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Effect of Stirrup Corrosion on Concrete Confinement Strength

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***Abstract*—**This study investigated how the concrete confinement strength and axial load carrying capacity of reinforced concrete columns are affected by corrosion damage to the stirrups. A total of small-scale 12 test specimens were cast for evaluating the effect of stirrup corrosion on confinement strength of concrete. The results of this study show that the stirrup corrosion alone dramatically decreases the axial load carrying capacity of corroded reinforced concrete columns. Recommendations were presented for improved inspection practices which will allow estimating concrete confinement strength of corrosion-damaged reinforced concrete bridge columns.

***Keywords*—**Bridge, column, concrete, corrosion, inspection, stirrup reinforcement.

I. Introduction

FOR the last 30 years, bridges in excess of 6.1 meters in total length located on public roads have received periodic inspections to ensure safety to the public and 27.5% of the total inventory were rated as structurally deficient [1], [2]. Since, these bridges are not able to serve for their whole service life; there is an urgent need to keep aging and deteriorating bridges in service with increased traffic volume and vehicle weights.

Inspectors assess the ratings that form the basis for assessing the structural condition of the bridge elements, in a visual fashion based on engineering expertise and experience. Some methods, which are mainly focused on the corrosion of longitudinal tensile reinforcement in RC beams, are developed to accurately correlate visual damage states with rating categories [3]. Recently, a research was conducted to evaluate the effect of stirrup corrosion on shear capacity of corrosion damaged reinforced concrete beams [3]. Several other researchers investigated uniaxial compression behavior of confined reinforced concrete deteriorated by reinforcement corrosion [4].

Stirrup corrosion has significant effects on load carrying capacity of the reinforced concrete columns therefore, the objective of this research is to assess the effect of stirrup corrosion on concrete confinement strength. This paper investigates the effect of stirrup corrosion on confined concrete strength and ultimately, it is expected that the results of this research may be used by practicing engineers and inspectors and therefore will help reduce maintenance and repair costs, avoid costly over-conservative ratings.

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II. Corrosion of Reinforced Concrete Bridge Columns

Durability issues are the main focus of considerable concern with respect to structural engineering. Increasing numbers of structures are experiencing significant amounts of deterioration prior to reaching their design service life. This premature deterioration is considered to be a problem in terms of the structural integrity and safety of the structure. In addition, deterioration of a structure has a considerable magnitude of costs associated with it [5].

The deteriorating effects of corrosion are evident but stirrup corrosion has significant effects on load carrying capacity of the reinforced concrete columns (i.e. relatively larger cross-section reduction, loss of concrete confinement because of loss of bond and loss of anchorage). These significant effects are expected because stirrups start corroding earlier than the longitudinal reinforcement and since they are smaller in diameter, same corrosion rate leads to larger relative reductions in stirrup cross-sections (Fig. 1).

Fig. 1 Close-up of corroded rebars [5]

When the stirrup starts to corrode, the confinement effect of stirrups is reduced because of the loss of bond between reinforcement and concrete (Fig. 2). When the cover to the longitudinal reinforcement cracks, the load carrying capacity starts to decrease at a faster rate due to the reduction of stirrup anchorage. Loss of transverse reinforcement, as shown in Fig. 2, leaves the column section unconfined. In addition, loss of bond between the corroded bars and the surrounding concrete, as shown in dramatically decreases the axial load carrying capacity of the column (Figs. 3 (a) and (b)).

Fig. 2 Effect of corrosion on reinforced concrete column [5]

Fig. 3 Corrosion damage of tall concrete bridge pier columns [5]

For bridges in need of retrofit, accurate evaluation of residual capacity is essential for the development of cost-effective repair strategies. With the rise of repair costs, it has become more important to quantify the residual strength of deteriorated reinforced concrete members. Therefore, the present study focused on evaluation of the effect of stirrup corrosion on confinement strength of reinforced concrete columns that were subjected to different degrees of corrosion damage.

III. Experimental Test

A. Preparation of Test Specimens

In order to evaluate the effect of stirrup corrosion on confinement strength of concrete, 12 test specimens were cast, (two for control purposes (CON-1, CON-2, CR-1 to CR-10 having different corrosion rates)). The columns had a square cross section 150×150 mm and length 350 mm. 12 mm diameter reinforcement was placed into the corners of the cross section. The transversal reinforcement was formed by closed stirrups with a diameter of 8 mm with a spacing of 10 cm (c/c). The detailed drawing of the specimens and their reinforcement is shown in Fig. 4.

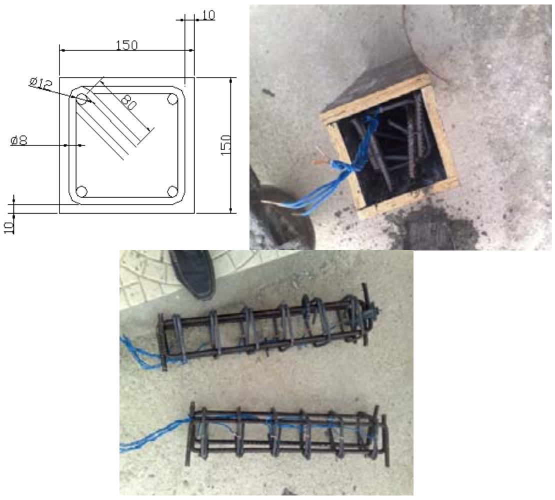

Fig. 4 Details of column specimens and reinforcement arrangement

The specimens were cast with a concrete of strength 21.8 MPa. The concrete mix design used for preparation of test specimens is shown in Table I. All specimens were cast from one unique batch. 1 day after casting all specimens were pulled out from their forms and wet cured for a period of 28 days in the laboratory curing tank. After curing, the accelerated corrosion process was started.

TABLE I
Concrete Mix Design for Test Specimens

	Amount
CEM – I 32.5 N Portland Cement	300 kg/m^3
W/C	0.55
Water	177 kg/m^3
Coarse Aggregate (maximum size = 26 mm)	1091 kg/m^3
Fine Aggregate (Natural river sand)	70 kg/m^3
Fine Aggregate	860 kg/m^3
Super plasticizer - GRACEWRDA 90	0.8% of the binder

Longitudinal steel bars of the test specimens were epoxy-coated to isolate corrosion to the stirrups within the tested columns. Stirrups within the tested columns connected to an electric current source via copper electricity wires. The ties were connected electrically to each other. The accelerated corrosion test continued until all the columns have reached moderate-severe damage states which is identified by structural deterioration (cracking and delamination) and rusty stains on column face.

Ten specimens were subjected to accelerated corrosion. Fig. 5 represents the accelerated corrosion setup. Each specimen was placed in a tank where 5% NaCl solution was used as an electrolyte. The solution level in the tank was adjusted to slightly exceed the columns upper part. The specimens were incorporated with a direct current power supply with an output of 6 Amps. The accelerated corrosion process was conducted to result in 5%, 10%, 15%, 20%, 25%, 30%, 35%, 40%, 45% and 50% stirrup section-loss. However, because of the non-uniformity of the corrosion, and the presence of other reactions, the stirrups inside the tested columns were removed

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and cleaned from rust and concrete. The corrosion damage, average cross-sectional area loss, was quantified by determining average weight loss.

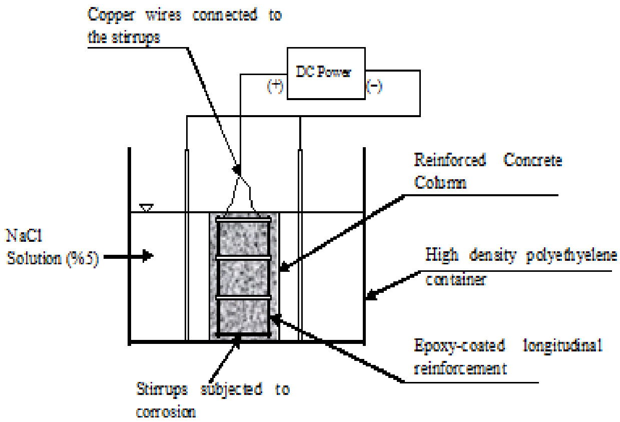

Fig. 5 Schematic representation of accelerated corrosion set-up

IV. Results

A. Corrosion of Stirrups

Following structural testing of corroded columns, stirrups were removed to determine the degree of corrosion damage and assess average section loss.

Fig. 6 shows a tested column and Fig. 7 shows a typical corroded column stirrup after cleaning from rust and concrete remains. In some cases, complete section-loss was also observed.

B. Experimental Test Results

The load carrying capacity of tested columns is given in Table II. The reduction in ultimate capacity with increasing levels of corrosion damage was obvious. The major findings of these tests are the importance of effect of stirrup corrosion, stirrup debonding from the concrete and cover cracking because of stirrup corrosion on concrete confinement strength and consequently on axial load carrying capacity of corroded reinforced concrete columns. Section loss corrosion is determined calculating the average weight loss of corrosion damaged stirrups in the tested column. For the sake of simplicity pitting corrosion is not taken into consideration. Results indicate that, the axial load carrying capacity of corroded reinforced concrete columns significantly decreases as the rate of stirrup corrosion increases. Therefore, in order to avoid unsafe/over-conservative ratings the inspection procedures shall identify stirrup section-loss and incorporate in the analysis phase.

Fig. 6 A corroded column specimen before compressive testing

Fig. 7 Typical corroded column stirrup

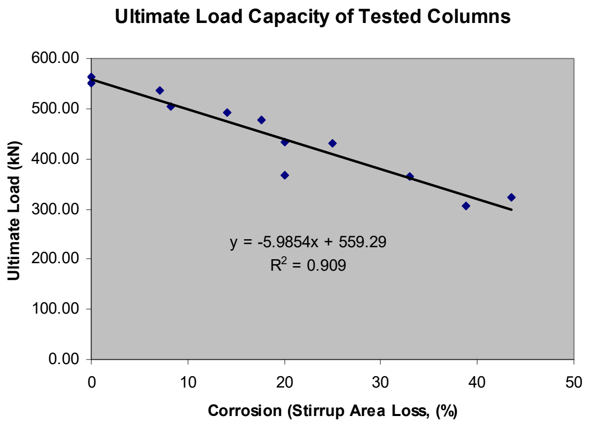

Fig. 8 Effect of stirrup corrosion on axial load carrying capacity of reinforced concrete columns

TABLE II
TEST RESULTS

Specimens	f_c' (MPa)	Longitudinal Reinforcement			Transverse Reinforcement				Section Loss Corrosion (%)	P_{exp} (kN)
		Number and Diameter, mm	ρ_t (%)	f_y (MPa)	Diameter, mm	s (mm)	ρ_t (%)	f_y (MPa)		
CON-1	21.8	4 No 12	2.01	420	8	10	2.18	420	0.00	563.35
CON-2	21.8	4 No 12	2.01	420	8	10	2.18	420	0.00	551.99
CR-1	21.8	4 No 12	2.01	420	8	10	2.03	420	7.06	536.92
CR-2	21.8	4 No 12	2.01	420	8	10	2.00	420	8.24	504.06
CR-3	21.8	4 No 12	2.01	420	8	10	1.87	420	14.12	493.19
CR-4	21.8	4 No 12	2.01	420	8	10	1.80	420	17.65	476.41
CR-5	21.8	4 No 12	2.01	420	8	10	1.74	420	20.00	434.60
CR-6	21.8	4 No 12	2.01	420	8	10	1.74	420	20.00	367.80
CR-7	21.8	4 No 12	2.01	420	8	10	1.64	420	25.00	430.35
CR-8	21.8	4 No 12	2.01	420	8	10	1.46	420	32.94	364.25
CR-9	21.8	4 No 12	2.01	420	8	10	1.33	420	38.82	305.19
CR-10	21.8	4 No 12	2.01	420	8	10	1.23	420	43.53	322.65

V. CONCLUSIONS

This study was performed to evaluate the concrete confinement strength of reinforced concrete columns that had undergone corrosion damage to the embedded stirrup reinforcement. Stirrup section-loss was quantified (i.e. the weight loss is corresponding to the average corrosion rate), for each test specimen. The relation between corrosion of stirrups and axial load carrying capacity of the tested columns are tabulated. Based on the results, the following conclusions are made:

- Section-loss along stirrups is found to be highly non-uniform. For simplicity, section loss due to corrosion is determined by calculating the average weight loss of corrosion damaged stirrups in the tested columns.
- Results indicate that the corrosion damage of stirrups reduces the ability of the stirrup to confine the concrete core.
- It is likely that the shear stirrup corrosion damage shortens the service life of reinforced concrete columns. Bridge columns with significant rebar corrosion and localized cross-sectional loss may fail abruptly under service loads. Therefore, emphasis should also be given to stirrup corrosion during regular bridge inspections to accurately evaluate load carrying capacity of corroded reinforced concrete columns. In the past, most of the emphasis has been on the loss of concrete cover and corrosion of longitudinal reinforcement.
- Inspections should identify reduced stirrup sections within the length of the column and the analysis of the corroded column should consider stirrup section loss.
- A detailed full-scale experimental study should be done in order to develop analytical equations that covers effect of stirrup corrosion on concrete confinement strength and axial load carrying capacity of corrosion damaged reinforced concrete bridge columns.

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