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Influences of location of reinforcement corrosion on seismic performance of corroded reinforced concrete beams

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ABSTRACT

The seismic performance of corroded reinforced concrete beams was investigated experimentally in this research. Corrosion was induced by the electrochemical accelerated corrosion method to reinforcement at various locations in the beams. After accelerated corrosion, the beams were tested under cyclic loading to investigate their seismic performance. Test results showed that as the corrosion level in tension reinforcement increased, the failure mode of the beam changed from flexural shear due to crushing of core concrete to flexural tension due to fracture of tension reinforcement. Corrosion of longitudinal tension reinforcement had a significant negative effect on the yield drift, yield load, and peak load, and on the ultimate drift when the failure was due to fracture of tension reinforcement. It had no or some degree of positive effect on the ultimate drift when the failure mode was flexural shear. Corrosion in compression reinforcement adversely affected the yield drift and had a minor negative effect on the ultimate drift when the failure mode is flexural shear. It had little effect on the yield load and peak load, and on the ultimate drift when the failure was due to fracture of tension reinforcement. Corrosion in transverse reinforcement had a negative impact on the yield drift and ultimate drift when the failure mode was flexural shear. It had insignificant effect on the yield load and peak load, and on the ultimate drift when the failure mode was caused by fracture of tension reinforcement.

1. Introduction

Corrosion of steel reinforcement is one of the most common durability issues for reinforced concrete (RC) structures. It reduces the strength and ductility of reinforcement [1–8]. Moreover, corrosion turns steel into rust, which has a volume 2–6 times that of steel [9]. This volume expansion exerts tensile stresses on surrounding concrete and weakens it [9–11]. Formation of rust reduces the ribs of reinforcement, which together with weakening of surrounding concrete decrease the bond and anchorage strength of reinforcement [12–16]. Consequently, the stiffness, strength and deformation capacities of RC members are reduced and the safety and serviceability of the structure are impaired [6,7,17–35].

A considerable number of studies have investigated the flexural behavior of RC beams with corrosion induced along the entire length of a beam, i.e. full-length corrosion [7,17–23], or along only a partial portion of a beam, i.e. partial-length corrosion [24–26]. For full-length corrosion, reduction in flexural strength was caused both by reduction in the cross-sectional area of reinforcement and anchorage strength [19]. For partial-length corrosion, reduction in flexural strength was mainly attributed to reduction in the cross-sectional area of reinforcement [31]. As the corrosion level of longitudinal tension reinforcement increased, the deflection capacity of corroded beams initially increased due to reduction in tension reinforcement area and then decreased due to reduction in the ultimate strain of corroded reinforcement [31]. As the corrosion level of transverse reinforcement increased, beams that were designed to fail in flexure could turned to fail in shear. Pitting corrosion of transverse reinforcement was the most important factor that affect the change of the failure mode [21,32]. Several studies have investigated the effects of corrosion on shear behavior of RC beams designed to fail in shear [33–35]. It was found that corrosion of transverse reinforcement reduced the shear strength and deflection capacity of corroded beams [33–35]. At high corrosion levels, severe pitting corrosion was observed, leading to fracture of transverse reinforcement at the ultimate condition [33,35]. Recently, studies on the effect of corrosion on RC deep beams have also been carried out [36–38]. It was found that corrosion could change the brittle shear failure mode of uncorroded beams to a more ductile flexural mode. This is because corrosion reduced the flexural capacity more than the shear capacity [37,38]. It must be noted

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that all the beams in the above studies were tested under monotonic loading.

Many earthquake prone regions such as Taiwan, Japan, California and New Zealand have their populated areas close to coastline. RC structures in these regions are therefore susceptible to the combined hazards of reinforcement corrosion and seismic actions. Growing attention in recent years have been devoted to investigate structural behavior under the combined effects of reinforcement corrosion and seismic damage [39–41]. However, experimental seismic behavior of corroded RC beams have not received sufficient attention. RC beams under seismic reversed loading conditions suffer more severe degradation to the flexural and shear strengths than monotonic loading. Kobayashi [42], Kato et al. [43], Ou et al. [44], and Ou and Chen [45] tested corroded RC beams under cyclic loading to examine their seismic behavior. The beams tested by Kobayashi [42] and Kato et al. [43] were subjected to four-point cyclic bending and hence the central critical region was not affected by shear. The beams tested by Ou et al. [44] and Ou and Chen [45] were tested in a cantilever manner with cyclic loading applied to the free end and hence the critical region around the fixed end was subjected to both flexure and shear, which is more representative of the loading condition of plastic hinge regions of real beams under seismic actions than the four-point bending loading. Test results showed that when corrosion was induced both to longitudinal and transverse reinforcement, the ultimate drift, ductility, and energy dissipation of the beams initially increased and later decreased with increasing corrosion level [44]. When corrosion was induced mainly to transverse reinforcement, the flexural strength of the beams was not significantly affected while the deformation capacity was reduced significantly [45].

This study is a continuation of Ou and Chen's study [45] and is a part of a systematic experimental study on the seismic behavior of corroded RC beams with corrosion induced to reinforcement at different locations of the beam. In Ou and Chen's study [45], corrosion was induced mainly to transverse reinforcement. In this study, corrosion was introduced mainly to: (1) bottom longitudinal reinforcement; (2) both top and bottom longitudinal reinforcement; and (3) both longitudinal and transverse reinforcement. By combining the results of this study and Ou and Chen's study [45], the effects of corrosion in reinforcement at different locations on the seismic performance of corroded RC beams were examined quantitatively in this paper.

2. Experimental program

2.1. Specimen design

The beam specimens had the same design as those examined in Ou and Chen's study [45] and was designed conforming to the requirements for the flexural members of special moment frames (ACI 318 code [46]). Fig. 1 illustrates the specimen design. The specimen contained a beam connected to an anchorage block. The specified concrete compressive strength was 28 MPa and the specified yield strength of longitudinal reinforcement and transverse reinforcement was 420 MPa. Actual material properties are listed in Table 1. The beam was designed with an equal amount of top and bottom reinforcement, each of which had three D29 deformed bars, and with D13 deformed hoops as transverse reinforcement having a horizontal spacing of 100 mm. The beam had a tension reinforcement ratio of 1.5% and a volumetric ratio of transverse reinforcement to the core concrete of 1.8%. Shear strength of the beam was designed based on shear demand corresponding to the maximum probable moment strength calculated based on 1.25 specified yield strength of longitudinal reinforcement. Concrete shear strength was not considered in the shear strength calculation (ACI 318 code [46]). The ratio of the design shear strength to shear demand ($\phi V_n/V_u$) is 1.06.

Table 2 summarizes the design variables examined in the entire experimental program including type Bt specimens that have been presented by Ou and Chen [45]. The corroded specimens are classified into five types depending corrosion locations. Specimen types B, TB, Bt, and TBH had corrosion induced to bottom longitudinal reinforcement, top and bottom longitudinal reinforcement, transverse reinforcement, and all reinforcement, respectively, in the potential plastic hinge region. The number at the end of each specimen name denotes the average actual corrosion mass loss of all longitudinal reinforcement in the corroded region for specimen types TB, TBH, and TBt, that of all bottom longitudinal reinforcement in the corroded region for specimen type B, and that of all transverse reinforcement in the corroded region for specimen type Bt [45]. The potential plastic hinge region is the region from the fixed end of the beam (connected with the anchorage block) extending 600 mm towards the free end of the beam (Fig. 1(a)). Type TBt had corrosion induced to top and bottom longitudinal reinforcement in the transition region of the beam, which is the region between 300 mm and 900 mm from the fixed end (Fig. 1(a)). Specimens TB-0 and Bt-0 were the control specimens without reinforcement corrosion. Steel reinforcement that was within and beside the intended corroded region and not to be corroded was coated with an anti-corrosion coating to prevent corrosion. The transverse reinforcement of specimens TB-32, types B and TBt were tightly wrapped with a thin layer of plastic tape in addition to the epoxy coating for further corrosion protection.

2.2. Accelerated corrosion

After curing the specimens for at least 28 days, corrosion was induced to reinforcement by electrochemical accelerated corrosion method. Each longitudinal bar or each hoop to be corroded in the corroded region was connected with an electrical wire (Fig. 2(a)) to the positive terminals of DC power supplies and acted as anode in the corrosion process. The corroded region was enclosed by wood plates (Fig. 2(b)). The space between the corroded region and the plates were filled 5% NaCl solution to provide electrolyte for the corrosion process. The negative terminals of the power supplies were connected to four copper plates placed into the NaCl solution around the corroded region. The copper plates acted as cathode in the corrosion process. The impressed current density was approximately 600 $\mu A/cm^2$ for both longitudinal and transverse reinforcement. Fig. 2(c) and (d) illustrates the corrosion setup. The current density is higher than the maximum values found in natural corrosion conditions (10–100 $\mu A/cm^2$ [10]). Note that increasing current density may affect the mechanical properties of corroded reinforcement [47], the bond strength between reinforcement and concrete [48] and the corrosion crack width of concrete [49]. Therefore, care should be taken in using the finding of this research in natural corrosion conditions.

2.3. Test setup and instrumentation for cyclic loading

After accelerated corrosion for the corroded specimens and after curing for at least 28 days for the control specimens, the specimens were subjected to cyclic loading to investigate their seismic performance. The specimens were tested in a cantilever fashion (Fig. 3(a)). The anchorage block of the specimens were fixed to the strong floor. A hydraulic actuator was attached to the free end at a distance 1200 mm from the fixed end to apply cyclic loading. The loading was displacement controlled to prescribed drift levels (Fig. 3(b)). A displacement transducer was installed right below the loading point (Fig. 3(b)) to measure the relative displacement between the loading point and the fixed end, which