Structural Performance Monitoring of GFRP Reinforced Concrete Flat Slab Parking Garages

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ABSTRACT: Parking garages are among the reinforced concrete (RC) structures that suffer from corrosion and deteriorations due to the harsh exposure to chemicals and de-icing salts. In Quebec City, Canada, La Chancelière parking garage, which is 40 years old, showed a severe deterioration resulted from the corrosion of steel reinforcement. These deteriorated conditions led to the need of costly rehabilitation of the parking garage. Since the structural system of the parking was flat slab and the corrosion of steel reinforcement was very severe in almost all the slabs, it was decided to replace the entire flat slabs of the parking with new ones while maintaining the main supporting elements (columns and retaining walls). The design of the parking garage was conducted using glass fibre-reinforced polymer (GFRP) reinforcing bars as main reinforcement for the flat slabs of level one which was the first word-wide application of its type. The slabs were instrumented at the critical locations for strain measurements using fibre optic sensors (FOS) attached to the surface of the GFRP bars or embedded in concrete. This study provides the design, construction, and instrumentation details and evaluates the structural performance of GFRP-reinforced concrete flat slabs of the parking garage under real service loading and environmental conditions.

1 INTRODUCTION

The corrosion of steel reinforcement has become a serious concern in Canada and all over the world. The extensive use of de-icing salt during the winter has created a harsh environment accelerating the corrosion of the steel reinforcement in structures like bridges and parking garages. The corrosion and related deterioration necessitate costly repairs and reduce the service life of concrete structures. In flat slab systems, the slabs serve as structural elements transferring the dead and live loads to the supporting columns which induce flexural and punching-shear stresses. Thus, the corrosion of steel reinforcement and its devastating effects may lead to catastrophic failures of such structures.

Solutions have been proposed to reduce the potential of corrosion and related degradation of parking structures, such as using galvanized steel bars and epoxy-coated steel bars. The former faces some use restrictions in certain countries and the latter is no longer allowed for parking structures under CSA S413-07 (2007) due to the debate on the material's durability. On the other hand, replacing corrodible steel reinforcement with noncorroding fibre-reinforced polymer (FRP) bars provides a suitable solution for eliminating the potential of corrosion and the related deteriorations.

At the University of Sherbrooke (Sherbrooke, Quebec, Canada), an extensive research project is being conducted to evaluate the performance of GFRP-reinforced concrete flat slabs and introduce this technology to parking garages. Through this project, a total of 30 full-scale slab-column connections were designed, constructed, and tested (Dulude et al. 2010; 2011a & Hassan et al. 2011) as shown in Figure 1. The project included the following parameters: (a) slab thickness (200 and 350 mm); (b) reinforcement type and ratio (steel and GFRP with a wide range of reinforcement ratios); (c) concrete strength; and (d) column dimensions (300 mm or 450 mm square columns). The specimens were tested up to the punching-shear failure under monotonic increasing load. The test results of this projected provided a clear overview of the structural behavior of such elements. Besides, the test results were also used to calibrate the new punching-shear equation of the Canadian Standards for the design and construction of buildings reinforced with FRP bars (CSA S806, 2012).

Figure 1. Testing of flat slab specimens at the University of Sherbrooke.

After that, the first field implementation for GFRP bars in two-way flat slab parking structure was achieved through a demonstration area (350 m^2) in Hôtel de Ville parking garage in Quebec City, Canada (Dulude et al. 2011b). This pilot project confirmed the feasibility of using GFRP bars in such applications which has been in service since 2010. The behavior of this GFRP-reinforced section was similar to that of the steel-reinforced counterparts in the parking.

In 2011, based on the valuable experience gained from the structural testing and the pilot implementation of GFRP bars in Hôtel de Ville parking garage in Quebec City, it was decided to use the high modulus GFRP reinforcing bars (Grade III – CSA S807, 2010) as main reinforcement for the flat slabs of level one of La Chancelière parking garage (the first application of this approach in the world). This paper presents the design and construction details and evaluates the in-service performance of GFRP-reinforced concrete flat slabs of the parking garage based on monitoring results.

2 DESCRIPTION OF THE PARKING GARAGE

La Chancelière parking garage, which is located in Quebec City, Canada is a 40 years old reinforced concrete structures. The structural system of this parking is a two-way flat slab supported on columns and retaining walls. La Chancelière parking garage showed a severe deterioration resulted from the corrosion of steel reinforcement and the consequent spalling of the concrete cover (as shown in Figure 2) which led to faster degradation and reduction in the cross-sectional area of the steel reinforcement. These deteriorated conditions led to the need of costly rehabilitation of the parking garage. As the structural system of the parking was flat slab and the corrosion of steel reinforcement was very severe in almost all the slabs, it was decided to replace the entire slabs of the parking with new ones while maintaining the main supporting elements (columns and retaining walls) and repairing them when needed. Figure 3 shows the layout of La Chancelière parking.

Figure 2. Corrosion of steel reinforcement of in parking garage.

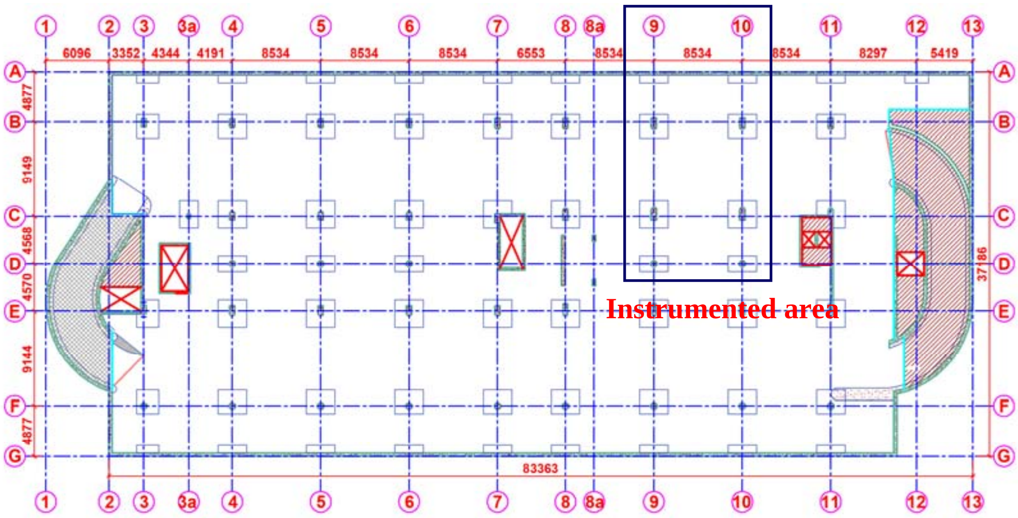


Figure 3. Layout of La Chancelière parking garage.

3 DESIGN AND CONSTRUCTION

The demolition and re-construction of the flat slabs was conducted in three phases. Phase 1 included the area between Axis 1 and 5. Phase 2 included the adjacent section until Axis 8a while the remaining area was constructed as the last stage (Phase 3). During the demolition, the slabs were totally removed and a steel bracing system was provided to protect the columns and the retaining wall against excessive buckling.

The design was made according to the CSA S413 (2007) for parking structures and CSA S806 (2012) for design and construction of building components with fibre reinforced polymers. The two-way flat slabs of La Chancelière had maximum span of about 9.0 m. The loads were calculated according to the National Building Code of Canada (NBCC 2005) where the dead load was 6.15 kPa and the live load was 2.4 kPa. The bending moments were calculated based on column and field strips in both directions. In the column strips, the maximum factored positive bending moment was 180 kN.m while the maximum factored negative bending moment was 624 kN.m. In the field strips, however, the maximum factored positive bending moment was 60 kN.m while the maximum factored negative bending moment was 155 kN.m. The flat slabs were reinforced with GFRP bars of 22 mm diameter. The GFRP bars of Grade III (CSA S807, 2010) had a guaranteed tensile strength of 1100 MPa and a tensile modulus of elasticity of 65.5 GPa. The slabs were designed as over reinforced sections as specified by the CSA S806 (2012) while the concrete cover was maintained as 60 mm as fire-endurance design requirement. The design was made using normal-weight concrete having a target 28-day compressive strength of 35 MPa. The serviceability requirement, deflection and cracking, were considered in the design and the deflection at service load level was less than *l*/360 and the crack control parameter, *z*, was less than 38,000 N/mm. The concrete was cast on August 10, 2011. Figure 4 shows the reinforcement configuration and concrete casting.

The thickness of the slabs was 250 mm which increased to 355 mm over the columns through drop panels. The increased thickness over the columns was devoted to satisfy the punching stresses around the columns' area. The punching strength of the flat slabs was verified using the new punching-shear equations incorporated in the new version of the S806 Standard (CSA S806, 2012). More details about the design and construction of the parking garage can be found elsewhere (Benmokrane et al., 2012).

It should be mentioned that continuity of the flat slab at the locations of the existing supporting elements (columns and retaining walls) was achieved through the anchorage of the GFRP bars in drilled holes using rotary pits and cement adhesive.

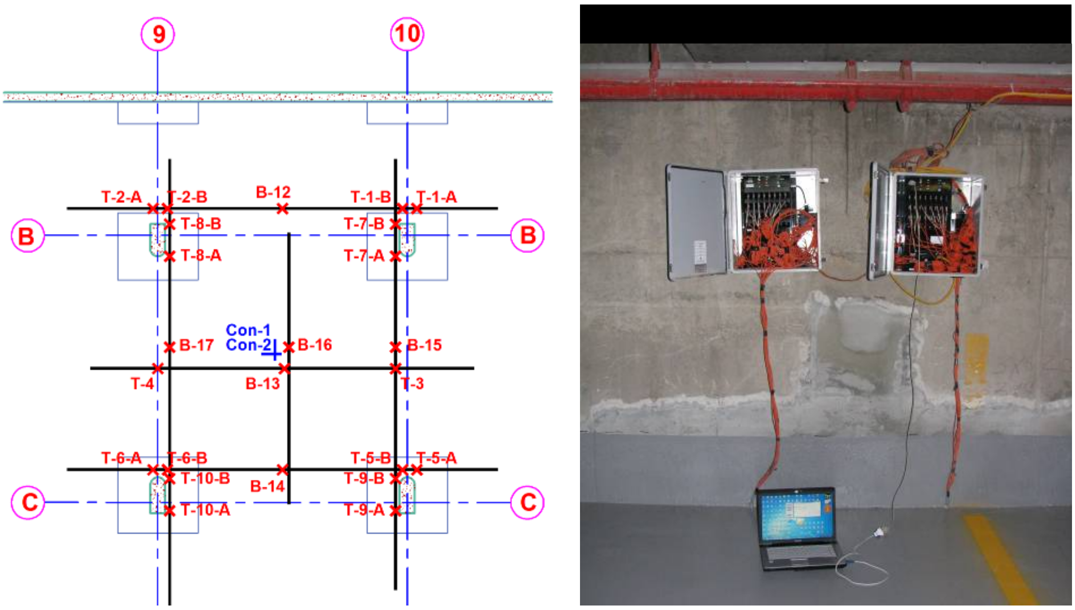
(a) Reinforcement configuration (b) Concrete casting

Figure 4. Reinforcement configuration and concrete casting.

4 INSTRUMENTATION WITH FIBRE OPTIC SENSORS (FOS)

To monitor the behavior and evaluate the performance of the GFRP-reinforced flat slabs of the parking, a representative area of the parking, shown in Figure 3, was selected. The GFRP reinforcing bars as well as the concrete section of the slab were instrumented at critical locations for strain data collection using fibre optic sensors (FOS). The GFRP bars were instrumented thereafter were transported to the construction site. Figure 5 shows the instrumentation of the GFRP bars. A total of 26 FOS were glued on bottom and top reinforcing bars in the two orthogonal directions at the location of the maximum expected stresses (maximum bending moments). In addition, two FOS were glued on two dummy bars embedded in the flat slab inside a PVC tube so that the temperature variation effect on the strain readings could be captured. The compressive concrete strain at the mid-span was also captured using two FOS embedded in the concrete. Figure 6 shows the locations and identifications of the different sensors as well as the readout units.

Figure 5. Instrumentation of GFRP bars.



(a) Identifications of the different sensors (b) Readout units (data loggers)

Figure 6. Locations of the FOS and the data loggers.

The FOS utilized in the parking were controlled by two 16-channel data acquisition systems (Figure 6b) (data loggers) for long-term monitoring and structural performance evaluation. For the moment, there is no phone lines connected to the data loggers. However, arrangement for permanent location and phone line connection is being considered to facilitate acquiring the monitoring data. The FOS and the data loggers will allow for the long-term monitoring and performance evaluation of the flat slabs reinforced with glass FRP bars under real service loading and environmental conditions.

5 MONITORING RESULTS

Figure 7 shows the strain measurements from the FOS attached to the GFRP bars and embedded in concrete. The initial readings for the strains were recorded on August 9, 2011 at 8:00 pm (few hours before casting). Thus the reported strain values included the shrinkage of concrete. Besides, the high temperature due to the cement hydration at early age of concrete can be captured. The sudden variation in the strains due to the dead load after removing the formwork can be also seen in the strains of the bottom and top GFRP bars and the concrete strains as well.

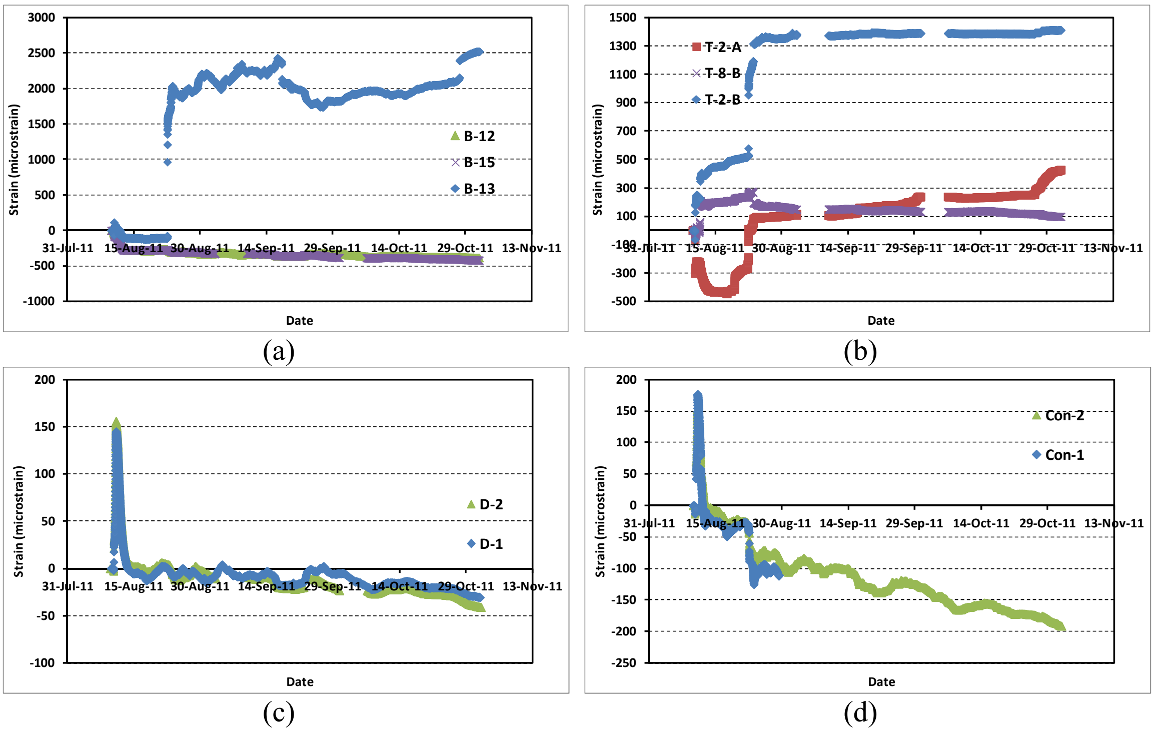


Figure 7. Strain measurements using FOS: (a) Bottom bars; (b) Top bars; (c) Dummy bars; (d) Concrete.

From Figures 7a it could be noticed that sharp increase in the strain of the bottom GFRP bars when the formwork was released is about 2000 με. After that, the strain increased to about 2500 με when the parking opened to public. The 2500 με represent about 15% of the strain capacity of the used GFRP bars. Similar behavior was observed for the top reinforcing bars but the maximum strain was about 1400 με which represents 8% of the strain capacity of the GFRP bars. On the other hand, Figure 7c indicates that the two dummy bars showed a strain increase of about 150 με due to the hydration temperature after casting. After that, there was no significant difference in their strain readings due to the fact that there was no significant variation in the temperature inside the parking in summer months. The top GFRP bars showed also almost the same strain increase due to hydration temperature as indicated in Figure 7b.

The concrete strain presented in Figure 7d shows the early age strain variation resulted from the hydration and shrinkage. A sudden increase of about –125 με was recorded due to the dead load when the formwork was removed. The maximum recorded concrete strain was about –200 με.

6 VERIFICATION OF FOS STRAIN MEASUREMENTS

The used FOS sensors were of +/– 2500 με measuring range. Since the readings resulted from the bottom GFRP bars (Figure 7a) were close to 2500 με, the FOS was calibrated to verify its ability capture any further strain increase or not. To achieve that, an FOS was glued to a GFRP bar (from the same production lot used in the parking garage) and was tested in tension on a universal loading BALDWIN machine to determine the stress-strain relationship and measure the maximum strain that FOS sensor can capture. Figure 8 shows the relationship between the stress in the GFRP bar and the corresponding strain measured from the FOS sensor. The figure indicates that the FOS is capable of achieving a reasonably high strain level (up to about 3700 με) without any problems.

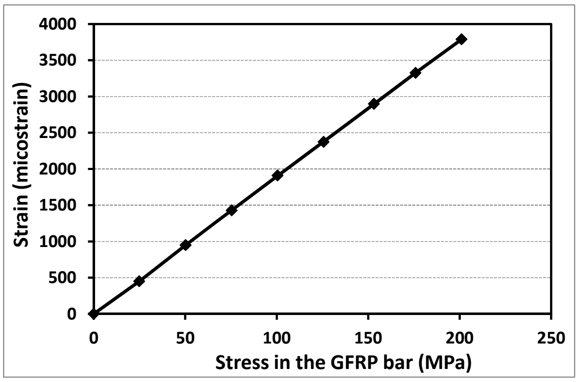


Figure 8. Strain-strain relationship of the GFRP bars from FOS strain measurements.

7 CONCLUSIONS

This paper presented the first world-wide application for GFRP bars in flat slab parking structure (La Chancelière). The flat slabs of the parking were totally demolished and reconstructed using high modulus GFRP bars (Grade III) while maintaining the main supporting elements (columns and retaining walls). The slabs were instrumented at the critical locations for strain measurements using fibre optic sensors (FOS) attached to the surface of the GFRP bars or embedded in concrete. Based on the results and discussion presented herein the following concluding remarks can be drawn:

- This successful application shows the effective usage of the GFRP reinforcing bars in two-way flat slab parking structures for the first time in the world. This shows a great advancement to the FRP technology.
- The structural performance of this first world wide application of its type and scale, based on the monitoring and continuous observations, is as expected. No major problems or any un-expected performance-associated troubles appeared during the construction or after being in service for months. The maximum measured strains in the GFRP bars did not exceed 15% of the strain capacity of the GFRP bars employed in the project.
- The long-term monitoring of the parking will enable understating the structural behavior and the performance in real environmental and service conditions.

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