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Structural performance of differently confined and strengthened corroding reinforced concrete columns

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HIGHLIGHTS

- Effects of corrosion of confining reinforcement on columns behavior.
- Deformability got more severely deteriorated than strength.
- GFRP wraps far better than ferrocement jacketing for strengthening.
- Initial degree of confinement played a crucial role for behavioral improvement.

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ABSTRACT

As earthquake resistant provisions have been taken for due consideration in recent codes only, the older reinforced concrete structures are, in fact, supposed to be constructed without ductile detailing. With ongoing corrosion of embedded rebars the strength and ductility of the structures get further sacrificed. An experimental investigation was undertaken for observing the effects of continuing corrosion process on the strength and ductility aspects of differently confined reinforced concrete short columns. Effect of subsequent strengthening on these degraded columns was also studied. The experimental program consisted of 53 small scale columns with variably confined sections subjected to accelerated corrosion tests. The structural response of under confined sections was observed to be substantially poorer than the properly confined sections, which further degrades considerably due to corrosion of embedded reinforcement. One set of corroded specimens was strengthened with ferrocement jacketing. On another set of degraded columns the glass fiber reinforced polymer (GFRP) wraps were used for strengthening. Quantification was made for the reduction of structural and ductility aspects of both types of columns having different confinement levels. The study emphasizes the immediate need for proper strengthening measures to be adopted for the existing corrosion experiencing structures for improving their much needed ductility considering any seismic event in the future.

1. Introduction

Various recent international building codes recommend that the structural columns subjected to lateral forces must be designed according to the displacement or performance based approach. Transverse ties in reinforced concrete (RC) columns play an important role in enhancing their strength and ductility. The ductility is imparted in probable plastic hinge regions of RC columns by the provision of these transverse reinforcements. These ties confine the core of the compressed concrete. A number of research studies have shown that the confinement of ordinary strength concrete by transverse reinforcement results in a significant increase in strength and ductility of the compressed concrete [1–3]. The effectiveness of internal confinement depends upon a number of factors, such as tie configuration, tie spacing and also their volumetric ratio. It has also been observed that the efficiency of the lateral ties vary along the length and cross section of columns. The confinement pressure is maximum at the location of the laterally supported longitudinal bar and minimum between two such adjacent ties [4–6]. The ductile detailing of RC elements should be properly taken into consideration at the

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time of design only. However the ductility requirements have been included in the codes during last couple of decades only. Obviously the existing older structures lack in having adequate ductility and this, in fact, can be crucial in the happening of any future seismic event.

Corrosion occurs when a material deteriorates due to its interaction with the surrounding media in which an electrochemical reaction consumes the material through oxidation. With the advancement of corrosion, the structure's material properties get degraded. Corrosion of embedded reinforcement introduces expansive stresses on surrounding concrete on account of several fold volume increase of rebars. "Almusallam et al. [7]" found that corrosion of reinforcement leads to degradation of the steel–concrete interfacial bond strength. Initially, increase in bond strength was observed up-to 4% corrosion, followed by loss of bond strength for degree of corrosion from 4% to 6%. Beyond 6% corrosion substantial slippage of rebar occurs. At this stage concrete cracking on account of corrosion induced expansive stresses may become critically important. Very little corrosion is required to reduce bond strength to unacceptable levels thereafter. "Fang et al. [8]" in a study observed that for deformed bars without confinement, bond strength was very sensitive to corrosion levels and generally decreased with the corrosion level. Bond strength at 9% corrosion was observed to be only one third to that in non-corroded specimens. From the detailed literature survey performed [7,8,10,16,17], it was noticed that most of the previous studies were targeted on corrosion of main longitudinal reinforcement and its effects thereafter on structural elements. Nevertheless the corrosion of confining reinforcement itself, which naturally is supposed to occur earlier and at faster rates due to the transverse reinforcement being nearer to the surface of concrete structures. This eventually may lead to substantial loss in the degree of confinement and slippage on application of any kind of stress. The situation is also supposed to be much different in load damaged structures in which existing surface cracks may compound the problem and deteriorate the serviceability of the structures prematurely.

2. Research significance

The degree of confinement in existing older RC structures may not match up to the requirements as per the current international codes available. Further in RC structures at the time of their design, the issue of degradation of strength and ductility with advancement of corrosion process of embedded rebars is generally not taken into account. International codes on RC design consider the provision of durability protection through the passivating layer of concrete by ensuring minimum required cement content and maximum permissible water to cement ratio and also the concrete cover to the rebars. These parameters are decided according to the anticipated environmental conditions. However, this measure may not be applicable during the entire structural service life particularly when the exposure conditions are severe. Therefore, it is expected that with the passage of time the effectiveness of confining reinforcement would reduce appreciably. It becomes important to quantify this loss of confinement level. Further, the accidental over loading situations may also occur with the increasing traffic conditions. This may compound the problem due to the increased permeability of concrete structures because of the networking of interconnection of existing pores with the development of cracks due to loads coming. These aspects are not considered at the time of initial design of structures. The present paper aims to bring about the quantitative information on the structural behavior of differently confined corroding RC columns and the improvement in their response to be expected after adopting different strengthening measures.

3. Experimental program

The test variables identified in the study were degree of initial confinement, degree of corrosion, and the type of strengthening measures adopted (Table 1). Two types of confinement were used, well confined i.e. confinement as per provisions mentioned in the codes and under-confined. The target degrees of corrosion were uncorroded i.e. 0%, corroded i.e. 3% and 6%. Two types of popularly known strengthening measures were adopted, ferrocement jacketing and glass fiber reinforced polymer (GFRP) wraps. Plain concrete specimens were also cast. All of the specimens were tested under concentric compression at a constant strain rate. Finally the residual condition of the reinforcement was evaluated for the actual material losses occurred due to the accelerated corrosion process used in the experimental investigation.

3.1. Selection of materials

Different materials used along with their properties are shown in Tables 1 and 2. Target slump for concrete was 75–125 mm. Care was taken to acquire corrosion-free steel for main and transverse reinforcement.

3.2. Casting of specimens

Prior to casting of the specimens, steel cages were prepared for the proposed program. Main longitudinal reinforcement was cut into two sizes, 425 mm and 525 mm. The longer length was taken for projecting the bars from column ends for making the electrical connections later. Confining reinforcement comprised of closed hoops with a 135° bend at the ends. The steel in each specimen was carefully weighed and noted before casting [9]. The interface of the projected part of the main reinforcement and concrete was covered with an anti-corrosive epoxy coating just after casting before curing. Then this interface zone and the projected rebar were applied with a layer of good quality grease to eliminate any possibility of corrosion during curing. The specimens were of 150 mm × 150 mm × 450 mm size. Casting of the specimens was done on six consecutive days for eliminating the effect of changing ambient environmental conditions among concrete batches. Sixteen different types of specimens in triplicate and additional 5 plain concrete specimens (P1 to P5) were cast (Table 3). Average 28 days cube strength of the specimen was 37.1 to 41.3 MPa. Four, 12 mm diameter bars were used as main reinforcement with c/c spacing of 72 mm in plan. Spacing of hoop reinforcement in well confined and under confined specimens was 37.5 mm and 75 mm respectively.

3.3. Accelerated corrosion scheme

Since natural corrosion process takes years to occur, the accelerated corrosion was induced through externally impressed direct electrical currents (DC). The specimens planned to be subjected to impressed currents for accelerating the corrosion process were first subjected to chloride impregnation treatment by dipping in a 3.5% NaCl solution and drying on alternate days for a week time. Electrical current required to corrode the metal is governed by the well known Faraday's law, reproduced as below:

$$\Delta m = MIt/zF \quad (1)$$

where Δm = mass of steel consumed (g), M = atomic weight of metal (55.85 g for Fe), I = current (amperes), t = time (seconds), z = ionic charge [2], and F = Faraday's constant (96,500 amperes/s).

Corrosion was induced by applying an electrochemical potential between the reinforcing steel (anode) and an external cathode [10]. The cathode was made up of two stainless steel plates kept at opposite ends of the tank to provide an even supply of current (as far as possible) to the anodes. Removal of the coated layer of epoxy was carried out just before the current inflow for acceleration of corrosion of embedded steel through the use of MS files and electrical grinder. Thus the end part of the projected steel surface was well cleaned of the applied epoxy and made bright finish. Researchers [10] have recommended that the current density of 200 $\mu A/cm^2$ should not be exceeded in impressed current studies for proper simulation of corrosion experiments performed in laboratories with the real exposure situations in field. The target degree of corrosion was assumed to be reached by

Table 1
Material properties.

Material	Specification	Mix ratio for concrete	Mix ratio for ferrocement
Cement	OPC 43 grade	1	1
Fine aggregate	Zone II	1.942	0.8
Coarse aggregate	12.5 mm	1.741	–
Water	From tap	0.46	0.35
Silica fume	–	–	0.15
Super plasticizer	Glenium	–	0.009