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Effect of corrosion damage on seismic behaviour of existing reinforced concrete beam-column sub-assemblages

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ABSTRACT

Environmental degradation of reinforced concrete (RC) in the form of reinforcement corrosion poses greater threat to both strength and serviceability of existing RC structures. If this corrosion damaged structures are situated in the zones of higher seismicity, there would be a great threat to their safety under earthquakes and hence it is extremely important to understand their seismic performance in order to formulate suitable remedial measures. In view of this, in present study, an exterior beam-column sub-assemblage of a residential building is taken up and is designed for two levels, namely (i) designed for seismic load without ductility detailing (non-ductile specimen), and (ii) designed for lower seismic load and with ductility detailing (ductile specimen) to represent the existing RC structures of different design evolutions. Two specimens are cast for each level of design and one specimen from each of these two categories is subjected to accelerated corrosion. The experimental investigations are carried out on the uncorroded and corroded beam-column sub-assemblages under reverse cyclic loading. Corrosion of reinforcement changed the damage progression from joint shear failure to longitudinal and splitting cracking along the reinforcement bars followed by fracturing of corroded reinforcement bars. The corroded specimens showed poor hysteretic performance in the form of huge in-cyclic strength degradation. Furthermore, the cumulative energy dissipated by corroded non-ductile and corroded ductile specimens are respectively only 0.4 times and one-seventh of that of the corresponding uncorroded specimens. Thus, the seismic performance of corrosion affected existing structure is an alarming issue and warrants immediate retrofit intervention.

1. Introduction

Corrosion of reinforcement steel is a major threat to safety of reinforced concrete (RC) structures. In a tropical country like India with long coast line, temperature and humidity conditions are conducive for the corrosion of steel reinforcements, especially for RC structures located in the coastal regions. Besides coastal regions, corrosion of reinforcements is also prevalent in the industrial belts where the corrosion of reinforcement bars happens through carbonation. Corrosion of reinforcement steel is the most commonly occurring environmental degradation which results in premature deterioration of reinforced concrete (RC) structures. The depletion in strength of RC structures due to corrosion may not always lead to collapse under service loads. But under extreme loading events such as cyclones and earthquakes, corrosion affected RC structures may undergo catastrophic failure. Hence, it is vital to evaluate the seismic performance of existing corrosion affected reinforced concrete structures.

Corrosion of reinforcement is nothing but electrochemical oxidation of steel to its oxides. This involves anodic and cathodic reactions and formation of ferrous hydroxide ($Fe(OH)_2$) which is a highly unstable compound and precipitates to different forms of hydroxides and oxides of Iron depending on the availability of oxygen, water and the pH. The ferrous hydroxide further becomes ferric hydroxide and finally to form hydrated ferric oxide or rust.

The volume of unhydrated ferric oxide is about twice as that of the original steel. The hydrated ferric oxide has more volume when compared to the unhydrated ferric oxide and produces an expansive force in the surrounding concrete. An increase in volume of about two to ten times can occur at the interface of steel and concrete [5] due to corrosion of reinforcement. The resulting expansive forces make the concrete to crack once its tensile strength is surpassed. Alonso et al. [2] tried to quantify the cracking of concrete due to corrosion of reinforcement. It was reported that about 15–50 μm of loss in radius is required to generate the first visible crack of less than 0.1 mm width.

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Further, corrosion of reinforcement results in the bond degradation between the steel and concrete. Considerable efforts were made to relate the bond degradation as a function of level of corrosion, strength of concrete, depth of cover concrete, type of reinforcement, confinement, spacing of stirrups, and corrosion of stirrups [8,34,38,32,20]. Furthermore, corrosion of reinforcement reduces the mechanical properties and also deformation capacity of the reinforcement [7,31,6,4,33,27,13]. Apostolopoulos [3] investigated the low cycle fatigue behaviour of corroded reinforcement. It was reported that corrosion of reinforcement reduces the load carrying capacity as well as energy dissipation capacity of rebars. It was also reported that, corrosion reduces the fatigue life of the rebar. Hawileh et al. [12] studied the behaviour of corroded steel reinforcing bars under monotonic and cyclic loadings. With increasing level of corrosion, the yield and tensile strength of corroded bars shown increasing degradation. Kashani et al. [17] studied the cyclic response of corrosion damaged reinforcing bars. The reinforcement corrosion altered the buckling behaviour of rebars under cyclic loading. The non-uniform distribution of pitting corrosion results in unsymmetrical buckling of corroded bars. It was also reported that corroded rebar fractures earlier in tension after buckling of reinforcement in compression. Kashani et al. [18] proposed a hysteretic model for corroded steel reinforcements incorporating the effects of buckling of reinforcement, post-buckling compressive strength due to strain history and the impact of low-cycle fatigue on tension response. Thus, corrosion of reinforcement steel not only shortens the service life of RC structures but also reduces the strength, stiffness, ductility of the RC structures considerably. All these factors have influence on the performance of RC structures under seismic scenario. Thus, corrosion of reinforcement would affect the seismic performance of existing structures drastically. This was very well witnessed during Ecuador earthquake, April 2016 [36]. Hence, seismic performance evaluation of existing RC structures with corrosion affected reinforcements assumed significance.

Recently, efforts were made to evaluate the performance of corrosion damaged structural members under seismic loading. Ma et al. [23] studied the seismic behaviour of column with different levels of reinforcement corrosion and axial load ratios. It was reported that the higher level of corrosion worsens the ductility. Further, it was reported that till the level of corrosion of 14%, energy dissipation of corroded specimens is same as that of control specimens at same displacement level. Meda et al. [25] studied the behaviour of the corroded column under cyclic loading. It was reported that the corrosion of column reinforcements affected structural ductility drastically. Li et al. [21] studied the influence of level of corrosion and other parameters such as initial earthquake damage, loading history and retrofit method. It was reported that reinforcement corrosion deteriorated the cyclic behaviour of RC columns in terms of strength, ductility, low-cycle fatigue life, secant stiffness and cumulative energy dissipation capacity. Yang et al. [35] investigated the cyclic behaviour of column and concluded that corrosion reduces the ductility, energy absorption, flexural strength with the increase in level of corrosion. Goksu and IlKi [10] studied the behaviour of corroded column with different levels of corrosion and proposed expression for calculating the deformation capacity of RC columns as function of corrosion level for reliable seismic safety evaluation. Ou and Nguyen [26] studied influence of location of corrosion on the seismic performance of the beams. It was reported that the location of reinforcement corrosion had a significant influence in changing the failure mode. Yuan et al. [37] studied the cyclic behaviour of piers with non-uniform corrosion. It was reported that hysteretic performance of the corroded members is not affected compared to uncorroded ones up to the average mass loss of 8.69% of longitudinal reinforcement. Specimens where mass loss is greater than 17.59% showed significant reduction in deformation, strength and energy dissipation capacities. Ma et al. [24] studied the seismic performance of low-corroded in-service RC columns. It was reported that with the increase in axial force ratio, the failure modes are shifted; the ductility and energy dissipation capacity of corroded column are decreased. Qiang et al. [30] assessed behaviour of the columns with corroded stirrups and proposed method for predicting the lateral strength of reinforced concrete columns confined by corroded stirrups. A new numerical model based on fibre element formulations was developed by Kashani et al. [19] and Afsar Dizaj et al. [1] to evaluate the nonlinear cyclic response of corroded structural members. The model incorporates the effect of corrosion cracking, softening of concrete due to cracking, reduction in mechanical properties of rebar due to corrosion including the post-buckling behaviour of reinforcing bars in compression. The efficacy of the model was validated with the experimental results.

Very few studies were reported on the seismic performance of corrosion affected sub-assemblage or structure. Zou et al. [39] evaluated the dynamic properties of the corroded reinforced concrete frame. It was reported that the corrosion had significant impact on the dynamic properties, namely frequency and damping ratio. Guan and Zheng [11] studied the seismic behaviour of interior beam-column joint subjected to corrosion due to acid rains. It could be observed that at lower level of corrosion the bearing and deformation capacity of the beam-column specimens are improved slightly and with the increase in level of corrosion, bearing capacity and energy dissipation are decreased. Liu et al. [22] investigated the behaviour of corroded reinforced concrete moment resisting frame under seismic type of loading. It was reported that the load drop was nearly linear with the increase in corrosion ratio. It was reported that the damages of column were least affected by corrosion ratio when compared to that of the beams.

It could be observed that considerable efforts were made to study the seismic performance of corrosion damaged structural components but very few studies were reported to understand the seismic behaviour of corroded beam-column sub-assemblages which are the most crucial components of RC structures. The exterior beam–column sub-assemblage is the most critical from both seismic and corrosion point of view. Hence, in the present study, experimental investigations are carried out on uncorroded and corroded exterior beam-column sub-assemblages under seismic type of loading. A typical three storied residential framed structure is designed as per the Indian Standards [15,14,16] that are commonly used in the Indian sub-continent. An exterior beam-column sub-assemblage is chosen for experimental investigations. The seismic performance of the uncorroded and corroded beam-column sub-assemblages are evaluated critically in terms of damage progression, hysteretic behaviour, cumulative energy dissipation, strength and stiffness degradation. The study brings out clearly, the imminent seismic risk associated with the corroded RC structures.

2. Details of beam-column sub-assemblage considered for the study

In present study, the specimens are designed according to Indian standard codes of practice IS 456 [15] and IS 1893 [14]. IS 1893 [14] recommends a response reduction factor of 3 for ordinary moment resisting frames which are not meeting ductility detailing requirements prescribed in IS 13920 [16]. Whereas, a response reduction factor of 5 is recommended for special moment resisting frames (SMRF) which are detailed to provide ductile behaviour and comply with the detailing requirements prescribed in IS 13920. Since the design horizontal seismic coefficient is inversely proportional to the response reduction factor, SMRF with ductility detailing are designed for lesser seismic force. An exterior beam column sub-assemblage (as highlighted) of typical three storied RC framed building depicted in Fig. 1(a) is designed for two levels to represent the existing buildings of different design evolutions. Totally, four beam-column sub-assemblage are cast. Out of which, two specimens are designed for seismic force but not provided with ductility detailing (non-ductile specimen) and the other two specimens are designed for lesser seismic force and provided with ductility detailing (ductile specimen). The uncorroded non-ductile and