ACCELERATED AND RESILIENT REPAIR OF BRIDGE COLUMNS

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ABSTRACT

Upgrade and repair of existing structures is an expensive and time consuming process. In this research, an accelerated procedure was developed for the repair of bridge columns damaged primarily by the corrosion of steel. The procedure was used for the retrofit of columns in a major highway bridge and monitored for their long-term performance. The procedure involved building of columns to their original shapes and wrapping them with glass FRP. Monitoring included measurement of strains in FRP and evaluating corrosion potential and risk. The field data showed sound performance of the repair and continuous reduction of corrosion over the years.

INTRODUCTION

There is a large inventory of existing bridges that have become deficient as a result of corrosion of reinforcing steel. Upgrade and repair of these structures is an expensive and time consuming exercise in most cases. For structures such as bridges, it is especially serious considering the disruptions in traffic and related costs. Corrosion of steel is accelerated in regions where de-icing salts are used to clear the roads of the snow and ice. The chloride from these salts contaminates the concrete and is very corrosive for the reinforcing steel. Expansion of steel caused by corrosion results in expansive forces that causes delamination and removal of concrete cover further exacerbating the process and reducing load carrying capacity of structures. Figure 1 shows such a bridge with damaged corroded columns and girders. The concrete cover was completely spalled off in a number of columns and the effectiveness of spiral steel was almost completely lost.

Fig. 1. Highway Bridge damaged by steel corrosion

Traditional methods of repairing such a structure would require a number of steps such as providing temporary supports for the structure, removal of contaminated and damaged concrete from the columns, replacement of corroded steel with new steel, and building of columns to their original shapes with new concrete. Each of these steps involves costly operation that takes time to complete. The costs associated with the disruptions in traffic and the resulting chaos are enormous and difficult to quantify.

In the research presented here, an accelerated procedure was developed for the repair of columns such as those shown in Figure 1. It was stipulated that if the access of water and oxygen into the retrofitted columns could be stopped or at the very least minimized, the corrosion process can be slowed down if not completely stopped. This required providing an impervious layer on the outside and effectively sealing the columns from the environment as far as the water and oxygen ingress was considered. The contaminated concrete could thus be left inside the members as long as it is reasonably sound. It was also felt that the corroded steel can also stay in place and additional reinforcement can be provided to compensate for the reduction due to corrosion. Only the spiral steel was observed to have been corroded in all the columns. The materials selected for replacement of concrete to build the columns included different types of grouts including one based on the expansive cement especially developed for such applications. Reinforcement provided consisted of glass fiber reinforced polymer wraps.

EXPERIMENTAL WORK

Columns under concentric compression

The research based on which the repair techniques were developed involved simulating the behavior of the damaged and repaired columns in a laboratory study using half scale models of the field columns and testing them under axial load (1). In this test series discussed here, four column specimens, 406 mm in diameter and 1.37 m long, each reinforced with 6-20M longitudinal reinforcing bars and 10M spirals with 75 mm pitch were constructed. Regular weight concrete with specified compressive strength of 30 MPa and the steel bars with 400 MPa yield strength were used. Three of these four specimens were subjected to accelerated corrosion to reproduce the damage similar to that observed in the field.

Figure 2 shows three of these columns at different stages of investigation. One column shows the damage due to corrosion of steel which resulted in complete loss of concrete cover as was observed in the field columns. It was observed that as in the field columns, corrosion was mainly limited to spiral. Of the four columns in this test series, one column was not subjected to the corrosion process and one corroded column was not repaired. These two columns acted as control specimens against which the performance of the repaired columns could be evaluated to judge various repair techniques for their abilities to upgrade the columns. The two control columns also provided a direct comparison to evaluate the loss of a column's load carrying capacity and the deformation capacity.

Fig. 2. Columns at various repair stages

Two corroded columns were repaired using two different accelerated retrofit techniques with the aim of minimizing the time required to complete the field work and the total cost (Figure 2). In each of the procedures investigated, the corroded steel and the contaminated concrete were not removed from the damaged column. Only loose concrete and debris were cleaned with a steel brush. The columns were built to their original shapes with different types of grouts before wrapping them with GFRP. Savings in cost and time for repair primarily stems from the fact that contaminated concrete and corroded steel were left inside the repaired column. It was observed in the field as well as in the lab experiments that the corrosion was limited to the transverse spiral reinforcement only and the longitudinal steel bars were not damaged.

One column was repaired with grout based on the expansive cement especially developed for such applications (exp-repaired) by Sheikh et al (2). A 3 mm thick polymer sheet was bent around the damaged area of the column and held in place with five clamps so as to act as formwork for the column repair. The expansive cement grout was then poured in place. Four hours after grouting, the column was wrapped with two layers of GFRP on top of the 3 mm thick polymer formwork sheet.

A commercially available rheoplastic, shrinkage-compensated grout containing non-ferrous fibers named Emaco was used to build the second column to its original shape. The repair patch was covered with epoxy coating to avoid direct contact of GFRP with the new cementitious material. After 24 hours of curing, the column was wrapped with two layers of GFRP. All the columns were stored in the laboratory at room conditions with temperature of about 23^{o}C and 50% relative humidity until testing.

The barrier between the GFRP and the fresh grout was used in this study because, on the basis of the lab studies in which fibers alone were immersed in sodium hydroxide solution, researchers (e.g Uomoto and Nishimura 1999) had reported that glass fibers were adversely affected by exposure to alkalis. The GFRP system used in the lab specimens and for the field work was based on nominally 1.25 mm thick fabric with glass fibers oriented in one direction and sparsely spaced aramid fibers in the transverse direction. The tensile strength of the GFRP was 563 N/mm width averaged from 8 coupon tests. The tensile behavior of the GFRP was essentially elastic until rupture at an average strain of about 2.28%.

Figure 3 shows the results from the tests on columns under axial load. It can be seen in the figure that damage caused by corrosion of the spiral and the loss of concrete cover resulted in about 20% reduction of the axial load carrying capacity of the column compared with the healthy undamaged column. Reductions in ductility and energy dissipating capacity were even more significant. Figure 4 shows the columns after their tests. While the undamaged healthy column displays the role of spiral reinforcement in keeping the integrity of the column core intact, the corrosion in the damaged column rendered the spiral steel completely ineffective. Pitting corrosion created weak spots where the spiral ruptured at relatively small axial strain in the column. The ruptured pieces of the spiral that flew off the column during testing are shown in Figure 5. The pitted corrosion can be clearly seen at several locations including points of rupture. Confinement that is needed at large strains is obviously not available in the corroded columns.

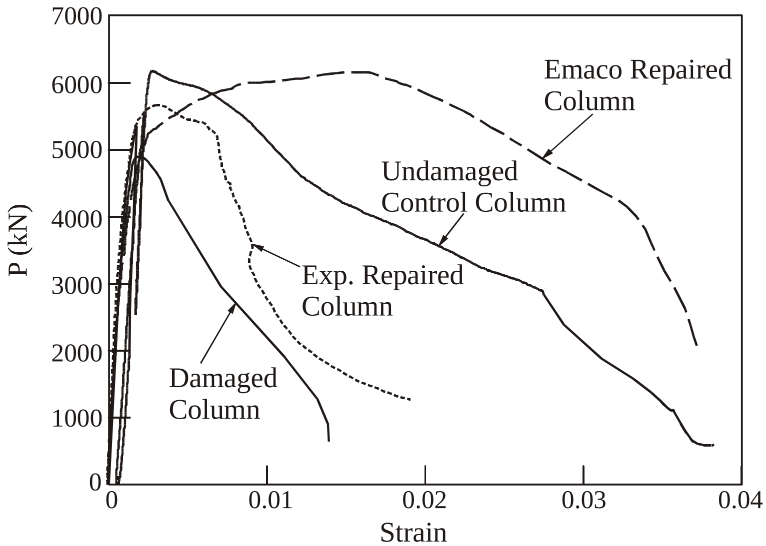

Fig. 3. Behavior of columns under axial 1oad

EMACO Repaired

Expansive Repaired

Damaged Control

Undamaged Control

Fig. 4: Columns after testing


Fig. 5. Ruptured pieces of spiral

The two repaired columns displayed improved behavior compared with the damaged column. The Emaco-repaired column showed better behavior than the original healthy column with substantially higher ductility and energy dissipation capacity. The axial load capacities of the two columns were similar. The exp-repaired column, however, did not perform as well as the Emaco-repaired column. The main reason was the premature failure of GFRP wrap. As the load on the column increased, the plastic sheet of the formwork opened out and engaged the GFRP wrap creating large local strain and rupture of the wrap, and hence failure of the column. Figure 4 clearly shows the localized failure of GFRP wrap due to the opening of the formwork sheet in the Exp-repaired column.

Columns under Simulated Earthquake Loads

The specimens in this second research program were designed to evaluate the effects of FRP retrofitting on the performance of columns under simulated earthquake loads (4). Each of the twelve columns in one test series of this program was 356 mm in diameter, 1.47 m long and cast integrally with a stub of dimensions 510×760×810 mm. All columns contained six 25M longitudinal bars uniformly distributed around the core. Clear concrete cover was 20 mm. The spirals consisted of US # 3 bars. Figure 6 shows a specimen in the Column Test Frame especially designed to test columns under axial load and lateral displacement excursions.

Fig. 6. Column tested under simulated loads

The moment-curvature responses of the critical plastic hinge regions of three columns that were tested under lateral displacement excursions while simultaneously subjected to a constant axial load of about 27% of the axial load capacity are compared in Figure 7. While the details of the entire test program are beyond the scope of this paper, pertinent information on the column design are provided in the figure.

Column specimen S-2NT contained spiral reinforcement which met the requirements for seismic design of various design codes of the time (5,6). This specimen represents a healthy column. Specimen S-4NT contained spiral steel at 300 mm spacing representing a deficient column with respect to transverse reinforcement. The presence of the concrete cover in Column S-4NT would overestimate its strength compared to that of a column damaged by corrosion that has lost the concrete cover, but this would only be true at small deformations prior to the loss of cover under increasing lateral displacement excursions. Column ST-5NT contained spiral steel at 300 mm spacing and was retrofitted with one layer of GFRP wrap. This specimen thus represented a repaired column in which the corroded spiral steel was not replaced and it was built to its original shape followed by the installation of a GFRP wrap.

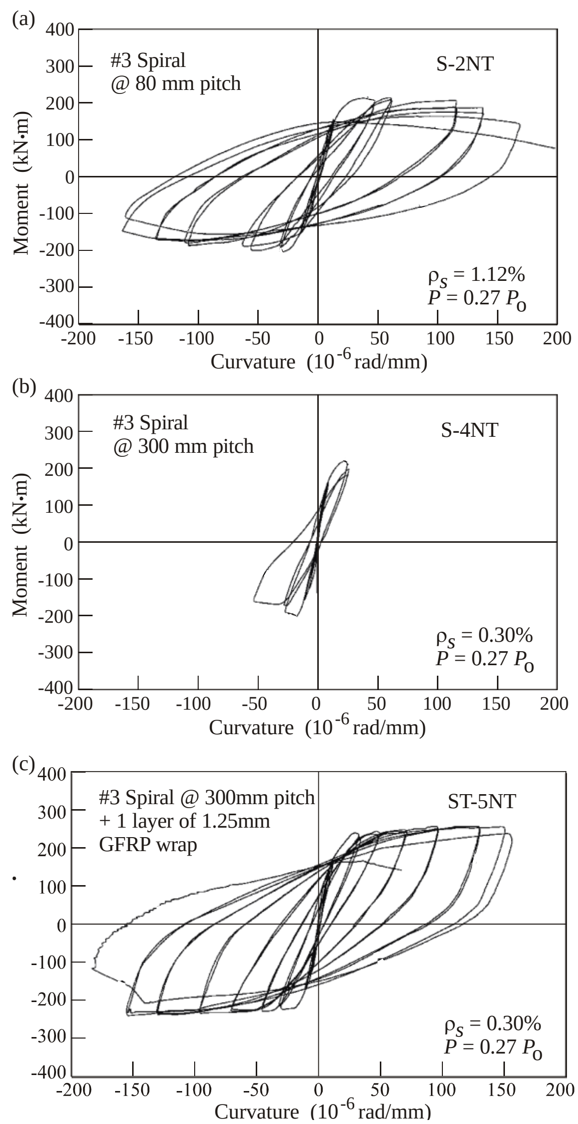

Fig. 7 Moment-curvature behavior of columns

A comparison of the moment-curvature responses of Specimens S-2NT and S-4NT underlines the importance of the spiral steel and its spacing on the seismic resistance of columns. Strength, ductility, energy dissipation capacity and the number of cycles of inelastic excursions that a column can sustain depend on the effectiveness of the spiral steel and the confinement it provides. The deficiency of the column caused by the reduced amount of spiral steel and its larger than required spacing could be easily overcome by the addition of only one layer of GFRP wrap as shown by the response of Specimen ST-5NT. Strength, ductility and energy dissipation capacity of the GFRP-retrofitted column ST-5NT are similar or superior to those of the control column S-4NT that met the code requirements.

FIELD WORK ON COLUMNS

The bridge structure shown in Figure 1 was repaired using the techniques developed during the research work briefly described above. Both columns and girders were repaired but only the column retrofit is discussed in the following.

Most of the columns were patched with Eamco grout followed by GFRP wraps but a few columns were built to their original shape with expansive cement grout or commercially available non-shrink grout. As discussed above, the corroded steel and the contaminated concrete were not removed from any of the columns. Only the loose concrete was removed with a steel brush.

Fig. 8. Formwork used for expansive cement grout

Emaco-based mortar is rheoplastic which did not require any formwork for the repair of columns. For expansive cement based grout and the non-shrink grout, steel formwork was used instead of the plastic sheet formwork that caused premature failure observed in the specimen tested in the lab. The grout was pumped in place to build the columns as shown in Figure 8.

Three of the field columns, one each repaired with Emaco, expansive cement and non-shrink grout were instrumented and monitored for their long-term performance. About twenty hours after grouting, the formwork for the column repaired with expansive cement was removed. After inspecting the repaired surface for any flaws, the column was first wrapped with a thin polyethylene sheet and then two layers of GFRP with glass fibers aligned in the circumferential direction to confine the column (Figure 9). Polyethylene sheet acted as a barrier between the new grout and glass FRP. Since the bond between GFRP and grout/concrete was not of any concern, the presence of the polyethylene sheet was not considered to have any effect on the column behavior under load.

Fig 9. GFRP wrapping of filed columns

Three days after the grout application, the column was instrumented with six strain gauges on the FRP in the circumferential direction, two each, 180^{o} apart, at mid-height, 750 mm above and 750 mm below the mid-point. The column repaired with non-shrink grout was treated the same way as the one repaired with expansive cement except that the formwork was removed four days after grouting. In the Emaco-repaired column, a protective epoxy coating was applied before the FRP wrapping and instrumentation.

Monitoring of field columns

In addition to measuring the lateral strain on the surface of the repaired columns, corrosion activity was also monitored with the help of three half cells (Silver/Silver Chloride) embedded in each of the three field columns discussed above. The cells were located at top, middle and bottom of the columns. The corrosion potential from these cells was measured in mV at regular intervals for more than 9 years. Figure 10 shows the lateral strain measured on three columns over a period of about two years. The strain values were observed to be as expected. Column 124-1 containing expansive cement showed substantial expansion while no significant lateral strain was measured in FRP in the other two columns, 124-2 and 124-3 that were repaired with non-shrink and Emaco grout, respectively. The maximum expansion of about 0.16% was observed in Column 124-1 at ten days after grouting which settled at about 0.14% at later age. Lateral GFRP strain in all columns remained fairly constant for about two years indicating stable expansive cement behavior and no significant creep of GFRP.

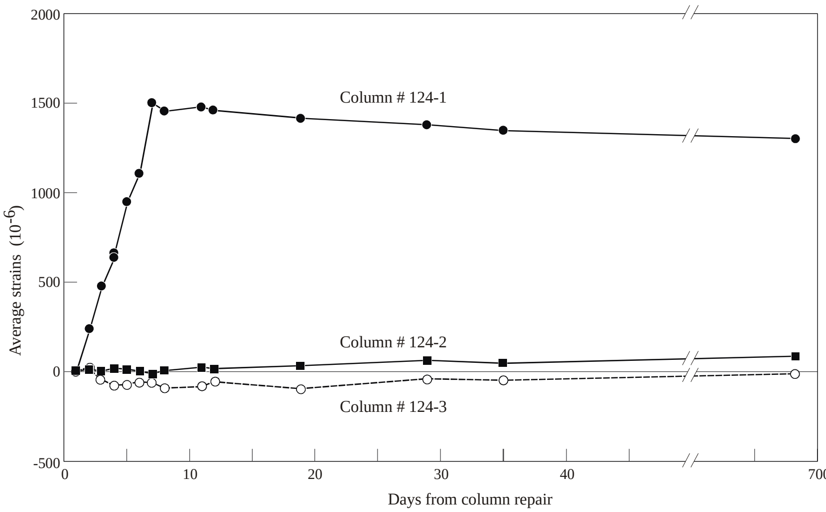

Fig. 10. Transverse GFRP strain in repaired colums

Corrosion activity recorded by half cells is shown in a graphical form in Figure 11 which displays the average corrosion potential in three columns at different locations along their height. The corrosion potentials can be used to provide some indication of the probability of corrosion activity in the columns at the time of the measurement (Broomfield 1997). The risk of corrosion thus determined is shown along Y-axis on the right side of the figure. Reduction in the corrosion activity and the reduced risk of corrosion over the years can be clearly seen in the figure. The average risk of corrosion in three columns at different locations along their height has reduced from high to low in about six years and remained low afterward. Monitoring of the corrosion activity was terminated at 100 months.

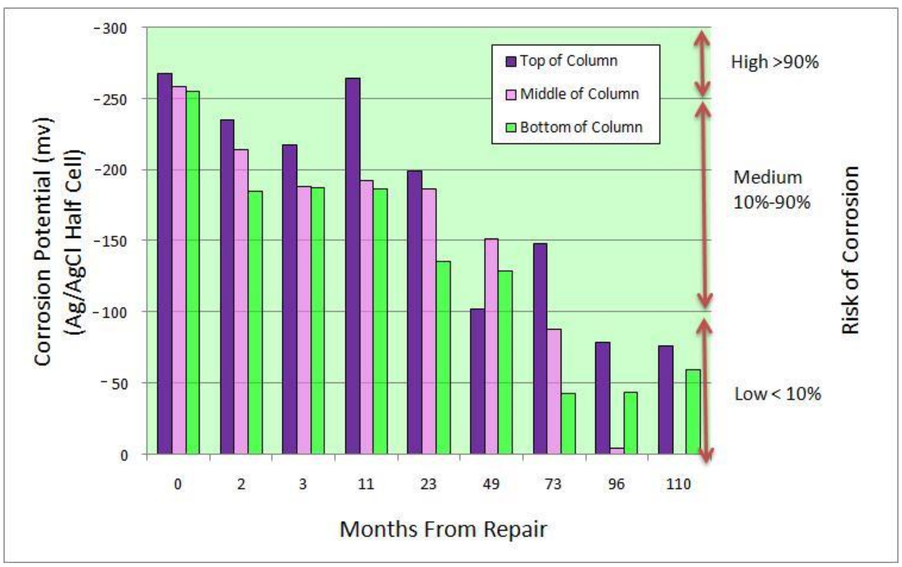

Fig. 11. Corrosion activity in repaired field columns

Figure 12 shows one of the columns before and just after the repair. The same column in its current condition is also shown in the figure. It is clear that after more than 22 years of service, the repair technique has stood the test of the time and performed flawlessly in an excellent manner. Traditional repair techniques have generally required a repeat of repair procedure every 8 years or so in similar cases.

a. Pre-repair *b. After repair in 1996* *c. Current condition*

Fig. 12. Sustainability of the repair techniques

CONCLUDING REMARKS

A large inventory of structures exists in North America and elsewhere where corrosion of steel has made these structures deficient. Efficient, cost effective, durable and quick repair techniques are needed to address this issue and repair the structures without causing undue strain on regular activities. In the research reported in this paper, a feasible solution has been described in which the corroded steel and contaminated concrete is left in place and the structure is retrofitted with special grouts and glass FRP wrap. The proposed techniques were investigated in the laboratory on half scale models of the bridge columns and then used in the field. Dozens of columns in a bridge on a major highway in Toronto were repaired of which three columns were monitored continuously for over 9 years. In the typical Toronto weather with temperatures ranging between -22^{o}C and +38^{o}C and a lot of snow during the winter, the performance of the repaired columns has been remarkably sound. Monitoring of the columns showed that the corrosion activity and the risk of corrosion have reduced consistently with time and changed from high to low in about 6 years. The repair techniques also impart excellent seismic resistance to the columns by providing confinement to the concrete.

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