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Sustainable Rehabilitation of Corroded Bridge Columns

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ABSTRACT: Several bridge columns damaged as a result of steel corrosion were repaired using techniques developed during this research program, which involved different types of grouts and GFRP wraps. In the first of the two test series, column specimens were subjected to accelerated corrosion and repaired. The field-simulated corrosion caused about 20% reduction in axial capacity of columns and much larger reductions in ductility. The performance of the repaired columns was better than that of the original column. In the second test series, GFRP retrofit was found to significantly enhance strength, ductility and energy dissipation capacity of columns under simulated earthquake forces which could easily compensate for the loss caused by the observed corrosion of steel. Long term monitoring of four rehabilitated columns in the field showed excellent performance with a marked reduction in the rate and risk of corrosion over time providing a more durable retrofitting technique than traditional ones.

1 INTRODUCTION

Environmental effects, ageing, overloading and updated stricter code provisions make numerous structures deficient. One of the most serious conditions under which the steel-reinforced concrete structures are damaged is the use of de-icing salts combined with cycles of freezing and thawing. A case study involving highway bridge columns that were damaged by corrosion of steel due to the application of de-icing salt and extreme weather conditions is presented here. Figure 1 shows the conditions of the bridge columns before repair. These columns are about 800 mm in diameter and the bridge was built in 1960s. The concrete cover was completely spalled off and the effectiveness of spiral steel had diminished significantly. The traditional repair techniques for corroded structures generally last only a few years before a repeat of repair is needed. These techniques are cumbersome and in most cases need closure of structures for long periods of time. An innovative and durable solution that involved the use of expansive or non-shrink grout and GFRP wraps was developed during this research leading up to the repair of field columns. The idea behind this technique was to seal the structure such that the corrosion process is starved of its essential ingredients such as moisture and air and the corroded lateral steel is compensated with GFRP. This would eliminate the need for removing the contaminated concrete and steel thus substantially reducing the cost of repair.

The research program consisted of two test series. In the first series of this investigation, the 406 mm in diameter lab column specimens were tested under concentric compression to evaluate the effect of steel corrosion. In a follow-up test program, behavior of retrofitted columns, 356 mm in diameter, was investigated under reversed cyclic lateral excursions while simultaneously subjected to axial loads thus simulating earthquake forces. In addition to the results from this experimental program, the paper also includes data from field monitoring over several years after the repair of the columns was carried out.

Figure 1. Corrosively damaged bridge columns.

2 EXPERIMENTAL INVESTIGATION

2.1 Columns under axial load

As noted above, a laboratory-based research program was carried out to investigate the feasibility of the proposed repair technique. In the first test series, half-scale specimens of bridge columns were constructed and tested under axial load. Five 406 mm diameter × 1.37 m long columns were constructed with 6-20M longitudinal steel bars and a 10M steel spiral with 75 mm pitch. Thirty four days after casting, four of these column specimens were subjected to accelerated corrosion to cause damage similar to that observed in the field. Figure 2 shows the damaged columns in different stages of repair. Three corroded columns were repaired using various retrofitting procedures. The un-repaired column damaged by corrosion acted as control specimen along with the un-corroded healthy column. The repair schemes were designed to minimize the costly fieldwork. Therefore, the corroded steel and the contaminated concrete were not removed from the damaged columns.

One damaged column was built back to original shape with a commercially available rheoplastic, shrinkage-compensated mortar called Emaco. This cement-based mixture contained propylene fibres and silica fume. After 24 hours of curing, the column was wrapped with two layers of GFRP. The second column was repaired with grout based on expansive cement especially developed for high expansive potential (Sheikh et al 1994). A 3 mm thick polymer sheet reinforced with polyethylene fibres was wrapped around the damaged area of the column and held in place with five clamps so as to act as a formwork for the expansive cement mortar. Four hours after grouting, the column was wrapped with two layers of GFRP on top of the polymer sheet which acted as a barrier between fresh grout and the GFRP wrap. The third column was repaired in a similar manner using non-shrink cement known as Type K. The columns were stored in the lab at 23°C temperature and about 50% relative humidity for three months before they were tested under axial load for their short-term mechanical behaviour. The results from the tests on four columns are presented here in Figure 3 along with the tested columns.

The corrosion in the lab specimens was limited to spirals as was the case in the columns of the bridge and caused about 20% reduction in strength and much larger reductions in ductility and energy dissipating capacities of the column (Figure 3). Pitting corrosion of spiral reduced area of steel drastically making it ineffective for confinement and caused its rupture at relatively small column strains. Repair improved the behaviour of damaged columns significantly. The axial load carrying capacity of the Emaco-repaired specimen was as large as that of the undamaged control column and its ductility and energy dissipation capacity were substantially better. The columns repaired with Type K and expansive cements behaved similarly and did not display good performance due to the fact that at large strains the plastic sheet of the formwork used in these columns opened out and engaged the fibre wrap at both ends, causing large local strain and premature failure of the wrap and the column. Uomoto and Nishimura (1999) had reported based on lab studies in which fibres alone were immersed in sodium hydroxide solution, that alkalis adversely affected the properties of glass fibres. The plastic sheet in the two columns was used to separate the GFRP wraps from the fresh cement and concrete products. In other repaired columns, the repair patches were covered with a protective epoxy coating to avoid direct contact between the new cementitious material and GFRP.

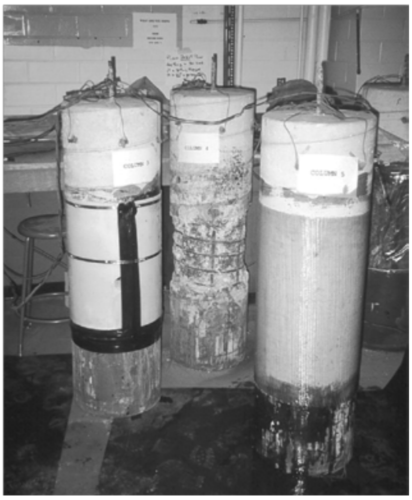

Figure 2. Simulated corrosion damage of columns and repair schemes.

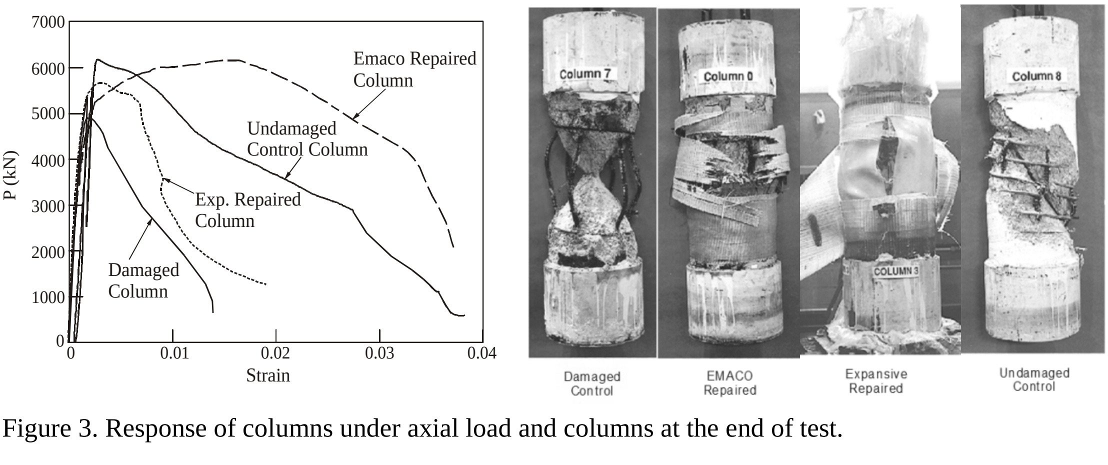

Figure 3. Response of columns under axial load and columns at the end of test.

2.2 Columns under axial load and cyclic lateral loads

A large experimental program has been underway to evaluate the performance of FRP-retrofitted columns under cyclic flexural and shear loads while subjected to constant axial loads. Results from three columns S-4NT, S-2NT, ST-5NT tested by Sheikh and Yau (2002) and a column P27-2GF-4 tested by Liu (2013) are presented here. Each column was 356 mm in diameter, 1.47 m long and cast integrally with a stub of dimensions 510 × 760 × 810 mm. All the columns were tested under an axial load in the range of 0.25P_o to 0.27P_o where P_o represents the theoretical axial load carrying capacity of the column. These columns were similar in all respects except the lateral confinement. Column S-4NT was a control specimen which contained spiral of #3@300 mm pitch in the test region. The #3 bar has a cross-sectional area of 71 mm^2. Column S-2NT had #3@80 mm steel spirals which were designed in accordance with the then current seismic provisions of ACI 318-95 for ductile concrete columns. Columns ST-5NT and P27-2GF-4 initially contained only minimal amount of steel spirals (US#3@300 mm) and were later retrofitted with one layer and two layers of externally bonded transverse GFRP wrapping, respectively.

Figure 4 shows the moment vs. curvature responses at the critical sections of these specimens. It is obvious from the figure that the control specimen S-4NT failed in the 4th lateral displacement cycle in a brittle manner indicating that the confinement provided by this kind of widely spaced spirals was almost negligible. Columns with deficient lateral confinement have very low ductility and energy dissipation capacities which may lead to brittle collapse of structures.

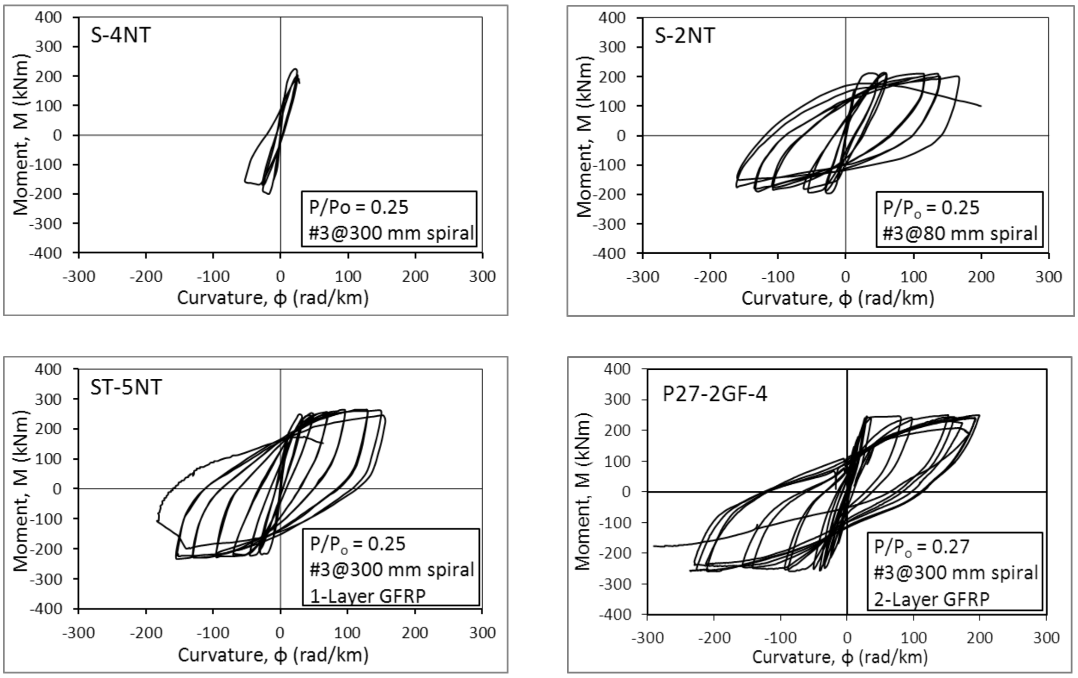

Figure 4. Moment vs. curvature responses of four circular columns.

Comparing the behaviour of columns S-4NT, SN-5NT and P27-2GF-4, it was concluded that substandard concrete columns were effectively retrofitted by externally bonded GFRP wrapping, which could significantly improve the seismic performance of columns and resulted in a remarkable increase of ductility and energy dissipation capacity. Furthemore, the behaviour of GFRP-retrofitted columns SN-5NT and P27-2GF-4 under simulated seismic loading exceeded the seismic performance of the conventional steel-confined column S-2NT which was designed in accordance with the seismic provisions of ACI 318-95. Columns retrofitted by FRP wrapping showed little degradation of flexural strength with the increase of lateral displacement excursion, which was distinguished from the seismic behaviour of conventional steel-confined columns. The experimental results showed that substandard columns with deficient lateral confinemnt can be effectively retrofitted by externally bonded FRP wrapping with relative ease to improve the seismic resistance of columns.

3 BRIDGE REPAIR

Columns in the damaged bridge, as shown in Figure 1, were repaired using the techniques discussed above without the plastic sheet. Four of the columns with three different repair schemes were monitored for several years.

Column 1 was repaired by building it to its original shape with expansive cement grout cover around the column. The formwork was removed about twenty hours after grouting and the column was wrapped with a thin polyethylene sheet and then two layers of GFRP with glass fibres aligned in the circumferential direction. The polyethylene sheet, used as a barrier between the new concrete and the GFRP, was not expected to affect the column behaviour. Three days after the grouting, the column was instrumented with six strain gauges installed on the FRP in the circumferential direction. Two gauges each, 180° apart, were installed at mid height, 750 mm above and 750 mm below the midpoint.

Columns 2 and 11 were repaired with commercially available non-shrink grout that was pumped in place with the steel formwork. The steel forms were removed after four days and the columns were wrapped with polyethylene sheet and GFRP in the same way as Column 1. Eight days after the grouting, these columns were instrumented with strain gauges in a manner similar to Column 1.

Column 3 was repaired with Emaco mortar which did not require and formwork. A protective epoxy coating was applied six days later followed by the GFRP wrapping. The strain gauges were applied to this column eight days after grouting/plastering. The thickness of the cover that needed to be built around each column was approximately 50 mm.

The corrosion activity was measured by embedding three half-cells in each of the four columns. The cells were placed at the top, middle and bottom of the columns. Table 1 shows the data from these cells for over nine years. Figure 5 shows the average corrosion activity and the related risk of corrosion in the four columns reduced continuously over the years. The GFRP wraps seem to have starved the corrosion process of essential ingredients of oxygen and water. It can be seen from Figure 6 that the repaired columns have been performing in an excellent manner over the last 15 years of service under severe weather conditions. Unlike the traditionally repaired structures these columns did not need any repeat of repairs.

Table 1. Corrosion potential in repaired columns

Day	Temp (°*C*)	Rel. Hum. (%)	Corrosion Potential (Embedded Cells, Silver/Silver Chloride)											
			Column 1			Column 2			Column 3			Column 11		
			Top (mV)	Mid. (mV)	Bot. (mV)	Top (mV)	Mid. (mV)	Bot. (mV)	Top (mV)	Mid. (mV)	Bot. (mV)	Top (mV)	Mid (mV)	Bot (mV)
0	23	79	-322	-274	-219	-259	-291	-292	-223	-211	-	-303	-108	-180
61	20	NA	-280	-234	-187	-230	-231	-	-196	-178	-183	-305	-90	-157
103	16	70	-266	-212	-176	-219	-209	-238	-169	-145	-149	-293	-84	-163
336	20	60	-336	-240	-204	-243	-217	-237	-214	-120	-118	-283	-86	-163
700	28	43	-335	-200	-182	-123	-257	-128	-140	-104	-98	-272	-80	-153
1485	24	46	-172	-195	-152	-72	-336	-146	-62	75	-90	-164	-72	-180
2218	26	44	-234	-174	67	-41	-173	-120	-170	82	-76	-123	112	21
2918	21	65	-197	-133	-69	-8	47	0	-31	73	-62	-180	5	-11
3337	23	40	-176	-84	-70	-14	17	-58	-39	84	-50	-159	20	-11

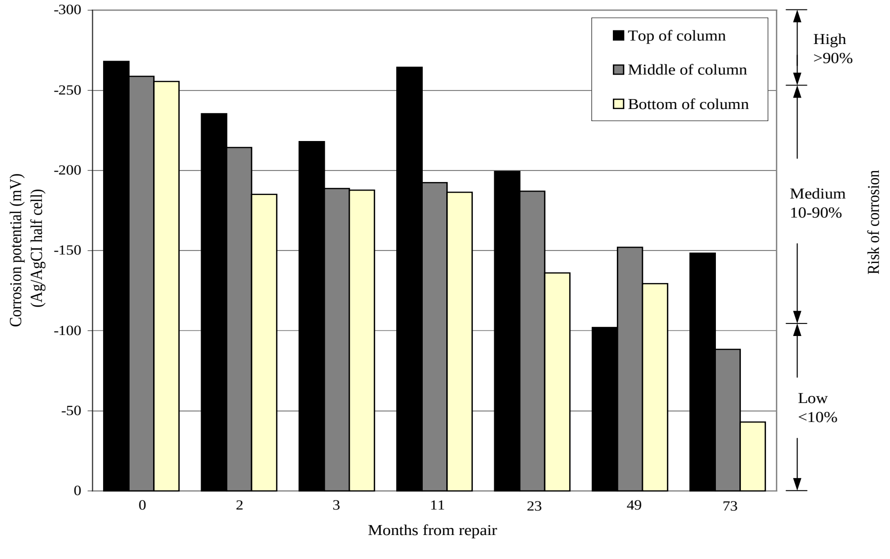

Figure 5. Corrosion potential and risk in repaired bridge columns.

Figure 6. Repaired columns after fifteen years of service.

4 CONCLUDING REMARKS

Several columns of a bridge along a major highway in Ontario, damaged by steel corrosion, were repaired using techniques developed in a research program. Research showed that the prevalent field damage would cause about 20% reduction in the axial load carrying capacity of the columns and much larger reductions in their ductility and energy dissipating capacity. The columns were rehabilitated using repair techniques developed in a research program which involved testing of half-scale models of field columns under axial load only and under simulated seismic loads. Four of the columns repaired in the field were extensively instrumented for strain measurements and corrosion potential.

In addition to visually monitoring all the repaired columns for soundness, data from the four instrumented columns was recorded regularly for over 10 years. The FRP-repaired columns have been in service for more than fifteen years and have displayed excellent performance without requiring any additional repair work. In the procedure used for repair, the corroded steel and the contaminated concrete were not removed from the structure and even then the corrosion activity and risk of corrosion in the columns reduced significantly with time. Columns strain data indicated no impending deterioration. Based on the laboratory studies and field monitoring, it was concluded that the repaired field columns have load-carrying capacities of at least equal to that of the originally designed columns and significantly higher ductility and energy dissipation capacity. This study combined the laboratory research with field applications and long-term monitoring of structures. Results from this work show that monitoring of a representative number of field elements can provide an economical, valuable and often an essential source of information for designing the laboratory specimens and for evaluating the health of a structure.

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