DESIGN, CONSTRUCTION, AND MONITORING OF THE FIRST WORLDWIDE TWO-WAY FLAT SLAB PARKING GARAGE REINFORCED WITH GFRP BARS

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Abstract
Severe corrosion of steel reinforcement in a 40-year old Quebec City parking garage necessitated a major rehabilitation of the structure. This included the use of glass fiber-reinforced polymer (GFRP) bars as main reinforcement for the flat slabs of level one which represents the first application of this approach in the world. 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 paper presents a summary of the design criteria for the slabs reinforced with GFRP bars, the construction details and the monitoring system for internal temperature and strain data.

Keywords: Concrete; Flat-slab; Two-way; Glass fiber-reinforced polymer (GFRP); Parking; Monitoring; Fiber optic sensors (FOS).

1. Introduction
The corrosion of steel reinforcement has become a serious concern in Canada and all over the world. The extensive use of deicing 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, reduce the service life of concrete structures, and may lead to catastrophic failures. On the one hand, 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 413-07 [1] due to the debate on the material’s durability. On the other hand, replacing corroding steel reinforcement with noncorroding FRP bars provides a suitable solution for eliminating the potential of corrosion and its related deteriorations.

Few studies were conducted to evaluate the performance of two-way flat slabs reinforced with GFRP bars [2-7]. These studies have demonstrated that the difference in mechanical properties between FRP and steel reinforcement—especially the relatively high tensile
strength and the relatively low modulus of elasticity—affect punching-shear behaviour and strength. Besides, given the difference in mechanical properties, the punching-shear equations for steel-reinforced concrete flat slabs cannot be directly employed for FRP-reinforced concrete ones. In addition, until 2010, there was no field application for such structural system using GFRP bars.

To understand the behaviour of GFRP-reinforced flat-slabs and provide a step forward from lab testing to field applications, a total of 20 full-scale two-way flat-slab prototypes were designed, constructed, and tested at the Department of Civil Engineering, University of Sherbrooke, Sherbrooke, Quebec, Canada [8-10]. This investigation considered 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 flat-slabs prototypes 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 behaviour of such structural elements. Besides, the test results were also used to calibrate the new punching shear equation that is being incorporated in the Canadian Standards for the design and construction of buildings reinforced with FRP bars (CAN/CSA S806 [11]). After that, the first field implementation for GFRP bars in two-way flat slab parking structure was achieved through a demonstration area (350 m²) in Hôtel de Ville parking garage in Quebec City, Canada [12]. This pilot project confirmed the feasibility of using GFRP bars in such applications which has been in service since 2010. The behaviour of this GFRP-reinforced section was similar to that of the steel-reinforced counterparts in the parking.

In 2011, based on the gained experience from the structural testing at the University of Sherbrook and the pilot implementation of GFRP bars Hôtel de Ville parking garage in Quebec City, it was decided to include the noncorroding GFRP reinforcing bars as main reinforcement in whole slabs of La Chancelière parking garage which was the first word-wide application of its type. This was expected to provide a maintenance-free structure with extended service life. This paper presents the design and construction details and evaluates the structural performance of GFRP-reinforced concrete flat slabs of the parking garage under real service loading and environmental conditions.

2. Research Project

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. Recently, La Chancelière parking garage showed a severe deterioration directly resulted from the corrosion of steel reinforcement and the consequent spalling of the concrete cover 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 two-way flat slabs and the corrosion of steel reinforcement was very severe in almost all the slabs, it was decided to replace all the flat slabs of the parking with new ones while maintaining the main supporting elements (columns and retaining walls) and repairing them when needed. Figure 1 shows the layout of La Chancelière parking.
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. Figure 2 shows the parking during the demolition and reconstruction phases.

This design was made according to the CAN/CSA-S413-07 [1] for parking structures and CAN/CSA-S806-02 [13] 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 thickness of the slabs was 250 mm which increased to 355 mm over the columns through the drop panels. The increased thickness over the columns was devoted to satisfy the punching stresses around the columns’ area. The punching strength of the two way slabs were verified using the new punching equations that are being incorporated in the new version of the S806 Standards [11]. The punching strength is verified using the least of the following equations:
\[ V_c = 0.028\lambda \phi_c \left(1 + \frac{2}{\beta_c}\right) \left(E_f \rho_f f'_c\right)^{1/3} b_{o,0.5d} d \] (1)

\[ V_c = 0.147\lambda \phi_c \left(\frac{\alpha_f d}{b_{o,0.5d}} + 0.19\right) \left(E_f \rho_f f'_c\right)^{1/3} b_{o,0.5d} d \] (2)

\[ V_c = 0.056\lambda \phi_c \left(E_f \rho_f f'_c\right)^{1/3} b_{o,0.5d} d \] (3)

where \( V_c \) is the punching shear capacity (N); \( E_f \) is the modulus of elasticity of the FRP reinforcement (MPa); \( d \) is the effective slab depth; \( \rho_f \) is the FRP reinforcement ratio; \( f'_c \) is the compressive strength of the concrete (MPa); \( b_{o,0.5d} \) is the critical perimeter at a distance of 0.5\( d \) from the column face (mm); \( \alpha_c = 4,3,2 \) for interior, edge, and corner column, respectively; \( \lambda \) is a factor to account for density of concrete (\( \lambda = 1 \) for normal-density concrete).

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 (CAN/CSA-S807-10) had an ultimate 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 CAN/CSA-S806-02 [13] 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 3 shows the Reinforcement configuration and concrete casting.

![Figure 3. Reinforcement configuration and concrete casting.](image)

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. In addition, after casting and removing the formwork, steel brackets were attached to the columns and the retaining walls serving as heads to contribute to reducing the punching stress around the columns. Figure 4 shows the anchorage of the GFRP bars while Figure 5 shows the steel brackets over the columns and the walls.
4. Instrumentation with Fibre Optic Sensors (FOS)

To monitor the behaviour and evaluate the performance of the GFRP-reinforced flat slabs of the parking, a representative area of the parking was selected which is shown in Figure 1. 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. The GFRP bars were instrumented thereafter were transported to the construction site where they were stored until the installation. Figure 6 shows the instrumentation of the GFRP bars. A total of 26 fibre optic sensors (FOS) were glued on bottom and top reinforcing bars in the two orthogonal directions at the location of the maximum expected stresses. In addition, two FOS were glued on two dummy bars were 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 7 shows the locations and identifications of the different sensors.

The FOS utilized in the parking were controlled by two 16-channel data acquisition systems (Figure 7) (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 collecting the monitoring data. The FOS and the data logger will allow the long-term monitoring and field evaluation of the behaviour of two-way flat slabs reinforced with glass FRP bars under real service loading and environmental conditions.
5. Monitoring Results

Figure 8 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 8. Strain measurements using FOS: (a) Bottom bars; (b) Top bars; (c) Dummy bars; (d) Concrete.
From Figures 8a it could be noticed that sharp increase in the strain of the bottom GFRP bars when the formwork was released is about 2000 microstrain. After that, the strain increased to about 2500 microstrain when the parking opened to public. The 2500 microstrain represent about 15% of the strain capacity of the GFRP of 22-mm diameter used in the parking. Similar behaviour was observed for the top reinforcing bars but the maximum strain was about 1400 microstrain which represents 8% of the strain capacity of the GFRP bars. On the other hand, Figure 8c indicates that the two dummy bars showed a strain increase of about 150 microstrain 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 8b.

The concrete strain presented in Figure 8d shows the early age strain variation resulted from the hydration and shrinkage. A sudden increase of about -125 microstrain was recorded due to the dead load when the formwork was removed. The maximum recorded concrete strain was about -200 microstrain.

6. Conclusions

This paper presented the first world-wide application for GFRP bars in two-way flat slab parking structure (La Chancellerie). The flat slabs of the parking were totally demolished and reconstructed using high modulus GFRP 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:

- The GFRP bars provided an efficient and noncorroding alternative to overcome the steel corrosion and related deterioration problems.
- So far, the GFRP reinforced concrete two way flat slabs of the parking shows normal structural performance after 3 months in service.
- 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 behaviour and the performance in real environmental and service conditions.

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8. References


