shear walls. The concrete clear cover was 10 mm, and the reinforcement used was smooth bars except for deformed bars, which were used as the boundary's longitudinal reinforcement, which consisted of four Grade HRB335 vertical bars. The vertical and horizontal web reinforcements were 6-mm-diameter bars with grade HPB235. Axial and lateral loads were transferred to the walls through the beams constructed over the wall webs. Wall foundations were clamped to the laboratory strong floor. Cross-section and reinforcement details of the four wall specimens are shown in Fig. 1. It should be noted that the shear span ratio of the tested shear wall specimens under FTCs is limited to 1.14, and test on wall specimens with a shear span ratio of 3 under FTCs (which might be dominated by flexural failure) is now on progress and will be reported in the future.

The mixing ratio for C50 concrete was 400 kg/m^3 of cement, 980 kg/m^3 of sand, 810 kg/m^3 of fine gravel, 95 kg/m^3 of water and 80 kg/m^3 of fly ash. Ordinary Portland cement P.O 42.5R and medium sand were used, and the maximum size of the fine gravel particles was 15 mm. Three standard cubic specimens of concrete were prepared under the same conditions as the shear walls. The real strengths of the concrete and the reinforcement bars were determined via material property tests. The average cubic compressive strength of the concrete was 55.08 MPa, and the properties of the reinforcement bars are shown in Table 2.

2.2. Freeze-thaw cycle in the environmental chamber

The environmental chamber, which can simulate various environments such as varying temperature and humidity, salt spray, solar irradiance, acid rain and carbon dioxide levels, was used for the durability testing. The chamber was manufactured by Wuhuancq model (ZHT/W2300) with a temperature range of −20 to 80 °C and dimensions of 2.5 m long, 2 m tall and 2 m wide [21], as shown in Fig. 2(a). The primary technical specifications are:

(1) Temperature range: −20 to 80 °C, temperature departure: ±2 °C, temperature fluctuation ⩽ ±0.5 °C, heating rate: 1–0.7 °C/min (−20 to 80 °C, empty), cooling rate: 1–0.7 °C/min (80 to −20 °C, empty).
(2) Humidity range: 30–98% RH without heating samples, humidity departure: ① 2 to −3% (>75%RH) and ② ±5% (⩽75%RH).

Due to the limited dimensions of the environmental chamber, the wall specimens were divided into shear walls, loading beams and foundation blocks and were subsequently casted together in sequence. The shear wall parts were first casted and cured for 28 days under a natural environment, and then placed in 15–20 °C water for four days before being placed into the environmental chamber, as shown in Fig. 2(b). The freeze-thaw testing process is shown in Fig. 2(c). After the setting cycles were finished, the wall was re-casted with the loading beam and foundation block, as shown in Fig. 2(d).

The environmental parameters of the FTCs are shown in Fig. 3; each freeze-thaw cycle lasted 5.5 h. To produce better freeze-thaw effects, 5 spray cycles were applied before each freeze-thaw cycle began; each spraying cycle lasted for 3 min (1 min of spraying, followed by 2 min without spraying). The freeze-thaw process

Table 1
Design parameters of wall specimens.

Specimen number	λ	Concrete strength grade	n	ρ_{be} (%)	ρ_h (%)	ρ_v (%)	P (kN)	Freeze-thaw cycle (times)
SW-1	1.14	C50	0.2	2.26	0.283	0.320	515.76	0
SW-2	1.14	C50	0.2	2.26	0.283	0.320	515.76	100
SW-3	1.14	C50	0.2	2.26	0.283	0.320	515.76	200
SW-4	1.14	C50	0.2	2.26	0.283	0.320	515.76	300

Notes: λ is the shear span ratio; n is the axial compression ratio; ρ_{be} is the ratio of the flexural reinforcement in the boundary elements; and ρ_h and ρ_v are the ratio of the horizontal web reinforcement and the ratio of the vertical web reinforcement, respectively; P is the axial load.