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Low-cycle fatigue behavior of corroded and CFRP-wrapped reinforced concrete columns

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HIGHLIGHTS

- Cumulative seismic damage of columns with or without corrosion was studied.
- The effect of using CFRP wraps on seismic behavior of columns was evaluated.
- Cyclic loads with constant amplitudes and variable amplitudes were applied.
- Steel corrosion significantly reduces low-cycle fatigue life of columns.
- The seismic damage indexes of columns with or without corrosion were estimated.

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ABSTRACT

An experimental study was taken to investigate the cumulative seismic damage of reinforced concrete columns with or without steel corrosion and to evaluate the effect of using CFRP wraps on the seismic behavior of the columns. Eleven identical rectangular reinforced concrete columns were constructed and tested under standard cyclic loads with variable drift amplitudes or low-cycle fatigue loads at different constant drift amplitudes. The column models included five un-corroded columns and six columns corroded using an external current method. Test results indicate that steel corrosion reduces the strength, ductility, low-cycle fatigue life, and cumulative energy dissipation capacity of reinforced concrete columns under cyclic loads, whereas the use of CFRP wraps greatly improves the above-mentioned behavior except the strength of un-corroded and corroded columns. The corroded column with a steel corrosion level of about 10% and retrofitted using CFRP wraps exhibited lower loading capacity but much better ductility and cumulative energy dissipation capacity than un-corroded columns. The seismic damage indexes of the columns with or without steel corrosion were also estimated based on the Park–Ang damage model and the relationships between damage indexes and experimental observations were discussed.

1. Introduction

Chloride-induced corrosion of steel reinforcements has become a major concern for existing reinforced concrete structures exposed to marine environments or de-icing salts. The corrosion in reinforced concrete structures is a long-term and complicated process. When chloride ions penetrate concrete cover and react with steel reinforcements, the corrosion is initiated. The corrosion not only decreases the effective cross-sectional area of steel reinforcements but also affects their mechanical properties. Furthermore, the formation of corrosion by-products creates an expansive pressure to cause cracking and eventual spalling of concrete cover, degrading the bond between steel reinforcements and their surrounding concrete. Thus, the adequacy of the deteriorated structures, particularly those in seismic zones, to withstand the loadings for which they were originally designed is highly questionable.

Extensive studies on the behavior of reinforced concrete members with corroded steel reinforcements subjected to static loads [1–3] or high-frequency fatigue loads [4,5] have been conducted in the past, and some attempts have been made to solve the problem of steel corrosion by taking fiber-reinforced polymer (FRP) bars [6,7], or epoxy-coated reinforcing steel [8] as a substitute. However, fewer studies on the seismic behavior of structures with

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corroded reinforcements can be found to date, and the use of fiber composites for seismic retrofitting of corroded structures has received less attention regardless of the wide acceptance of fiber composites for the seismic retrofitting of un-corroded structures [9–11]. The tests conducted by Lee et al. [12], Ma et al. [13] and Meda et al. [14] indicated that reinforced concrete columns damaged by reinforcement corrosion can exhibit not only reduction of their load capacities under cyclic loads but also an alteration of the collapse mechanism with a reduction of structural ductility. The deterioration of the seismic behavior of corroded columns was mainly caused by the decline in the confining effect due to the falling off of concrete cover and the reduction of mechanical properties of corrosion rebar. To restore the structural capacity of corroded columns, some reversed cyclic load tests on the corroded columns retrofitted with FRP composites were conducted by Lee et al. [12], Bousias et al. [15], Aquino and Hawkins [16], Li et al. [17], and the effects of the number of FRP layers, the type of fiber material, the corrosion level of reinforcing bar and column cross sectional aspect ratios on seismic retrofitting with FRP wraps were evaluated. Their test results indicated that the strengthening using FRP wraps is a very effective retrofit technique that prevents bond splitting cracks and shear cracks from growing and improves the ductility of reinforced concrete columns with corroded bars. Note that all the above mentioned tests focused on standard loading protocols with ramping drift amplitude to obtain the seismic behavior, but without considering the effects of drift amplitudes and the number of cycles on damage accumulation. Corroded columns with defects caused by steel corrosion may be more susceptive to low-cycle fatigue under seismic loads. However, the effects of steel corrosion levels and the use of CFRP wraps for seismic retrofitting on the low-cycle fatigue behavior of reinforced concrete columns have not been studied yet. The research on the cumulative seismic damage model for corroded and CFRP-wrapped columns also has not been conducted yet.

In this study, experiments on eleven column models subjected to different loading patterns including standard cyclic loads with variable peak displacement amplitudes and low-cycle fatigue loads at different constant peak lateral displacement amplitudes were performed, and the effects of steel corrosion levels and the use of CFRP wraps on the low-cycle fatigue behavior were evaluated. The test results also intended to provide a basis to calibrate existing cumulative seismic damage models for damage assessment of reinforced concrete columns with or without steel corrosion.

2. Experimental program

2.1. Column models

The test matrix for the experimental program is given in Table 1 and the details of all column models are shown in Fig. 1. The symbols of the column models coupled with their corresponding meanings are also explained in Table 1. A total of eleven identical rectangular reinforced concrete column models in reinforcement layouts and 250 × 250 mm in cross section were constructed and tested. The column models had a height from the loading point to the top surface of column foundation equal to 1250 mm and thus a span-to-depth ratio of 5. All the model columns were longitudinally reinforced with four Φ14 steel bars with a nominal bar diameter of 14 mm and transversely reinforced with Φ6 stirrups spaced at 60 mm at the potential plastic hinges to ensure a flexural failure. The longitudinal steel bars were bent at the bottom of the column foundation to prevent pullout failure while the stirrups had 135° hooks with a length of 60 mm at their free ends to provide efficient confinement to the concrete. The clear concrete cover for stirrups was 25 mm. Each column model consisted of an 850 mm(length) × 300 mm (breadth) × 365 mm(depth) stiff column foundation and a 450 mm long top loading stub with a cross section of 250 mm(breadth) × 300 mm(depth). Both the column foundation and top loading stubs were heavily reinforced to prevent any premature failure during testing.

The main test parameters in this study were steel corrosion levels, loading protocols and the use of carbon fiber-reinforced polymer (CFRP) wraps. The column models included five un-corroded reinforced concrete columns and six corroded reinforced concrete columns with an expected corrosion level of steel reinforcements equal to 10%. The corrosion level of steel reinforcements is defined by the mass loss herein. Two un-corroded columns and three corroded columns were retrofitted using CFRP wraps. For the un-corroded column models retrofitted by CFRP wraps, the column corners were firstly rounded off to a radius of 25 mm, and then two layers of CFRP wraps with epoxy adhesive were applied along the bottom-most 400 mm of the columns. For the corroded columns, the cracks induced by steel corrosion were firstly repaired with epoxy resin, and then the corrosion by-products and loose concrete were chipped away. Finally, the retrofitting methods same to those of un-corroded columns were carried out.

For all tests, an axial load equal to 320 kN was first applied to the column models and held constant during the test. The lateral loading sequence was controlled by the displacement at the shear force application point, and two types of lateral loading protocols including standard cyclic loading with variable drift ratios and low-cycle fatigue loading at different constant drift ratios were carried out. Column models UC-VA, CC-VA and CC-VA-R were subjected to standard cyclic loadings while all the other column models were subjected to low-cycle fatigue loadings at different constant drift amplitudes. The standard cyclic loading was applied to obtain the hysteretic response and the force–deformation envelope curves. During the testing, one complete loading cycle for each peak displacement was applied corresponding to an increment of peak displacement equal to 25% of the anticipated yield displacement Δ_y, until Δ_y was reached. Subsequent loading was conducted with three cycles corresponding to each of the peak displacement equal to Δ_y, $2.0\Delta_y$, $3.0\Delta_y$, $4.0\Delta_y$, and then with two cycles corresponding to each of the peak displacement equal to $5.0\Delta_y$, $6.0\Delta_y$, etc., until the model failed. When a drop in the peak lateral force by over 20% of the previous peak force occurred or major physical failure such as sudden fracture of stirrups were observed, the model was deemed as failure herein. The low-cycle fatigue testing was carried out to calibrate cumulative seismic damage models and evaluate the effects of steel corrosion and the use of CFRP wraps on the damage indexes of model columns. Un-corroded columns were subjected to two types of constant peak drift ratios equal to 2% and 4% while corroded columns were cyclically loaded at constant drift ratios of 1% and 2% for their relatively low ductility.

2.2. Accelerated corrosion process

An external current method proposed by Jin et al. [18] was utilized to induce steel corrosion in the column models. Since seismic actions cause maximum moment at the column base, only the bottom-most 500 mm of the column was selected for corrosion and this zone was wrapped by sponge, stainless mesh and waterproof plastic one by one, as illustrated in Fig. 2. The sponge contacting with the corroding column directly was used to absorb the saline solution (5% NaCl) while the stainless steel mesh was used as an external electric pole. The total

Table 1
Testing matrix of column models.

Model symbols	C_l (%)	C_s (%)	Loading pattern	f_{cu} (MPa)	P_{max} (kN)	Fatigue life (half-cycles)	E_{cum} (kJ)
UC-VA	0	0	Variable drift amplitude	34.79	61.04	–	38.9
UC-CA2	0	0	Constant drift amplitude at 2%	33.55	57.89	142	48.8
UC-CA4	0	0	Constant drift amplitude at 4%	32.53	58.62	48	58.7
UC-CA2-R	0	0	Contant drift amplitude at 2%	34.66	60.26	220	74.5
UC-CA4-R	0	0	Constant driftamplitude at 4%	32.42	57.62	64	66.9
CC-VA	9.87	12.56	Variable drift amplitude	31.92	46.85	–	22.4
CC-CA1	9.96	13.57	Constant drift amplitude at 1%	30.80	38.10	140	15.9
CC-CA2	10.31	13.75	Constant drift amplitude at 2%	31.65	40.80	12	4.4
CC-VA-R	10.05	13.23	Variable drift amplitude	32.84	48.20	–	61.8
CC-CA1-R	9.26	13.43	Constant drift amplitude at 1%	31.65	46.11	190	29.9
CC-CA2-R	9.18	12.23	Constant drift amplitude at 2%	32.68	47.04	80	22.7

Note: UC – un-corroded column; CC – corroded column; VA – variable amplitude; CA1, CA2, CA4 – constant amplitude of 1%, 2%, 4%, respectively; R – column retrofitted using CFRP wraps. For example, CC-CA2-R means a corroded model column retrofitted using CFRP wraps and tested under constant drift ratio of 2%.