LONG-TERM PERFORMANCE MONITORING OF GFRP-REPAIRED BRIDGE COLUMNS

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Abstract

Concrete structures in most parts of Canada are subjected to severe environmental conditions. This combined with the use of de-icing salt on roads and highways cause extensive degradation in transportation structures. Several columns in various bridges, damaged primarily by the corrosion of steel, were repaired with glass fibre reinforced polymers (GFRP) in and around Toronto in mid-nineties. One of these bridges is located along Highway 401 over Leslie Street. The lab study indicated that the axial load carrying capacity of the damaged columns was reduced by about 20% due to corrosion of steel and loss of concrete cover. Three types of grouts were used to build the columns to their original shape before wrapping them with GFRP. The grouts were based on regular cement, non-shrink cementitious material or expansive cement.

Performance monitoring for over 11 years has shown that the repaired columns have been providing excellent service without any problems. No deteriorating has been observed in the GFRP or the columns during this time. Monitoring of corrosion activity indicated that the rate of corrosion in GFRP-repaired columns and the associated risk of corrosion have reduced significantly over time. This paper provides a brief overview of the background research work, repair details of the bridge columns and results from the field monitoring.

INTRODUCTION

There is a large number of concrete structures around the world that have been damaged by extreme environmental conditions, overloading or simply as a result of normal aging. These structures are unsafe to use and urgently need repair for continued use. Corrosion of steel in reinforced concrete structures as a result of chloride ion ingress is one of the main reasons for concrete deterioration in areas where de-icing salt is used on the roads. In addition, design inadequacies, unsound construction practices and a lack of quality control combined with inadequate maintenance practices have been responsible for most of structural damage.

Since 1994, authors have been involved in the repair and strengthening of several concrete structures with surface-bonded fibre reinforced polymer (FRP) sheets (1). A number of these structures have been monitored for their performance. These FRP applications cover a large spectrum of structures including a concrete platform in an oil refinery, bridge columns and culverts along major highways, high-rise apartment and condominium buildings and heavy industrial structures. The repaired components include slabs, beams, walls and columns.

This paper concentrates on a study involving a bridge with its columns damaged primarily by chlorides from de-icing salt. The bridge is on Highway 401 in Toronto, which was built in the sixties. The highway has 7 westbound and 6 eastbound lanes at this location. The columns are about 920 mm to 1010 mm in diameter. Figure 1 shows a bridge bent before repair in 1995.

Figure 1: Damaged highway bridge

The damage was mostly concentrated at the bents that are directly below the expansion joints. The joint sealant had deteriorated with time, allowing the de-icing salt solution to soak the reinforced concrete bents. Accumulation of this solution at the bent top and its continuous flow downward along the columns resulted in deterioration of concrete as well as corrosion of steel. The columns were also exposed to salt attacks from the cars using the area under the bridge as a parking lot. The structure is also subjected to usual Toronto environmental effects that include freeze thaw cycles, wet dry cycles, temperature variations, etc. The spiral steel in the columns and tie steel in the beams severely corroded as a result of this exposure. The expansive forces thus generated caused the cover concrete in both columns and girders to be severely delaminated.

Before repairing the columns in the field, an extensive laboratory-based research project was undertaken to investigate the feasibility of using GFRP for repair. Three types of grouts were used to rebuild the columns to their original shape. These consisted of two commercially available grouts and one based on specially developed expansive cement. Brief details of the two non-traditional materials used, namely expansive cement and glass fibre reinforced polymers (GFRP), are given below.

Expansive Cement

Timusk and Sheikh (2) developed a type of expansive cement with large expansion potential. The cement had rapid set properties making it unfeasible in large volume applications. Further studies resulted in a new cement formulation that overcame this deficiency (3). The new expansive cement was a mixture of normal Portland cement and an expansive component consisting of hydrated high alumina cement, hemi-hydrated gypsum and hydrated lime

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Glass Fibre Reinforced Polymers (GFRP)

GFRP wrap was used to retrofit columns in the lab and in the field. The glass fabric was nominally 1.25 mm thick with glass fibres oriented in one direction and aramid fibres in the perpendicular direction. The aramid fibres were sparsely spaced and had minimal contribution to the strength of the fabric. They were primarily used to keep the glass fibres together and aligned in a fabric form.

Test coupons for GFRP were made by impregnating the fabric with a two-part epoxy. The average tensile strength of one layer of GFRP measured from the coupon tests was found to be about 563 N/mm and the average rupture strain was about 2.3 %. The tensile strength values ranged between 540 and 586 N/mm for eight coupons. Since the thickness of the hand prepared FRP specimens can vary significantly, the tensile strength is represented in force per unit width (N/mm).

GFRP Application

After the damaged columns were rebuilt to their original shape, the hardened concrete surface was thoroughly cleaned prior to GFRP application. The column surface was then coated with epoxy and the glass fabric, cut to the required size, was also saturated with epoxy. The impregnated fabric was then tightly wrapped around the column with the main fibres aligned in the hoop direction. Attempts were made to ensure that there were no voids or air pockets between the FRP and the column surface. A minimum overlap of 100 mm was provided to develop adequate bond between FRP layers (4).

PREPARATORY EXPERIMENTAL WORK

Before the repair work was carried out in the field, an extensive laboratory-based research program was undertaken at the University of Toronto to evaluate the feasibility of using FRP for repair and the expected performance of FRP-repaired columns. Half-scale specimens of bridge columns were constructed and tested under either axial load only or under combined axial and cyclic flexural and shear loads (5,6). A brief overview of the experimental work on axially loaded columns that were subjected to corrosion environment is presented below.

Columns under axial load

In this test series, ten half-scale models (406 mm diameter x 1.37 m long) of the field columns were constructed (5). Five of these columns were intended for short-term test program and the other five for a long-term investigation. Each column was reinforced with 6-20M longitudinal reinforcing bars and a 10M spiral with 75 mm pitch. Eight of these specimens were subjected to accelerated corrosion at the age of 34 days to produce damage similar to that observed in the field. Six columns damaged by corrosion were repaired using different retrofitting procedures. Two un-repaired corroded columns were used as control specimens along with two un-corroded columns. The repair work was carried out with the aim of minimizing the costly fieldwork. It was decided that the corroded steel and the contaminated concrete would not be removed from the damaged columns.

One column (Emaco-repaired) was patched with commercially available rheoplastic, shrinkage-compensated mortar called EMACO. This cement-based mixture contained propylene fibres and silica fume. The patch was covered with a protective epoxy coating to avoid direct contact between the new cementitious material and GFRP. On the basis of simulated lab studies in which fibres alone were immersed in sodium hydroxide solution, researchers (7) had reported that alkalis had adverse effects on strength of glass fibres. After 24 hours of curing, the column was wrapped with two layers of GFRP.

Another column was repaired with grout based on the expansive cement discussed in the previous section (exp-repaired). 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 hose clamps so as to act as formwork for the column repair. Next, the expansive cement mortar was 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 which acted as a barrier between fresh grout and the GFRP wrap. The columns were stored in the lab at 23°C temperature and about 50% relative humidity for three months before they were tested for their short-term mechanical behaviour. The results from the short-term tests on four columns are presented here in Fig. 2.

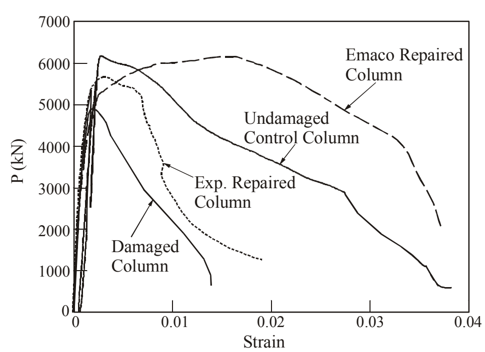

Figure 2: Behaviour of columns under axial load

It can be seen from Fig. 2 that the damaged column had about 20% lower strength and substantially lower ductility and energy dissipating capacity than the undamaged control column. The corrosion rendered the spiral steel completely ineffective in the damaged columns. Pitting corrosion of spiral reduced its effectiveness for confinement and caused its rupture at relatively small column strain.

Behaviour of repaired specimens was significantly better than that of the damaged unrepaired specimen. The axial load carrying capacity of the Emaco-repaired specimen was as large as that of the control undamaged column and its ductility and energy dissipation capacity were substantially better. The Exp-repaired column did not display as good a performance as the Emaco-repaired column. This is due to the fact that at large strains the plastic sheet of the formwork used in the Exp-repaired column opened out and engaged the fibre wrap at both ends, causing large local strain and premature failure of the wrap and the column.

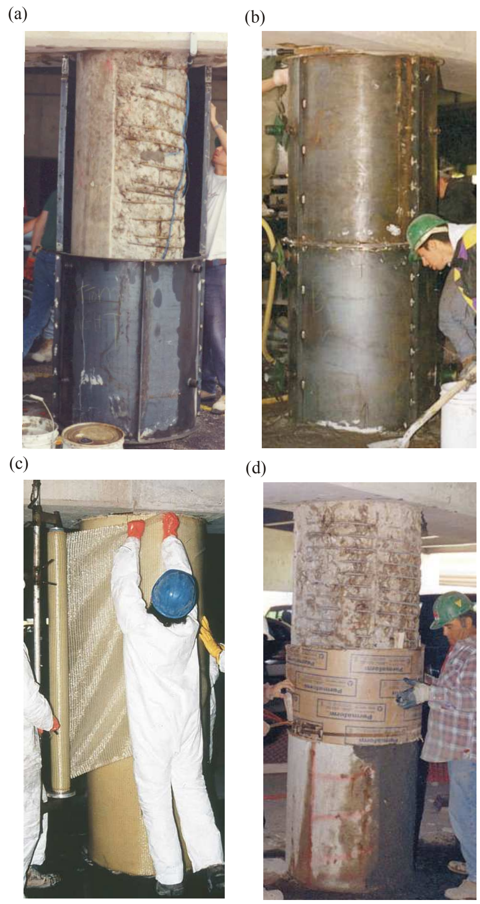

Figure 3: Various steps in column repair

FIELD REPAIR

Repair of field columns (Fig. 1) followed the same procedure that was used for the lab tests described above. Concrete cover had spalled off completely and spiral steel had corroded extensively in all the columns. No attempt was made to remove the corroded steel or the contaminated concrete from any of the columns. Only the loose concrete that could be removed without much effort was brushed off. The plastic sheet formwork was not used in the field considering the premature failure observed in the lab specimen. Instead, steel forms were used, if needed, to pump the grout in place to build the columns and removed before the columns were wrapped with GFRP.

Repair Schemes

Four of the columns in the bridge were repaired using three different repair schemes and were monitored for their long-term performance.

Column 1 was repaired with expansive concrete grout using steel formwork (Figs. 3a and 3b). The thickness of the expansive concrete cover around the column was about 50 mm. 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 (Fig. 3c). The polyethylene sheet was used as a barrier between the new concrete and the GFRP and 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 mid point.

Columns 2 and 11 were built to their original shapes 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, Column 2 was instrumented with strain gauges in a manner similar to Column 1.

Column 3 was repaired with EMACO-based rheoplastic mortar which did not require and formwork (Fig 3d). 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.

In order to monitor steel corrosion activity in the repaired columns three half-cells (Silver/Silver Chloride) were embedded in each of the four columns. The cells were located at the top, middle and bottom of the columns. The corrosion potential from these cells has been measured at regular intervals since the repair in 1996.

Field Data

Figure 4 shows variation of lateral strain with time from the field columns. As expected, Column 1 showed substantial expansion while no significant lateral strain was measured in FRP in Columns 2 and 3. The maximum expansion in Column 1, approximately 0.16%, was observed ten days after grouting and represents about 10% of GFRP rupture strain. Lateral GFRP strain in the three columns remained fairly constant for about two years indicating stable expansive cement behaviour and no significant creep of GFRP. Recording of strain data was terminated about two years after the repair.

Table 1 displays the half-cell potential measurements of four repaired columns taken over a period of six years. The potentials can be used along with the information given in Table 2 (8) to provide an indication of the probability of corrosion activity in the columns at the time of measurement. If the potential reading in any location is less (more negative) than –256mV, there is a greater than 90% probability that reinforcing steel corrosion is occurring in that area; if it is in the range of –106 to –256mV, the risk of corrosion is intermediate, but the probability is unknown; and if it is larger than (less negative) than –106 mV, there is a greater than 90% probability that no reinforcing steel corrosion is occurring. Soon after the repair in 1996, based on the average of potential measurements at three locations along the height of each column, the risk of corrosion in repaired columns 1 and 2 was high, and in columns 3 and 11 it was intermediate. In 2005, the risk of corrosion in column 1 was intermediate and in column 2, 3 and 11 it was low. Reduction in the corrosion activity and risk of corrosion can be clearly seen in Table 1 which shows the average corrosion potential in three columns at different locations along their height. The only anomaly is the reading at

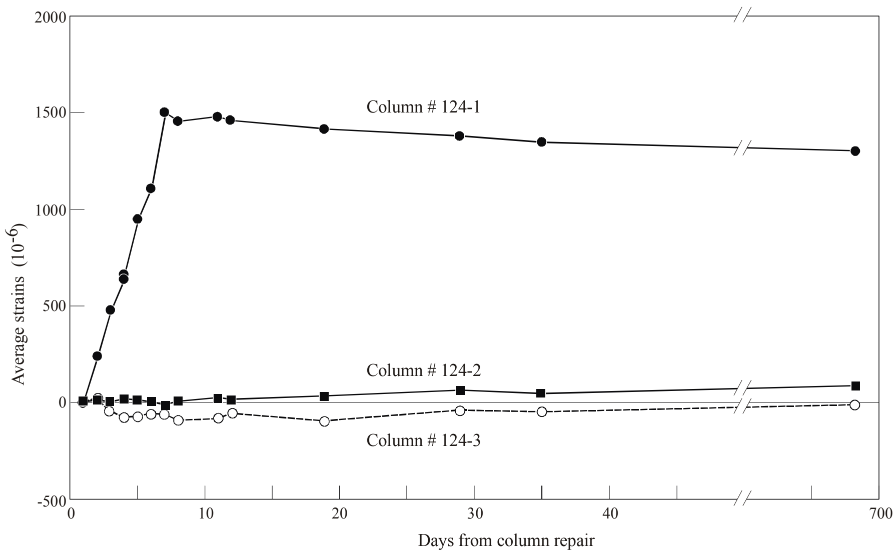

Figure 4: Lateral strain in GFRP in repaired columns

11 months at the top of the Columns 1, 2 and 3, which may have been caused by local effects such as wetness at that location. The data from each instrumented column over the last six years show that GFRP wraps have protected the columns from adverse environmental effects thus reducing the flow into the columns of essential ingredients that drive the corrosion process resulting in reduced corrosion activity.

Table 1. Results of condition survey of Leslie Street Bridge (from Ministry of Transportation Ontario)

Date	Temp (°C)	Rel. Hum. (%)	Corrosion Potential (Embedded Cells, Silver/Silver Chloride)								
			Column 1			Column 2			Column 3		
			Top (mV)	Mid. (mV)	Bot. (mV)	Top (mV)	Mid. (mV)	Bot. (mV)	Top (mV)	Mid. (mV)	Bot. (mV)
19-07-96	23	79	-322	-274	-219	-259	-291	-292	-223	-211	-
18-09-96	20	NA	-280	-234	-187	-230	-231	-	-196	-178	-183
30-10-96	16	70	-266	-212	-176	-219	-209	-238	-169	-145	-149
19-06-97	20	60	-336	-240	-204	-243	-217	-237	-214	-120	-118
18-06-98	28	43	-335	-200	-182	-123	-257	-128	-140	-104	-98
11-08-00	24	46	-172	-195	-152	-72	-336	-146	-62	75	-90
14-08-02	26	44	-234	-174	67	-41	-173	-120	-170	82	-76
15-07-04	21	65	-197	-133	-69	-8	47	0	-31	73	-62
07-09-05	23	40	-176	-84	-70	-14	17	-58	-39	84	-50

Table 2. Ag/AgCl potential for determination of probability of corrosion [8]

Measured Potential	Risk of Corrosion
< -256 mV	High (> 90%)
-106 mV to -256 mV	Intermediate (10% to 90%)
> -106 mV	Low (< 10%)

Field data on strain and corrosion rate and physical inspection over eleven years indicated a sound performance of the retrofit techniques used for the columns. Figure 5 shows Column1 before repair, soon after repair and in 2006. No deterioration was observed in any of the columns and risk of future corrosion has also reduced. There has also been no need to repeat the repair process in any of the columns repaired more than eleven years ago. In this first GFRP repair exercise, a thin polyethylene sheet was used in some columns as a barrier to separate new mortar or concrete from the GFRP to avoid any possible adverse effects of alkalis on the performance of GFRP in the long term. Since then, extensive testing has shown excellent long-term performance of GFRP sheets under alkaline environment (4, 9-11). Future repairs using GFRP can thus be carried out without the use of barriers. Although the presence of the barrier is not necessary for isolating glass from alkali, the barrier might have contributed toward the reduced corrosion activity in the columns.

Before repair　　After repair 1996　　2006

Figure 5. Columns before and after repair

CONCLUDING REMARKS

In the first field repair operation of a bridge along a major highway in Ontario using GFRP wraps, several columns damaged by steel corrosion were repaired about eleven years ago. The repair techniques were developed in a laboratory test program which indicated 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. Four columns repaired in the field were instrumented with corrosion monitoring half cells and three columns were fitted with strain gauges to measure lateral strains in the columns.

While all the repaired columns were visually monitored for soundness, data from the four instrumented columns was recorded regularly over the years. Although the corroded steel and the contaminated concrete were not removed from the structure, field measurements indicated that the corrosion activity and risk of corrosion have reduced with time in the repaired columns. Lateral columns strain data indicate no impending deterioration. Based on the laboratory studies and field monitoring, it is concluded that the repaired field columns have load-carrying capacities of at least equal to that of the original undamaged columns and significantly higher ductility and energy dissipation capacity. The FRP-repaired columns have been in service for more than eleven years and have displayed excellent performance without requiring any additional repair work. This study shows that monitoring of a representative number of field elements can provide an economical, valuable and often an essential source of information for evaluating the health of a structure.

ACKNOWLEDGEMENT

The research reported here was supported by grants from the Natural Sciences and Engineering Research Council of Canada (NSERC), Ministry of Transportation of Ontario and ISIS Canada, an NSERC Network of Centres of Excellence. The author would like to express his appreciation to Hena Schell, Dr. B. Tharmabala, and F. Pianca of the Ministry of Transportation of Ontario (MTO) and Dr. B. Bakht and A. Agarwal formerly of MTO for their help during the repair and monitoring of columns in the field. The experimental work was carried out in the Structures Laboratories of the University of Toronto.

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