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FATIGUE BEHAVIOR OF CONCRETE UNDERGROUND CHAMBERS REINFORCED WITH GFRP BARS

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ABSTRACT

Precast underground concrete chambers reinforced with steel bars are used frequently in construction and electrical industry for housing power cables and transformers. In Quebec, more than 30,000 of these chambers have been installed by Hydro-Quebec during the last 30 years. However, like other conventionally reinforced concrete structures, corrosion of steel reinforcement constitutes the major cause of chambers deterioration, leading to costly repairs and rehabilitation as well as a significant reduction in service life. This paper presents experimental data on the fatigue and static behavior of full-scale underground concrete chamber reinforced totally with glass fiber-reinforced polymer (GFRP) bars. The chamber measure 2,300 mm in width by 3,800 mm in length and the walls are 2,800 mm high. The chamber was tested under fatigue loading up to one million cycles then test under static load to simulate the traffic load on the manhole. The experimental results were reported in terms of strain and deformation behavior.

1. INTRODUCTION

Corrosion of steel reinforcement causes continual degradation to the worldwide underground concrete chambers such as that are used in electrical industry for housing power cables and transformers. Further, the existing of these structures in harsh environments has resulted in steady deterioration that shortens the lifetime serviceability of concrete structures. Harsh environments, such as those found in cold regions or Canadian climates, may expose structures to freeze-thaw cycles, marine sea spray or winter de-icing salts. Moreover, the constant hydro-static pressure increases water (often saturated with de-icing salts) infiltration rates to the underground structures. In Canada and the United States, maintenance and replacement costs of underground reinforced concrete (RC) structures are measured in billions of dollars. Government agencies and industrial firms are looking for infrastructure systems that are stronger, last longer, are more resistance to corrosion, cost less to build, maintain and repair. Engineers all over the world are challenged and in search of new and affordable construction materials as well as innovative approaches and systems to problem solving.

Nowadays in Canada, Hydro-Quebec used more than 30,000 underground steel-RC chambers that had been installed over the province for housing power cables and transformers. Each year, 2.0% (approximately 600) of these chambers are become corroded and need to be replaced. So, the challenge facing Hydro-Quebec is to design concrete underground chambers with noncorrosive materials such as fiber-reinforced-polymer (FRP) composite reinforcing bars.

FRP composite bars in general offer many advantages over conventional steel, including one-quarter to one-fifth the density of steel, no corrosion even in harsh chemical environments, and greater tensile strength than steel

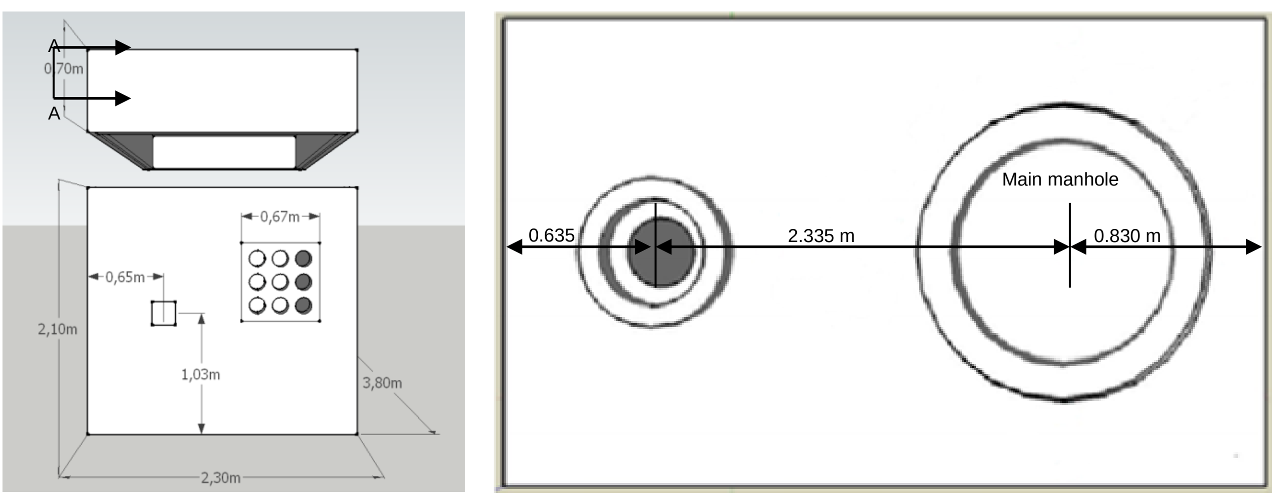
(Benmokrane et *al.* 2006; Mohamed and Benmokrane 2014; ACI 440.1R-06 2006). Since the early 2000s, a joint effort and collaboration between researchers, government organizations, and private industry have been established to develop and implement FRP bars in different applications, primarily focusing on developing and improving glass/carbon composite bars. These developments and improvements, along with numerous successful installations, have led to a much higher comfort level and exponential use of FRP bars by designers and owners. Since glass-FRP (GFRP) bars are more economical than the other available types of FRP bars (carbon and aramid), they have been used extensively in various infrastructure applications such as bridges, parking garages, tunnels, and marine structures (Mohamed and Benmokrane 2012; Mohamed et al. 2015). After years of investigation and implementation, public agencies and regulatory authorities in Canada have now included FRP bars as a premium corrosion-resistant reinforcing material in their corrosion-protection policy (ISIS Canada 2009). That notwithstanding, to date, there have been no implementations reported in the literature on the use of FRP bars in underground concrete chambers to resolve the expansive-corrosion issues to which they are subject.

Designing underground concrete chamber requires attention to different load scenario to be considered such as the self-weight, heavy traffic load, ground and water pressure and pulling of cables. Also, different types and sizes of these chambers are required in tri-dimensional shape. It is therefore difficult to predict theoretically the structural impact of replacing the steel bars with GFRP bars. This paper presents the fatigue and static structural behavior of full-scale precast underground concrete chamber totally reinforced with GFRP bars. Hydro-Quebec precast concrete underground chamber Type-3 was tested in the structural laboratory, department of civil engineering, University of Sherbrooke. The chamber was tested to evaluate the behavior under fatigue load and static compression load on the manhole.

2. EXPERIMENTAL PROGRAM

2.1 Details of Test Specimens

In this study, full-scale precast underground concrete chamber was cast and tested. The dimensions of the chamber specimens are illustrated in Figure 1. The chamber consists of two separate units: the base (bottom 2,300 × 3,800 × 2,100 mm) and the connection (top 2,300 × 3,800 × 700 mm). The wall thickness is 150 mm, while the bottom slab thickness varies from 210 to 250 mm (west to east, for drainage purposes) and the top slab is 250 mm thick.



(a) (b)

Figure 1: Schematic drawings of concrete chamber: (a) global dimensions of the base and the connection; and (b) distance of holes on the top slab of the connection

The chamber was totally reinforced with GFRP bars. The walls of the base are reinforced with one layer of No. 5 (15.9 mm) GFRP bars at 150 mm spacing in the vertical and horizontal directions. The connection is reinforced with No. 5 (15.9 mm) GFRP bars at 200 mm spacing. Figure 2 shows the reinforcement in the connection and the details of the wall/slab reinforcements.

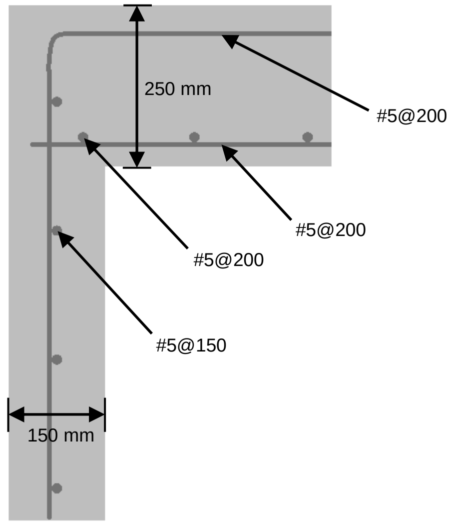


Figure 2: Schematic drawings of reinforcement detail in the wall/slab connection

2.2 Materials and Properties

Sand-coated GFRP bars No. 5 (nominal cross-sectional area of 199 mm^2, as indicated in CAN/CSA S807-10 were used to reinforce the chamber's two structural elements: the walls and slabs. Two grades of these bars were used: Grade II and III as classified in CAN/CSA S807-10 according to Young's modulus (50 and 60 GPa, respectively). Grade II and III GFRP bars were used as bent and straight reinforcement, respectively, in the walls and slabs. The guaranteed tensile strength for Grade II and III GFRP bars were 934 and 1105 MPa, respectively. The corresponding moduli of elasticity were 55.4, and 64.7 GPa, respectively, (Pultrall 2012).

The concrete used in fabricating the chamber was high-strength and self-consolidating with 5% to 7% of entrained air. More information about concrete mixtures and properties can be found at Lecuyer 2013. Average 28 day compressive strength of the chamber was of 71.7 MPa. On the day of testing, four concrete cylinders (200 mm × 100 mm) were tested. The average concrete compressive strength was 77.9 MPa.

2.3 Test Setup and Instrumentation

The chamber was tested under a single concentrated load at the center of the manhole. This load was applied through a 50.8-mm-thick circular steel plate that covers the manhole opening. A 20-mm-thick neoprene sheet was used between the steel plate and the concrete surface. A 1000 kN capacity with ±250 mm stroke actuator, monitored by a computer, was used to apply the fatigue loads. Fig. 3 shows a photograph of the test setup. Electrical resistance strain gauges were used to measure the strains in reinforcing bars and the concrete top and side surfaces, see Fig 4. Linear variable displacement transducers (LVDTs) were used to measure the deflection at different locations around the loaded area. Also, a high-accuracy (±0.001 mm) LVDT was installed at the position of the first crack to measure the crack width. A data acquisition system, monitored by a computer, was programmed to record the readings from strain gauges, LVDTs, and load cells during either the cyclic loading or the static loading steps.

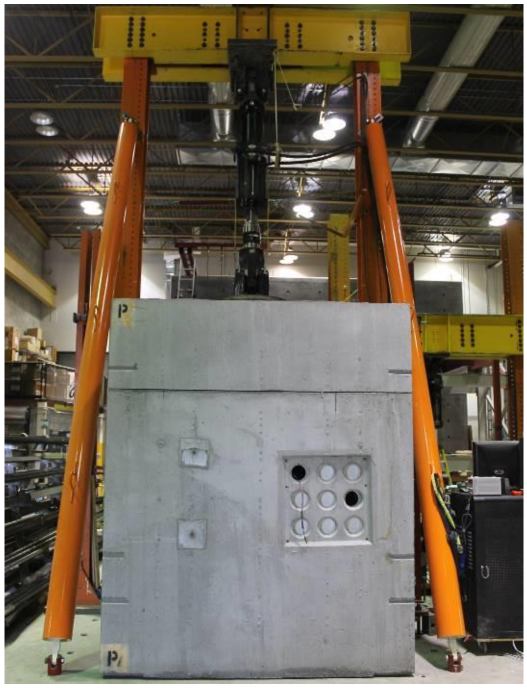
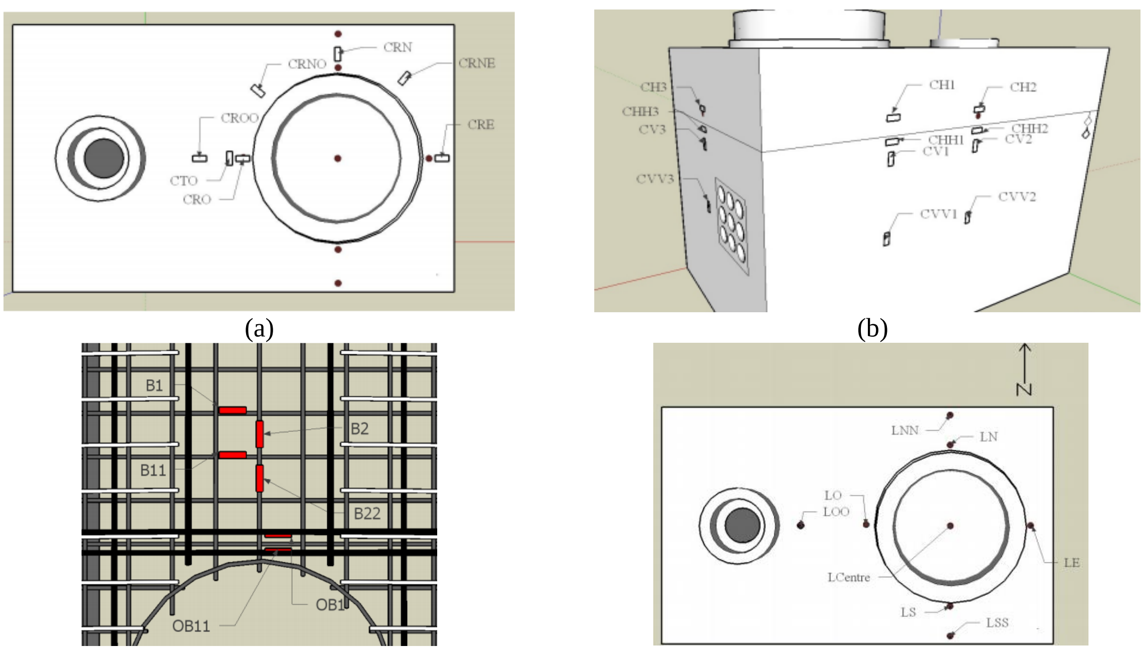


Figure 3: Test setup



(a) (b)

(c) (d)

Figure 4: (a) Concrete strain gages on the top slab, (b) Concrete strain gages on the walls, (c) GFRP reinforcement strain gages of the top slab and, (d) LVDTs on concrete slab.

2.4 Fatigue Loading

Scheme fatigue loading consisted of constant amplitude fatigue loading where test chamber was subjected to sinusoidal waveform fatigue load cycles between a minimum load level and a maximum load level (as shown in Figure 5). The minimum load level was set at 48 kN to prevent any impact effect during cyclic loading and also to represent the effect of the superimposed loads on a chamber (pavement, soil, etc.). A peak load was selected as the fatigue limit state specified by the CHBDC (2010). This fatigue limit state was calculated using the maximum wheel load of 87.5 kN with 40% dynamic allowance and a live load factor of 1.0 (P_{fls} = 87.5 × 1.4 × 1.0 = 122.5 kN) according to CHBDC, Clause 3.5.1. The fatigue loading steps (for example, 48 kN minimum load and 170.5 kN (48+122.5 kN) peak load) was applied for 1 ×106 cycles at a frequency of 2 Hz (duration of about one month).

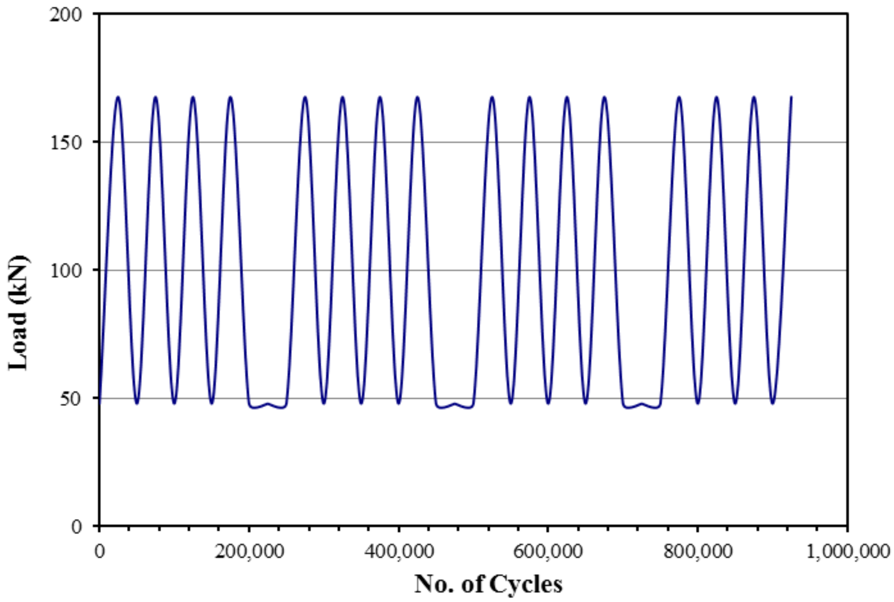


Figure: 5 Fatigue loading pattern used in this study

2.5 Static Loading

The chamber did not collapse during the cyclic test and therefore was then statically loaded up to the maximum capacity of the actuator with a single concentrated load applied at the center of the manhole. The chamber was reloaded with an increasing single quasi static load produced by the 1000 kN actuator at the loading speed of 4 kN per second to compare the residual stiffness of the top slabs. The static test consists of ten load–unload cycles from 50 kN up to 950 kN.

3. TEST RESULTS AND DISCUSSION

3.1 Fatigue Loading

The tested chamber did not collapse during the 1.0 × 10^6 cyclic test and therefore was then statically loaded up to 1000 kN the capacity of the acuter with a single concentrated load. The degree of fatigue damage can be estimated by the magnitudes of strains in reinforcement, crack widths, elastic deflections and residual (plastic) deflections. However, the tested chamber showed insignificant responses in term of strain, deformation, and cracks up to 1.0 × 10^6 cycles. Figure 6 shows the maximum and minimum displacements versus the number of cycles. The displacement showed insignificant response ranging from 0.1 mm to 0.45 mm. The figure did not show an indication of displacement increase up the complete of 1 × 10^6 cycles. The figure indicated that the chamber had reached a stable response after 4 × 10^5 cycles.

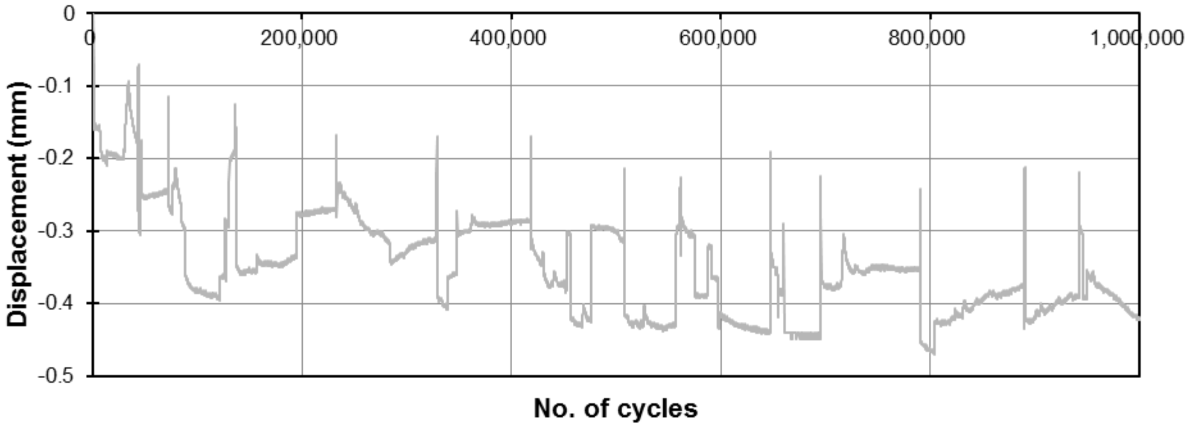


Figure 6: Jacks max and min displacements vs. number of cycles

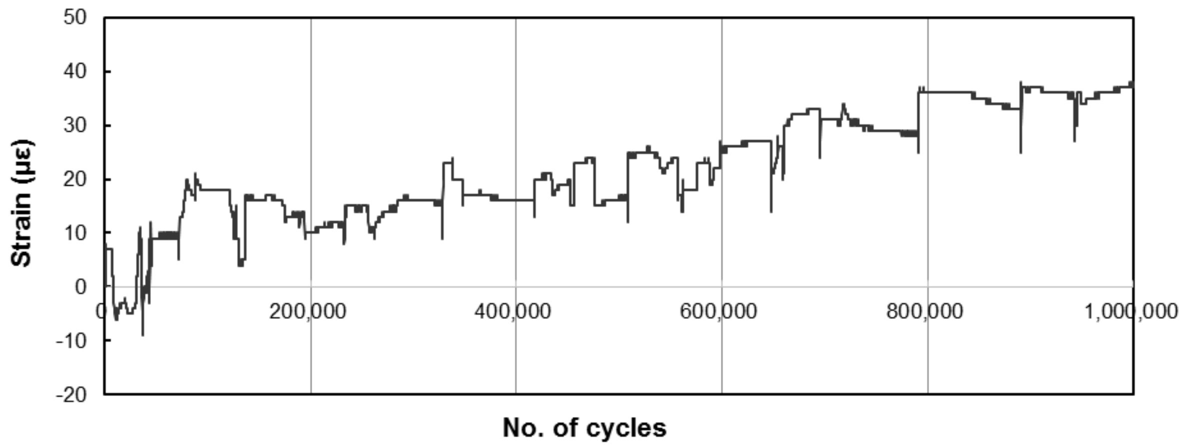


Figure 7: GFRP bar max and min strains vs. number of cycles

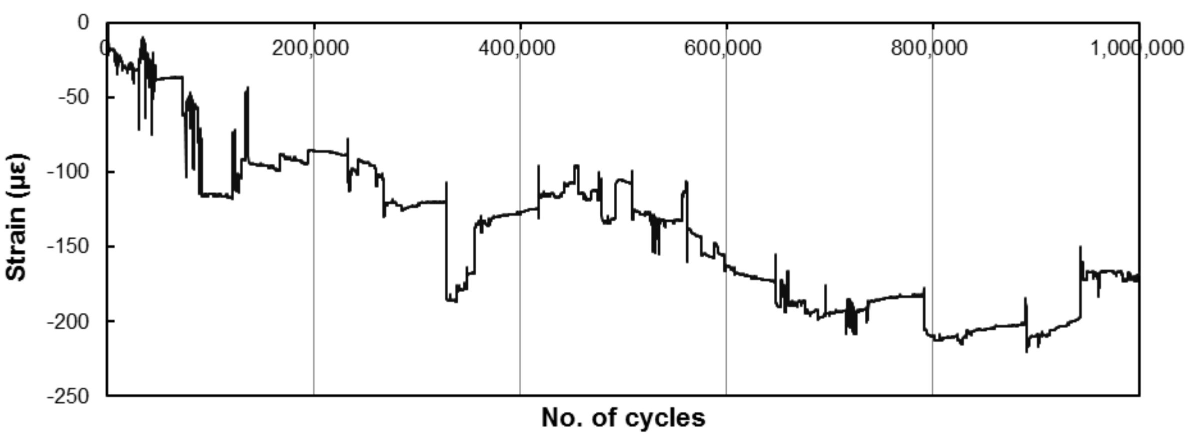


Figure 8: Concrete strains vs. number of cycles

Figure 7 shows the number of cycles versus the maximum and minimum strain relationship for the internal GFRP bars. As shown in this figure, the strain was minimal in the longitudinal reinforcing bars of the chamber's slab connection until the end of cyclic test (1×10^6 cycles). The strain in the FRP longitudinal reinforcement in the specimen did not reach 1.0% of the bars' ultimate tensile strain throughout the tests. No signs of anchorage problems were observed. The maximum strains in FRP bars were approximately 40 microstrains. In general, this low strain after million cycles in the chamber's FRP reinforcement shows that the investigated fatigue load level did not induce major stress in the FRP bars. This was confirmed since no flexural or shear cracks were observed. On the other hand, the figure clearly shows that the chamber had reached a stable response after 6×10^5 cycles.

Figure 8 shows the number of cycles versus the maximum and minimum concrete strain relationship. The figures indicate that, up to the end of cyclic test (1×10^6 cycles); the concrete strains were insignificant and ranged from 150 to 220 microstrains. These values are well below the concrete crushing strain of 3,000 microstrains specified in ACI 318-14 and the 3,500 microstrains specified in CSA standards (CSA S806-12, CSA A23.3-04), which is one of the indications that the fatigue did not affect the flexural behavior of the chamber since no cracks were observed. On the other hand, the figure clearly shows that the chamber had reached a stable response after 6×10^5 cycles.

These results suggest that, for the maximum applied load of 170.5 kN, (superimposed loads with the factored wheel load) the chamber could work for a number of cycles much greater than the investigated in this study. The data in Fig. 6 to Fig. 8 shows that the maximum deflection, GFRP strain, and concrete strain of the chamber were insignificant up to the million cycles. This observation confirms the respect of the used design criterion on the maximum deflection to satisfy the requirements of Hydro-Quebec their underground chambers. This successful fatigue test demonstrated the effective use of GFRP bars in a precast concrete chamber for electrical industry for housing power cables and transformers. The structural performance of this first investigation of its type and scale, based on the fatigue and static test observations, was anticipated. This application opens the door to major application of FRP reinforcing bars in reinforced-precast concrete chambers in North America. Reinforcing precast concrete chambers with GFRP bars would extend the life of such structures to 100 years or more compared to steel-reinforced concrete, which needs major restoration after 25 years.

3.2 Static Loading

The cyclic test was interrupted after one million cycles because the chamber had reached a stable response as indicated by the asymptotic behavior of the strain and deformation curves pressed before. Thereafter, quasi static load was applied on the center of the manhole up to the capacity of the actuator. Figure 9 shows the load-displacement curve of the tested chamber under quasi static load. The tested chamber demonstrated linear load–deflection behavior before cracking. The stiffness at this stage was high representing the behavior of the uncracked section using the gross moment of inertia of the concrete cross section. Once cracking occurred, at load level equal to 530 kN, stiffness decreased as the load increased. At this stage, the flexural stiffness was dependent on the axial stiffness of the reinforcing bars, which is a function of the area and modulus of elasticity of the longitudinal reinforcement. The data in Figure 9 shows that the curve indicated that the central deformation was insignificant at the factored ultimate load level (0.25 mm). Also, no cracks were observed at this level as it is confirmed from the load-deflection response. Also, it was found that the load-deflection behavior was not affected with loading and unloading scheme up to load level 3 times the factored load. Moreover, the maximum deflection at the center of manhole was close to 1.7 mm at load level equal to 950 kN. This low deformation presents the superior performance of the GFRP RC chamber at load level almost 5 times the factored ultimate load (170 kN).

Figure 10 shows the measured applied load on the chamber versus the maximum measured strain relationships for the internal GFRP longitudinal bars. As shown in this figure, the strain was minimal in the longitudinal reinforcing bars of the FRP until the concrete section cracked. The strain in the FRP longitudinal reinforcement did not reach 10% of the bars' ultimate tensile strain throughout the tests. No signs of anchorage problems were observed. The maximum strain in FRP bars was approximately 920 microstrains. In general, this relatively low strain at ultimate in the chamber reinforced with GFRP bars shows that fatigue loading did not affect the response of the FRP bars.

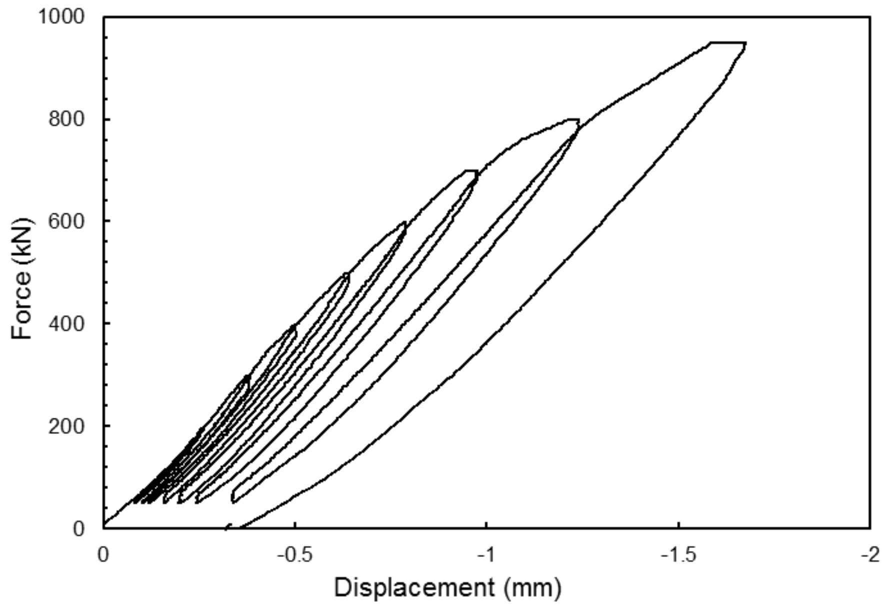


Figure 9: Load-central displacement response under static

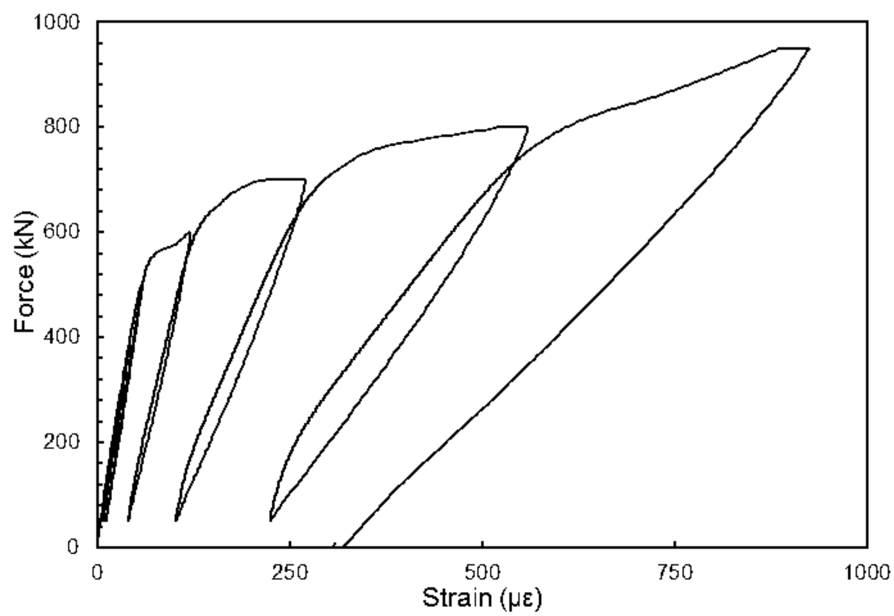


Figure 10: Load-GFRP strain response under static

4. CONCLUSIONS

Hydro-Quebec has decided to investigate the use of GFRP bars in reinforcing the precast underground concrete chamber Type-3. Full-scale concrete chamber reinforced with GFRP bars was prepared and cast at Lécuyer Ltd (Quebec, Canada). The chamber was tested to evaluate the behavior in fatigue load and static load to simulate the serviceability life of underground chambers. The successful fatigue and static tests demonstrated the effective use of GFRP bars in a precast concrete chamber for electrical industry for housing power cables and transformers. The structural performance of this first investigation of its type and scale, based on the fatigue and static test observations, was anticipated. This application opens the door to major application of FRP reinforcing bars in reinforced-precast concrete chambers in North America and across the world. Reinforcing precast concrete chambers with GFRP bars would extend the life of such structures to 100 years or more compared to steel-reinforced concrete, which needs major restoration after 25 years.

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