Ocean Systems Engineering, Vol. 2, No. 2 (2012) 159-171
DOI: http://dx.doi.org/10.12989/ose.2012.2.2.159

Impact of seawater corrosion and freeze-thaw cycles on the behavior of eccentrically loaded reinforced concrete columns

Bo Diao*[1], Yang Sun[1], Yinghua Ye[1] and Shaohong Cheng[2]

[1]Department of Civil Engineering, Beihang Univ., Beijing, P.R.China
[2]Department of Civil and Environmental Engineering, Univ. of Windsor, Windsor, Ontario, Canada

(Received March 5, 2012, Revised June 10, 2012, Accepted June 12, 2012)

Abstract. Reinforced concrete structures in cold coastal regions are subjected to coupled effects of service load, freeze-thaw cycles and seawater corrosion. This would significantly degrade the performance and therefore shorten the service life of these structures. In the current paper, the mechanical properties of concrete material and the structural behaviour of eccentrically loaded reinforced concrete columns under multiple actions of seawater corrosion, freeze-thaw cycles and persistent load have been studied experimentally. Results show that when exposed to alternating actions of seawater corrosion and freeze-thaw cycles, the compressive strength of concrete decreases with the increased number of freeze-thaw cycles. For reinforced concrete column, if it is only subjected to seawater corrosion and freeze-thaw cycles, the load resistance capacity is found to be reduced by 11.5%. If a more practical service condition of reinforced concrete structures in cold coastal regions is simulated, i.e., the environmental factors are coupled with persistent loading, a rapid drop of 15% - 26.9% in the ultimate capacity of the eccentrically loaded reinforced concrete column is identified. Moreover, it is observed that the increase of eccentric load serves to accelerate the deterioration of column structural behavior.

Keywords: freeze-thaw; sea water; reinforced concrete; deterioration; eccentric load; concrete columns

1. Introduction

Cold temperature and corrosive environment would significantly affect the durability of reinforced concrete structures (Sarja 2000, El-Reedy 2007). The rehabilitation cost is usually high. As a common type of structural member, column serves to transmit loads from upper levels to lower ones and is thus key to the safe performance of a structure. Its failure would cause adverse social and economical impact. When loaded, a reinforced concrete member would crack before the tensile reinforcement could contribute to the resistance capacity. Therefore, for reinforced concrete structures in coastal areas, such a fact allows easy penetration of seawater into concrete through cracks and touches the reinforcements. The steel bars will then be corroded due to rusting and consequently the effective cross-sectional areas will be less. This will not only reduce the bonding strength between concrete and reinforcing bars, but also the resistance capacity of reinforced concrete structures. In addition, for structures in cold regions, the influence of freeze-thaw cycles on

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*Corresponding author, Professor, E-mail: diaobo@buaa.edu.cn its performance cannot be overlooked. Therefore, a reinforced concrete structure in cold coastal regions is subjected to multiple damage process of seawater corrosion, freeze-thaw cycles, and external loads simultaneously. Though much research has been conducted to investigate low temperature effect and chemical action on the behaviour of concrete material, study of the coupled effects of these environmental factors in the presence of loading is rarely seen in the literature. The subject, though very challenging, is central to appreciate the behaviour of reinforced concrete structures in cold coastal regions. A decent comprehension of it will be essential for enhancing durability of reinforced concrete structures serve in such aggressive environment.

Majority of the existing studies were dedicated to the effects of freeze-thaw cycles and chemical corrosion on the mechanical properties of concrete and its durability (Sun *et al.* 2002, Mu *et al.* 2002, Liang and Lin 2003, Yang *et al.* 2006, Hansan *et al.* 2008, Zhang *et al.* 2011). Yang *et al.* (2006) investigated how water was transported in concrete damaged by tensile load and freeze-thaw cycles. It was found that when attacked by freeze-thaw cycles, the presence of load-induced cracks would accelerate the damage of concrete. A stress-strain model of frost-damaged concrete subjected to fatigue loading was developed by Hasan *et al.* (2008), based on which the compression and fatigue strength of concrete was studied. Zhang *et al.*, (2011), carried out the accelerated life test of concrete in a chloride environment. The results show that the service life of 10 mm concrete cover in the chloride environment is between 11.89 and 12.45 years.

Though in practice, reinforced concrete structures in cold coastal regions are subjected to combined actions of low temperature, corrosive environment and external loads, when assessing the durability of reinforced concrete structures in these areas, these factors are rarely considered simultaneously. To the authors' knowledge, only limited effort has been attempted to examine the coupling of environmental factors and loading effects on the behaviour of reinforced concrete structures. Sun *et al.* (2002) and Mu *et al.* (2002) investigated the mechanical properties of un-reinforced concrete under the coupled actions of sodium chloride (NaCl) solution, freeze–thaw cycles and external loads. It was found that compared with water, if sodium chloride solution was used as media for concrete freeze-thaw cycles, a more severe surface scaling and weight loss would occur. This indicated that the combined effects of freeze-thaw cycles, chemical attack and external loads would accelerate the degradation of concrete properties. Using SEM (Scanning Electron Microscope) tests, Zheng *et al.* (2010) studied the deterioration mechanisms of concrete when subjected to freeze-thaw cycles and corrosion of a mixed solution containing sodium chloride (NaCl) and sodium sulfate (Na_2SO_4). Micro-cracks and salt crystals were observed on the concrete surface. In addition, corrosion products such as salt were identified in the hardened cement paste, which was believed to be the cause of reduction in concrete strength. The mechanical properties of concrete specimens and reinforced concrete beams under the multiple actions of mixed corrosion, freeze-thaw cycles and persistent loads were tested by Diao *et al.* (2011). The experimental results showed that in the multiple-damage process, the increase of persistent load would significantly deteriorate the structural behaviour of reinforced concrete beams.

Durability of reinforced concrete structures in cold coastal regions should be assessed based on their practical service conditions, i.e., a combined action of freeze-thaw cycles, seawater corrosion and external loads. In this paper, the performance degradation of concrete material and five eccentrically loaded reinforce concrete columns in cold coastal environment has been experimental investigated. The seawater was simulated by a mixed solution of 3% NaCl and 0.35% $MgSO_4$, and the freeze-thaw cycles were applied to the specimens using a temperature control chamber. Freeze-thaw cycles and seawater corrosion are alternately applied to the concrete cubic specimens and reinforced concrete column specimens. In addition, each column specimen is subjected to persistent compressive load at different levels.

2. Experimental program

Two types of specimens were designed for the current experimental study, which included twelve plain concrete cubic specimens and five reinforced concrete column specimens. They were used to investigate the deterioration of concrete material properties and degradation of structural behaviour of reinforced concrete structures in cold coastal regions, respectively.

2.1Concrete mixture

The mixture formulation used the Chinese standards 425 Portland cement, river sand, and coarse aggregates with a maximum size of 15 mm. This mixture design well simulated the commercial concrete. In addition, high range water reducing admixture and Class *F* Type I fly ash were added to the mixture.

2.2 Specimen Preparation

The twelve plain concrete cubic specimens were divided into four groups based on the number of applied freeze-thaw cycles *N*, where $N = 0$, 102, 201, and 300, respectively. Each group had three specimens. The dimension of each specimen was 100 × 100 × 100 mm. The group with $N = 0$ was used as reference set, to which neither freeze-thaw cycles nor seawater corrosion was applied and the average compressive strength was tested to be 45.8 MPa.

The reinforced concrete column group contained five specimens. All of them had the same length, cross-sectional dimension and reinforcement ratio. The strength of the concrete was the same as that of the cubic specimens. The only difference between these column specimens were the magnitude of the eccentrically compressive persistent load applied on them. The dimensions and reinforcement arrangement in the column specimens are shown in Fig. 1. The total length of the column, l_0, was 700 mm. The width *b* and depth *d* of the cross-section in the middle portion of the column were 100 mm and 200 mm, respectively. The slenderness ratio of the column was $l_0 / b = 7$. Four typical reinforcing bars of 10 mm in diameter were used as longitudinal main reinforcements. They were

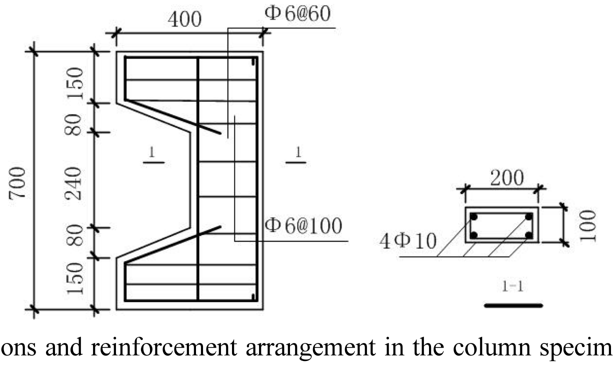


Fig. 1 Dimensions and reinforcement arrangement in the column specimens (Unit: mm)

arranged symmetrically at the four corners of the section. The double leg stirrup had a diameter of 6 mm and spacing of 100 mm. The thickness of the concrete cover was 25 mm. The yield strength of the 10 mm longitudinal bars and 6 mm stirrups was 360 MPa and 300 MPa, respectively, whereas the ultimate strength was 400 MPa and 350 MPa, respectively. The modulus of elasticity of the reinforcing bars was 2.15×10^5 MPa. To apply eccentric compressive load, brackets were designed for both column ends. The loading eccentricity was e_0=130 mm.

2.3 Testing procedures

This series of experimental study consists of material property tests on twelve plain concrete cubic specimens and structural tests on five reinforced concrete columns. The experiments were conducted in the Civil Engineering Laboratory at Beihang University, Beijing, China. A temperature control chamber with a temperature sensor installed on the inner wall was used to apply freeze-thaw cycles to the specimens. The procedure followed the Fast Freeze Method described in the "Standard for test methods of long-term performance and durability of ordinary concrete" (GB/T 50082-2009) in China, of which each freeze-thaw cycle should be completed within four hours with temperature varied between 8±2°C to −17±2°C. After every three freeze-thaw cycles, the specimens were immersed in the seawater for twelve hours. The alternating of freeze-thaw cycles and seawater immersion was repeated till the required number of freeze-thaw cycles N was reached. For example, thirty-four rounds of this alternation was needed for the cubic specimen group of $N = 102$ before standard compression test.

The corrosive agent used to simulate seawater environment in the current study was a mixed solution of sodium chloride (NaCl) and magnesium sulfate ($MgSO_4$), with a mass ratio of 3% and 0.34%, respectively.

To simulate the actual service conditions of reinforced concrete structures in cold coastal regions, multiple damage process was designed for the reinforced concrete column specimens. The columns were demolded after casting for 24 hours and cured under standard temperature and moisture conditions. At day 24, except one column specimen which was denoted as COL-0, the other four were immersed in the seawater for four days and taken out at the age of 28 days. They were denoted as COL-1, COL-2, COL-3, and COL-4, respectively. The persistent eccentric compressive load was then introduced to these four columns by tightening the bolts attached to the spiral rebars passing through the brackets at two ends of the column, as illustrated in Fig. 2. The magnitude of the persistent load was controlled by the strain of the longitudinal reinforcement in the column. The strain gauges were attached to the surface of the reinforcing bars before concrete was poured into

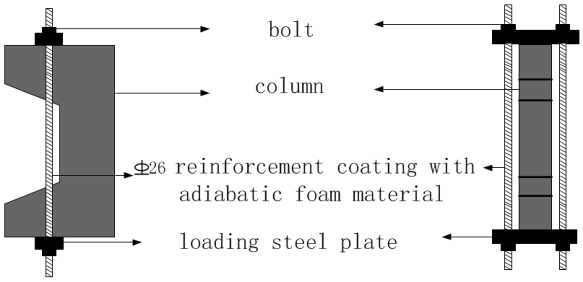


Fig. 2 Persistent loading system setup

Table 1 Testing conditions of column specimens

Specimens	Persistent load		Number of Seawater immersion	Number of freeze-thaw cycles
	Ratio	Magnitude (*kN*)		
COL-0	0	0	0	0
COL-1	0	0	100	300
COL-2	0.2	52	100	300
COL-3	0.3	78	100	300
COL-4	0.5	130	100	300

the molds of the column specimens. Static loading test was performed on column specimen COL-0 at 28 days without applying freeze-thaw cycles and chemical corrosion. The ultimate capacity of COL-0 was used as a reference to determine the persistent loading level of the other four columns. The ratio between the persistent load on specimens COL-1 to COL-4 and the ultimate capacity N_{u0} of COL-0 was defined as the persistent loading ratio. This ratio was designed to be 0, 0.2, 0.3, and 0.5 for COL-1, COL-2, COL-3, and COL-4, respectively. By referring to the stress-strain relation of the longitudinal reinforcement in COL-0, the loading magnitude on the other four columns could be monitored by the change in the strain of the reinforcing bar. The bolts and spiral bars used to apply persistent compressive load were wrapped with rust-resistant material and insulations to minimize the environmental impact on the loading system. During the process of freeze-thaw cycles and seawater corrosion, it was difficult to monitor the variation of the persistent load. Afterwards, alternating freeze-thaw cycles and seawater corrosions were applied to COL-1 to COL-4, with the same procedure as that of the cubic specimens, i.e., the persistently loaded column specimens were immersed in the seawater for twelve hours after every three times of freeze-thaw cycles until a total number of $N = 300$ was completed. The persistent loading systems were then removed from COL-1 to COL-4. As the last step, eccentric static loading test was conducted on the four column specimens till failure. The loading position in the static test was kept the same as that of the persistent load. The testing conditions of the five column specimens were summarized in Table 1.

3. Experimental results and discussions

3.1 Plain concrete cubic specimens

When subjected to alternating actions of freeze-thaw cycles and seawater corrosion, it was found that with the increase of number of freeze-thaw cycles, the surface of the concrete cubic specimens became rougher. Scaling occurred first at the corners and edges of the specimens. The formation of micro-cracks at the locations of scaling was identified after 102 cycles of freeze-thaw actions. When the number of freeze-thaw cycles increased to 201, the exposure of coarse aggregates at the corners and edges of the specimens and more localized scaling were observed. The fine cracks and surface scaling became more visible after applying freeze-thaw cycles for 300 times.

When the designed number of freeze-thaw cycles was completed, the compressive strength of the cubic specimens was measured by the standard compression tests. The average strength of the three specimens in the same group was taken as the representative value of the group. This set of results

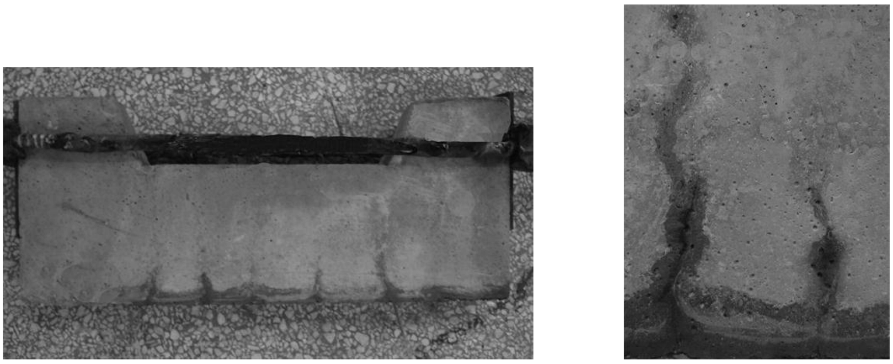
Table 2 Compression test results of concrete cubic specimens

Group	1	2	3	4
Number of freeze-thaw cycles N	0	102	201	300
Compressive strength (MPa)	45.8	40.3	36.5	30.7

was summarized in Table 2. As expected, the compressive strength of concrete reduced progressively with the increased exposure duration to the aggressive environment similar as the cold coastal areas. Based on the current set of results, a 33% reduction in the concrete compressive strength was found after 300 times of freeze-thaw cycles accompanied by seawater corrosion.

3.2 Reinforced concrete column specimens

The impact of alternating freeze-thaw cycles and seawater corrosion on the surface condition of reinforced concrete columns was found to be similar as that in the case of plain concrete cubic specimens, i.e., scaling became more serious with the increasing number of alternating rounds. For COL-2, COL-3, and COL-4, horizontal flexural tensile cracks induced by persistent eccentric compressive force formed. This allowed easy penetration of seawater into the columns through these cracks and caused rusting corrosion of steel bars. As can be seen in Fig. 3(a), the saturation level at the crack locations was higher than other places on the column surface. In COL-3 and COL-4, the cracks induced by persistent eccentric load were observed to extend 3 mm and 7 mm, respectively. In addition, the exposure of coarse aggregates could be observed at many surface locations. The seepage and deposit of brown corrosion product film at the cracks can be seen in Fig. 3(b). These suggest that the coupling of external loads with the environmental factors will accelerate the performance degradation of reinforced concrete structures in cold coastal regions. Due to the existence of load-induced cracks, the physical and chemical environment around the steel bar over its entire length is not uniform. These cracks tend to provide easy access for the penetration of chemicals and facilitate the onset of reinforcement corrosion and accelerate its development rate. Therefore, external loads should be considered along with the environmental impact to properly understand the behaviour of reinforce concrete structures in these areas.



(a)High saturation at the crack on the column surface (b) Seepage and deposit at cracks

Fig. 3 High saturation and Seepage at cracks on column surface

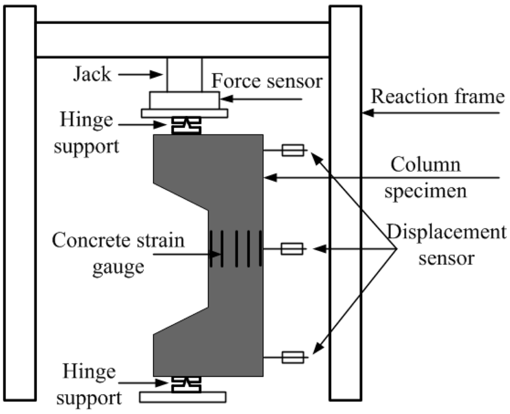


Fig. 4 Setup of static loading tests on columns

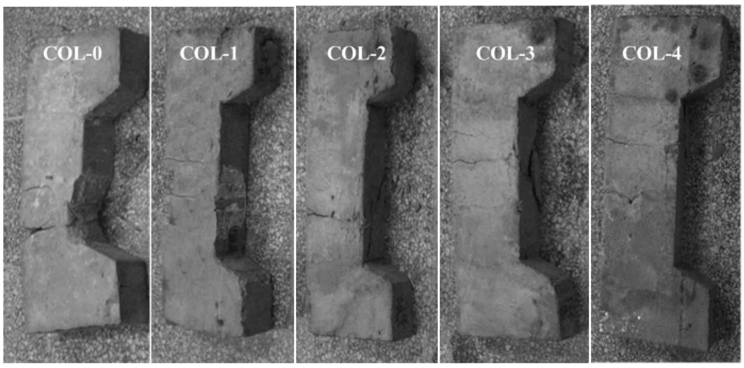


Fig. 5 Columns after failure by static loading tests

The set up of static loading tests is shown schematically in Fig. 4. The ultimate load and mid-height transverse displacement of column specimens were measured by a load cell and a displacement sensor, respectively. All five reinforced concrete columns were statically loaded till failure. Fig. 5 shows the status of the specimens after failure. It was observed that though all the specimens failed due to typical tension controlled flexural tensile failure, the ultimate loading capacity and failure modes differ based on the persistent loading ratio. The static testing results are summarized in Table 3 with detailed descriptions as follows:

COL-0: No freeze-thaw cycles and seawater corrosion were applied to this reference specimen. It manifested typical tension controlled flexural tensile failure.

COL-1 (no persistent load applied): This column was only subjected to freeze-thaw cycles and seawater corrosion. It exhibited the same failure process as that of COL-0. Though compared to COL-0, the cracking load of COL-1 reduced by 25.8%, the reduction in yield strength and ultimate loading capacity caused purely by environmental factors were found to be less, which were 4.6% and 11.5%, respectively.

COL-2, COL-3 and COL-4: These three columns were subjected to persistent eccentric compressive load during freeze-thaw cycles and seawater corrosion. Before static loading tests, persistent load-induced flexural tensile cracks already occurred in the tension zone of the columns,

Table 3 Results of static loading tests

Column	Persistent loading ratio (%)	Number of freeze-thaw cycles N	Cracking load (kN)	Yielding load (kN)	Ultimate load (kN)	Failure mode
COL-0	0	0	155	195	260	flexural tensile
COL-1	0	300	115	186	230	flexural tensile
COL-2	0.2	300	95	177	221	flexural tensile
COL-3	0.3	300	80	180	207	flexural tensile
COL-4	0.5	300	70	175	190	flexural tensile

which continuously grew with the increasing number of freeze-thaw cycles. No new horizontal flexural tensile crack was identified during the static loading tests. When the static load reached 80% of the ultimate capacity of the column, tensile reinforcements yielded first. The horizontal flexural tensile cracks were observed to grow rapidly. Finally, concrete in the compression zone crushed and the columns failed in a ductile mode. The recorded ultimate loads of these three columns were all lower than that of COL-0, and they decreased gradually with the increase of persistent load ratio. In addition, it was interesting to note that the difference between the yielding load and the ultimate load became less with larger persistent loading ratio. The recorded yielding load and ultimate load of COL-4 were 175 kN and 190 kN, respectively, with a difference of only 8.6%.

3.3 Discussion of results

Results of the static loading tests on the five reinforced concrete column specimens were summarized in Table 3, in which the cracking load, the yielding load, the ultimate load and the failure mode are presented. It can be seen from the table that when subjected to the same number of freeze-thaw cycles and seawater corrosion, the cracking load, the yielding load and the ultimate load would decrease with the increase of persistent loading ratio, with the least impact on yielding load. This suggests that if persistent load is coupled with environmental factors like freeze-thaw cycles and chemical corrosion, the deterioration of structural behaviour of reinforced concrete columns would be accelerated. The cracks induced by the persistent load would allow corrosive solution to penetrate easily into the reinforced concrete structure and reach the steel reinforcing bars. The exposure of concrete and reinforcement to the corrosive solution is thus considerably increased. The adverse effect of the chemical attack is further enhanced by the accompanying freeze-thaw cycles, which results in the accelerated degradation of concrete material properties and rusting of longitudinal reinforcing bars. Rust corrosion not only decreases the resistance capacity of the reinforcement by reducing its cross-sectional area, but also significantly weakens the bonding between concrete and steel bars due to rust expansion along the reinforcement. All these facilitate to decrease the load carrying capacity of reinforced concrete structure and significantly degrade its structural behaviour. This is likely to be the reason why the ultimate load of COL-4 was observed to be the lowest among the five specimens. The relations between cracking load, yielding load, and ultimate load with the persistent loading ratio are also portrayed in Fig. 6, from which the impact of persistent load on the deterioration of reinforced concrete structure behaviour can be clearly observed.

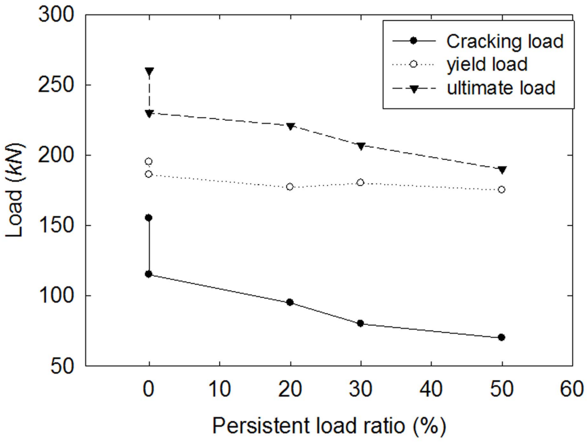


Fig. 6 Impact of persistent load on the column load carrying capacity

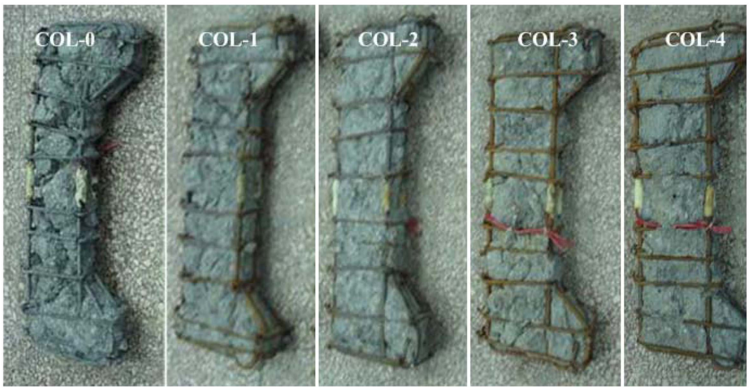


Fig. 7 Corrosion status of steel bars after static loading tests

After the static loading tests, the concrete covers of all column specimens were removed to study the rusting condition of the reinforcements. As shown in Fig. 7, the steel bars in COL-0 had an electric blue color, which is typical for an uncorroded steel reinforcement. The stirrups in COL-1 were all rust corroded and about 70% surface area the longitudinal bars was covered by a thin rusting layer. The rusting layer covering the longitudinal steel bars increased to about 90% in the case of COL-2, of which a more significant rust corrosion was identified at the location where stirrups and longitudinal bars were connected. In COL-3 and COL-4, all the longitudinal reinforcing bars were rust corroded. In general, compared to longitudinal reinforcements, stirrups were found to be more affected by rusting corrosion due to a thinner layer of concrete cover. The rusting corrosion in columns with higher persistent ratio was observed to be more serious. The steel bars located at where the initial cracks occurred were found to be corroded the most.

The coupling effect of persistent load with freeze-thaw cycles and seawater corrosion on the behaviour of eccentrically loaded reinforced concrete columns was analyzed based on the static load testing results and presented in Table 4. By using COL-0 as reference, it was found that with the increase of persistent loading ratio from 0 to 0.5, the ultimate load of COL-1 to COL-4 reduced by 11.5% to 26.9%. As discussed earlier, the combination of external loads and environmental effects

Table 4 Analysis of column static loading test results

Column	Ultimate load (kN)	Persistent load (kN)	Number of freeze-thaw cycles N	Δ_1(%)*	Δ_2(%)**	Δ_1- Δ_2(%)
COL-0	260	0	0	0	-	-
COL-1	230	0	300	11.5	0	11.5
COL-2	221	52	300	15.0	3.9	11.1
COL-3	207	78	300	20.4	10.0	10.4
COL-4	190	130	300	26.9	17.4	9.9

*The total reduction in the ultimate load due to multiple damage process of freeze thaw cycles, seawater corrosion and persistent load.

**Reduction in the ultimate load due to persistent load only.

would speed up the performance degradation of reinforced concrete structures. To isolate the impact of persistent load on the structural behaviour of reinforced concrete structures in cold coastal regions, the resistance capacity of COL-2 to COL-4, which were subjected to persistent load with a ratio of 0.2 to 0.5 along with freeze-thaw cycles and seawater corrosion, were compared with that of COL-1, which was only exposed to low temperature and chemical attack. As can be seen from Table 4, the load carrying capacity of COL-2, COL-3 and COL-4 was reduced by 3.9%, 10.0% and 17.4%, respectively. These two sets of comparison clearly indicate the importance of persistent load on affecting performance and durability of reinforce concrete structures in cold coastal areas. The significance of its role would be promoted with larger magnitude. In Table 4, Δ_1 represents the total reduction in the ultimate load due to multiple damage process of freeze-thaw cycles, seawater corrosion and persistent load, whereas Δ_2 represents the reduction in the ultimate load due to persistent load only. Therefore, the difference between these two, i.e., $\Delta_1-\Delta_2$, can be considered as the impact of freeze-thaw cycles and seawater corrosion on the load carrying capacity of the columns. Based on the current set of testing data, it has an average value of 10.7%. This fact suggests that though the loss in the column resistance capacity due to alternating rounds of freeze-thaw cycles and seawater corrosion is almost the same for COL-1 to COL-4, with the existence of persistent load, such a loss differs considerably depending on the magnitude of the applied load. Therefore, to properly understand the behaviour of reinforced concrete structures in cold coastal regions, the actual service conditions of the structures should be reproduced faithfully, i.e., not only freeze-thaw cycles and chemical attack need to be considered, the expected service loads on the structures should also be included in the study. The durability of reinforced concrete structures in such an aggressive environment should be assessed by a multiple damage process.

The combined effects of freeze-thaw cycles, seawater corrosion, and persistent load on the stiffness of the studied reinforced concrete columns are presented in Figs. 8 and 9. Fig. 8 illustrates the effect of low temperature and chemical corrosion on the deformation of reinforced concrete columns by load-deflection curves at the mid-height of COL-0 and COL-1. The comparison of these two curves shows that the reduction in the column stiffness is relatively small. Thus, the deterioration rate of stiffness due to aggressive environment alone can be considered slow. The effect of persistent load on the reinforced concrete columns subjected to freeze-thaw action and seawater corrosion is described in Fig. 9, of which the load-deflection curves at the mid-height of COL-1 to COL-4 are presented together for the convenience of evaluation. A progressive reduction

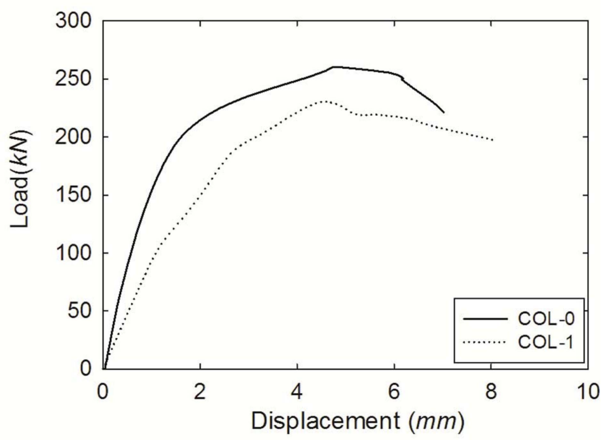


Fig. 8 Load-displacement curves of columns COL-0 and COL-1 in static loading tests

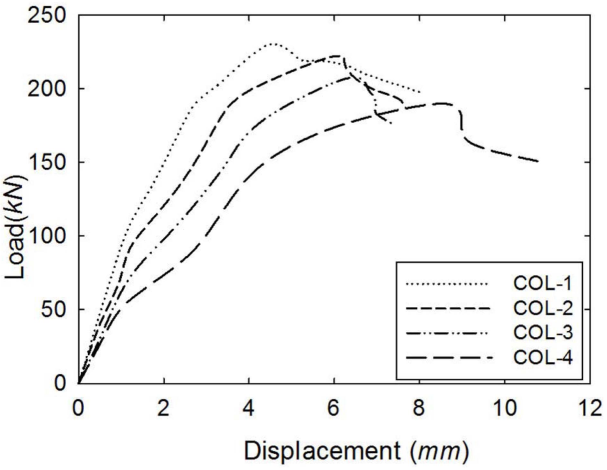


Fig. 9 Load-displacement curves of columns COL-1 to COL-4 in static loading tests

in the column stiffness with the increase of persistent load can be clearly seen, which indicates again that the existence of persistent load will serve to promote performance degradation of reinforced concrete structures in cold coastal regions.

4. Conclusions

An experimental study on the performance and durability of reinforced concrete structures in cold coastal regions has been presented in this paper. The impact of alternating freeze-thaw cycles and seawater corrosion on the mechanical properties of concrete material, as well as the performance degradation of reinforced concrete columns due to the combined actions of persistent load and environmental factors have been discussed. The importance of accurate simulation of service conditions in the durability study of reinforced concrete structures in the aggressive environment has

been highlighted. Based on the testing and analysis results, the following can be concluded from the current study:
(1). When subjected to alternating freeze-thaw cycles and seawater corrosion, the compressive strength of concrete decreases when the number of such alternating rounds increases.
(2). If only subjected to the combined actions of freeze-thaw cycles and seawater corrosion, the reduction in the yielding load and the ultimate load of reinforced concrete columns is relatively small.
(3). When subjected to the multiple damaging agents of freeze-thaw cycling, seawater corrosion and persistent load, both the ultimate load and the stiffness of reinforced concrete columns drop. The deterioration in the structural behaviour of columns is found to be more significant with larger persistent loading ratio.

It is worth noting that the results presented in the current study are based on specimens made of only one type of concrete mixture and a chemical solution using one mixing proportion. The impact of multiple damage process including freeze-thaw cycles, chemical corrosion and persistent load on the structural behaviour and performance degradation of reinforced concrete columns needs to be further studied extensively using different strength of concrete material and different concentration of mixed solutions.

Acknowledgments

This work is part of the projects financially supported by the Chinese National Natural Science Foundation (NSF) Grant No. 51078015 and 51178020. The authors gratefully acknowledge the financial support received from the NSF.

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