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Cracking and failure of patch repairs in RC members subjected to bar corrosion

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HIGHLIGHTS

- Testing to simulate the internal expansion due to steel rebar corrosion.
- Repair patch shape, depth, width, and material strength were investigated.
- The crack patterns and failure modes were observed for various test specimens.
- Triangular and rectangular patches were compared for internal expansion and failure pressure.
- The ultimate load capacity increased with a patch depth beyond expanding rebar.

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ABSTRACT

Even after repairing a concrete structure, internal corrosion may continue in service state especially under a severe environment and this would deteriorate the newly applied repair material. In this regard, this study investigates the cracking and ultimate failure behavior of patch-repaired sections subjected to internal expansion pressures due to rebar corrosion. An experimental program was set up with major test variables being patch shape, patch depth, patch width, and bond strength of the patch material. The internal expansive pressure was applied through an expansive rubber at the location of a possible corroded rebar. While some patched sections were found to crack first directly above the expanding rebar, most of the patched sections eventually failed due to pop-out spalling along the patched edges. Patched sections deeper than the first layer of steel rebars were found to have higher load capacity until failure. The present study also indicates that the strength of patch material shows no sizable effects on ultimate load capacity of patched sections.

1. Introduction

The increasing number of reinforced concrete (RC) structures suffering from premature deterioration due to steel corrosion has promoted extensive research over the years [1–5]. The corrosion-induced damage mainly forms due to the expansive corrosion products which occupy larger volumes than the original steel reinforcement. The magnitude of this volume increase of corrosion products generally varies between two and six times the volume of the original steel [6–8]. The volume increase of corroded rebars causes expansion-induced pressure around the rebar and induce tensile stresses in the concrete [9–11]. The increase of tensile stresses may then cause concrete cracking.

Corrosion may continue to progress within the concrete, even after a section of deteriorated concrete has been removed and replaced with a new patching material. This is usually caused by the insufficient corrosion protection of existing corroded rebars. In this case, the internal pressures arising from continued expansion of corroded steel may induce cracking in the initial concrete or in the patched section depending upon the condition and geometry of patches. Therefore, it is important to explore the effects that some important parameters have on the performance of patched sections in order to guarantee a sufficient service life even under progressive corrosion. By observing closely the patterns of crack propagation in the patched sections, some insight can be drawn into the capacity of a repaired structure to withstand continuous corrosion of the embedded steel.

The repair or rehabilitation of a RC member may involve removing and replacing the damaged section, applying an overlay or surface treatment, or attaching a cathodic protection system to

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prevent further corrosion of the embedded steel in concrete. Among these methods, the most frequently-applied repair technique is to remove the deteriorated concrete and to replace it with repair mortar.

If the corrosion in the concrete was originally caused by chlorides, chlorides are likely to exist also in the surrounding undamaged concrete. Corrosion affects, therefore, not only the repaired zone, but also the surrounding concrete. Although little or even no chlorides are present in the patch, the repaired section can become passive itself due to the surrounding macro-cell corrosion.

When corrosion is expected to occur in existing structures, it is imperative to guarantee structural life-time and serviceability, and thus any concrete with repaired patching needs to be effective for resisting additional corrosion that may occur around the patched region. In this regard, it is necessary to explore the factors that affect the performance of a patched section, including how these factors affect the performance and cracking behavior of patched section. These factors may include the shape and size of patched sections and the bond strength of patch material. Therefore, the purpose of this study is to identify the effects of several important parameters such as the shape, depth and width of patched sections, and the bond strength of patch material on the performance of repaired sections. To this end, an experimental program was set up and comprehensive experimental campaign were conducted to examine cracking and failure in various patched sections. An internal expansion pressure was applied to the patched section to simulate the increasing formation of corrosion products on bar surface. The load at first cracking, the failure load, the maximum pressure, and the crack pattern were examined for various cases of patched sections. The present study provides valuable data on the performance and cracking behavior of patch-repaired RC members.

2. Experimental investigation

An experimental program was set up to explore the cracking and failure behavior of patch-repaired RC members subjected to corrosion-induced expansion of the reinforcement. The effects of patch sizes and material strength on the performance of patched sections were considered in this study. An internal pressure at the location of the rebar was applied to the repaired-patch to simulate the continued expansion due to corrosion. Measured values include the relation between internal pressure and radial displacement, cracking load, failure load, and crack patterns for two different sections of the patch (triangular section or rectangular section, the latter with different depth values). The detailed test variables, test materials, and experimental procedures are described below.

2.1. Materials

Three different repair materials were considered in this study that represent standard repair materials [12]. The mixture proportions of those repair materials are shown in Table 1. In this paper, three different patch material types of low (L), medium (M), and high (H) were based on the measured bond strength. The bond strengths of repair materials were 0.64 MPa, 2.0 MPa, and 2.4 MPa, respectively. Note that L, M, and H were determined based on average bond strength and they will be utilized to simplify the test analysis. Also shown in Table 1 is the mixture proportion of the parent concrete. All parent concrete specimens were cast with a cement content of 288 kg/m^3, a coarse–fine aggregate ratio of 1.02, and a water–cement ratio (w/c) of 0.62. Methyl cellulose was added as a thickening agent to improve the viscosity of the repair mortar. The parent concrete specimens were water cured in controlled conditions in the laboratory room.

Mechanical tests were performed on the parent concrete as well as on each patching mixture and the results are shown in Table 1. The compressive strengths were determined using an average of three standard cylinders with 100 mm diameter and 200 mm length, and tested at 50 days which is the same age with the loading test. The average compressive strength of parent concrete was 33.2 MPa which is very similar to the normal strength concrete in actual structures. The split-tensile strengths were determined using cylindrical specimens of 150 mm diameter and 150 mm long in accordance with JISA 1113 standard [13]. To evaluate the bond strength of three patch repair materials, pull-off tension bond tests were carried out in accordance with the JSCE-G 561-2005 standard [14]. For the bond test, a small slab of the parent concrete material was cast first and then the repair patch material with a 20 mm-thick overlay was placed on the top of the parent concrete. This overlay layer was cut into 40 mm square coupons prior to testing. A gage was glued to each coupon by means of an epoxy adhesive and the maximum tensile load necessary to pull off the coupon from the underlying parent concrete substrate was used to determine the bond strength. Table 2 summarizes the test variables according to the patch configurations and bond strength for various test series.

2.2. Design of specimens and test variables

The size of the parent concrete specimens was 400 × 400 × 150 mm. A preformed foam cutout was made in the parent concrete in order to patch a repair material as shown in Fig. 1. Major test variables for patch repair were shape, depth, and width of patch sections. Two different shapes of triangular and rectangular patches were considered and the depth of patches was 30 mm, 40 mm, and 70 mm respectively. The patch depth of 30 mm represents the depth from the concrete surface to the center of the corroded rebar (Fig. 1d) and the patch depth of 40 mm represents the depth from the concrete surface to the inner point of the corroded rebar (Fig. 1e), respectively. The patch depth of 70 mm represents the depth from the concrete surface to the point far beyond the internal secondary reinforcement layer as shown in Fig. 1f. The different depths of the patch were aimed to ascertain to what extent the depth affects cracking and failure modes because of the corrosion-induced expansion of the reinforcement. Actually, the angle of cracking that occurs in a concrete specimen due to corrosion expansion of rebar may be influenced by the patch shape, depth and width as illustrated in Fig. 2. Tsutsumi et al. [15] performed numerical simulations for the concrete with different cover depths and rebar diameters in order to determine the angle of crack propagation that occurs in the presence of the corrosion expansion. From these simulations, it was reported that the patch repairs made with an angle of 73 degree or less were found to produce spalling failures. In this study, the repair widths considered were 100 mm, 150 mm, and 200 mm, respectively, which correspond to the possible crack angles of 59, 68, and 73 degrees, respectively (see Fig. 2). It was considered that selected angles are reasonable to see the effect of the repair width on the cracking and failure behavior of patched section since it was reported that 73 degree or less produce spalling failure on the concrete surface [15]. Normal practice of patch repair is to have vertical lateral walls in the patched section. This was studied together with an alternative of a triangular patch in order to explore if the greater surface area of the triangle could change the bonding and failure behavior of the patch.

The reinforcing bars were installed according to a rectangular net with a spacing of 150 mm as shown in Fig. 1. The cover depth of outer rebar was 20 mm and that of inner rebar was 40 mm, respectively. The diameter and yield strength of rebar were 20 mm and 338 MPa, respectively. To have sufficient room for the patch repair, wood and Styrofoam blocks were placed at the designated location of patched section before casting the parent concrete. These forms were removed at 21 days after curing of parent concrete. The contact surface to be patched was

Table 1
Mixture proportions and properties for parent concrete and repair materials.

Parent concrete							Strengths (MPa)		
Slump (mm)	Air (%)	Water (kg/m^3)	Cement (kg/m^3)	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)		Compressive strength (f'_c)		Split-tensile strength (f'_{sp})
120	4.0	179	288	913	910		33.2		3.65
Repair mortars (mass ratio)							Strengths (MPa)		
Type	Water	Cement	Fine aggregate	Thickening agent	Anti-foamer	Polymer resin	Pull-off bond	f'_c	f'_{sp}
L	40	100	200	–	–	–	0.6	54.3	3.70
M	40	100	200	0.1	0.3	5	2.0	48.7	3.80
H	40	100	200	0.2	–	–	2.4	47.7	2.80