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Long-term applications of CFRP prestressing in Canada

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ABSTRACT: This paper describes a summary of some of the long-term research and practical applications of carbon fibre reinforced polymer (CFRP) prestressing in Canada based on research conducted at Queen's University. Much of this research was inspired by Prof. Meier's pioneering work in CFRP prestressing. The paper will describe the development of a system for prestressing CFRP sheets for repair applications starting from anchorage systems to performance in fatigue and cold regions. A successful field application (Winnipeg, Manitoba in 2003) of the technique will also be described. The paper also includes research on CFRP prestressing rods for new construction and replacement of corroded steel prestressing strands. The results of long-term monitoring of CFRP prestressed beams over 13 years in addition to fatigue testing will be described. A successful replacement of corroded post-tensioned strands with CFRP rods in a parking garage in Toronto (2007) will be detailed and the current condition of the structure will be described.

1 INTRODUCTION

Pioneering research into carbon fibre reinforced polymer (CFRP) prestressing by Prof. Urs Meier was the inspiration for the research programs described in this paper along with much other FRP research in Canada. Prof. Meier published a landmark paper on the potential for a bridge over the Straits of Gibraltar that could be possible if CFRP cables were used instead of steel (Meier 1987). This paper led to a visit to Europe by the Canadian Society for Civil Engineering (CSCE) Technical Subcommittee on Advanced Composite Materials in Bridges and Structures (ACMBS) (Mufti et al. 1991). The first bridge with prestressed CFRP in Canada was constructed shortly afterwards in Calgary (Rizkalla and Tadros 1994). At Queen's, research into CFRP prestressing started around the same time following the example of Prof. Meier.

Prestressing is an efficient method to take advantage of the high strength of CFRP and early work at the Swiss Federal Laboratories for Materials Science and Technology (EMPA) investigated the potential of prestressing CFRP plates for strengthening reinforced concrete beams (Meier 1995). Anchorage of the plates was a significant concern and the first attempts without anchorage resulted in the plates completely peeling off the beams (Meier 1995). This anchorage problem was eventually solved with a gradient anchor system (Stöcklin and Meier 2001; Michels et al. 2013; Czaderski and Motavalli 2007). El-Hacha and Soudki (2013) and Aslam et al. (2015) reviewed recent developments of FRP prestressed strengthening including near surface mounted systems.

For prestressing with CFRP rods, early research demonstrated promising behaviour (Abdelrahman and Rizkalla 1997; Fam et al. 1997) and several bridges have been built with CFRP tendons throughout the world (Rizkalla and Tadros 1994, 2003; Keller 2003; Grace et al. 2008). Long-term tests on FRP prestressed beams have been conducted (Currier et al. 1995; Matthys and Taerwe 1998; Zou and Shang 2007) and the fatigue behaviour has also been studied (Abdelrahman et al. 1995; Grace 2000; Mertol et al. 2006).

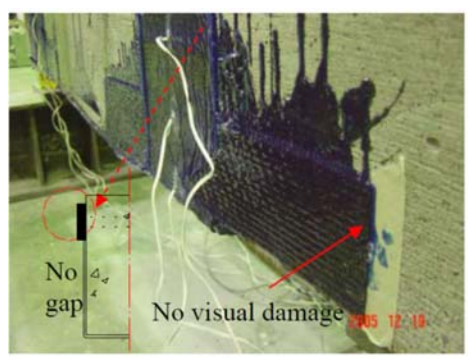
At Queen's, research has considered both strengthening systems with prestressed CFRP sheets and internal CFRP prestressed concrete systems. For strengthening with CFRP sheets, new anchorage systems were developed and the long-term and fatigue behaviour was studied in the laboratory. The system was also applied for a bridge repair in Winnipeg in 2003. For internal CFRP prestressing, laboratory research examined long-term and fatigue behaviour. A field application where FRP rods replaced corroded post-tensioned cables was successfully conducted in a parking garage in Toronto in 2007. The current paper summarizes these long-term research and practical applications of CFRP prestressing that have been conducted at Queen's.

2 STRENGTHENING WITH PRESTRESSED CFRP SHEETS

2.1 Anchorage

Since concrete cover delamination (peeling) failures were associated with the transfer of prestress in the strengthening of concrete beams with prestressed CFRP plates (Meier 1995), a mechanical anchorage system was developed for CFRP sheets. Initially, the sheets were wrapped around steel rollers that were then bolted to the beams at the ends (Wight et al. 2001). This system was shown to prevent peeling at prestress transfer. Furthermore, this anchorage system prevented peeling failures at ultimate and thus enabled the full strength of the FRP sheets to be employed (Wight et al. 2001). Further refinement of the system resulted in the rollers being replaced with plates as shown in Figure 1(a). A non-metallic anchorage system was also developed (Figure 1(b)) and shown to be most effective when the vertical sheets on the sides of the beam were mechanically anchored at the top of the beam (Kim et al. 2008).

(a)



(b)

Figure 1. Anchorage systems (a) Plate anchor (Photo: L. Mancs) (b) Non-metallic anchor (Kim 2006).

2.2 Long-term testing

To demonstrate the effectiveness of the FRP prestressing system for strengthening, long-term tests were conducted on strengthened beams at both room temperature (+22 °C) and low temperature (-28 °C) for up to one year. The exposure to low temperature caused prestress losses of approximately 3 % of the ultimate strength of the sheets. Measurements of prestress losses were recorded for one year, and the results were extrapolated to predict long-term losses after 50 years of approximately 5 % of the ultimate strength of the sheets (El-Hacha 2000).

2.3 Fatigue performance

Cyclic load tests were conducted on five prestressed concrete beams (160 × 280 × 3600 mm) strengthened with CFRP prestressed sheets as summarized in Table 1 (Ford 2004). The average 28 day concrete strength was 38 MPa, and the beams were pretensioned with one internal steel prestressing strand (13 mm diameter) to a stress of 1300 MPa. The beams were pre-cracked before strengthening.

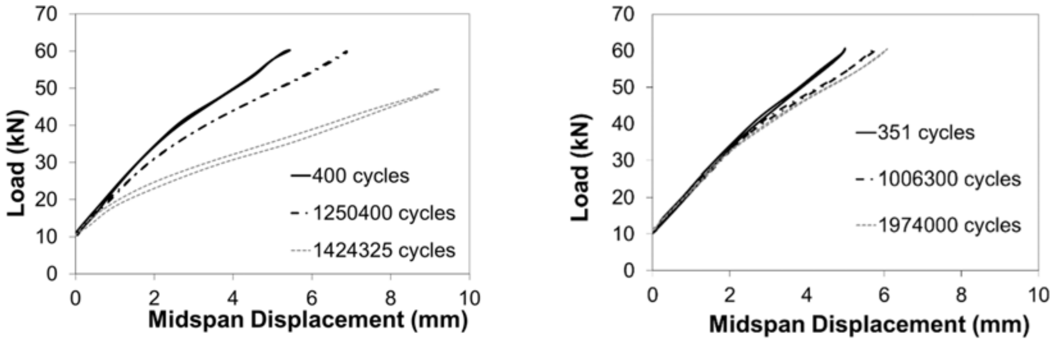
For strengthening, one layer of CFRP sheet (150 mm wide) was prestressed to the levels given in Table 1. The CFRP sheets had a guaranteed design stress of 3790 MPa, a design thickness of 0.165 mm, and an elastic modulus of 227 GPa as specified by the manufacturer. In most cases, the short-term prestress loss was less than 5 % of the ultimate strength of the sheets. Beam B4 inadvertently cracked during initial stressing thus causing an excessive prestress loss.

Three of the five beams were exposed to 80 freeze-thaw cycles (-20 °C to +20 °C). The beams were frozen in air for 16 hours and then thawed in water for 8 hours for a total cycle length of 24 hours. In terms of fatigue testing, all beams survived over 1 million load cycles and the two beams that were not exposed to freezing and thawing survived 2 million cycles. The freezing and thawing process accelerated deterioration because it caused additional cracking in the concrete as shown by the degradation of Beam B2 in Figure 2(a) after 1.4 million cycles. In contrast, Beam B5 that was not exposed to freeze-thaw survived 2 million cycles without fatigue failure (Figure 2(b)). In the case of Beam B1, the freezing and thawing process caused an air bubble between the epoxy and the steel anchor plate to grow in size. The air bubble was a fabrication error; an epoxy injection repair was attempted before exposing to freeze-thaw cycles but this repair was not sufficient to prevent damage.

Table 1. Summary of fatigue tests on strengthened beams (Ford 2004)

Beam	Prestress level†	Short-term prestress loss†	Freeze/thaw	Fatigue load range ††	Maximum # of cycles	Failure load (kN)	Cyclic failure mode
B1	32 %	5.7 %	80 cycles	10% – 61%	1.4 x10^6	---	Debonding
B2	38 %	0.2 %	80 cycles	10% – 61%	1.4 x10^6	44.3	Cracking
B3	47 %	4.5 %	80 cycles	10% – 61%	>2.0 x10^6	112.6	Unfailed
B4	19 %	28 %	No	10% – 51%	>2.0 x10^6	99.9	Unfailed
B5	36 %	4.8 %	No	10% – 61%	>2.0 x10^6	95.2	Unfailed

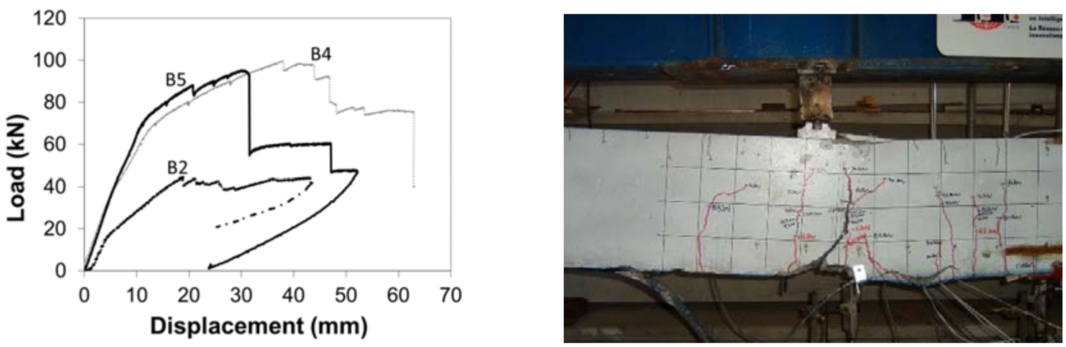
†: percentage of the manufacturer's ultimate design stress of 3790 MPa
††: percentage of the static ultimate load-carrying capacity of the strengthened beam



(a) (b)

Figure 2. Stiffness degradation during fatigue testing (a) Beam B2: Freeze-thaw and fatigue (b) Beam B5: Fatigue only.

B2



(a) (b)

Figure 3. Static loading to failure (a) Load-deflection (b) Failure mode of Beam B5 (Photo: J. Ford).

After the cyclic loading, beams B2 to B5 were statically loaded to failure. Figure 3(a) shows the load-deflection behaviour. The low strength of Beam B2 was a result of fatigue failure of the internal prestressing strand. Despite this fatigue failure, the beam still had some strength because the CFRP strengthening system was intact. The load-deflection plots for Beams B4 and B5 demonstrate that the strengthening system performed very well even after 2 million cycles of fatigue loading. Figure 3(b) shows the failure mode of Beam B5 that was caused by rupture of the prestressed CFRP sheets at the location of a large crack in the beam that developed underneath the loading point.

2.4 Field Application

A four span overpass bridge with a total length of 56.2 m in Winnipeg, Manitoba was damaged by an excessively high vehicle passing underneath the bridge and striking the outside prestressed girder. The impact ruptured some of the internal prestressing strands and damaged the concrete. The concrete was replaced and the girder was strengthened with 3 layers of CFRP sheets (325 mm wide) that were prestressed to 800 MPa (Figure 4). The material properties of the sheets were the same as those reported in section 2.3 of this paper. The strengthening was conducted in one day.

Figure 4. Bridge repair in Winnipeg, Manitoba (Photo: L. Mancs).

Figure 5. Sustained loading (Photo: R. Saiedi).

More details on the strengthening were reported by Kim et al. (2006). The intention was to monitor the performance of the repair over several years, but the bridge was struck by another high vehicle within one year of the repair and the CFRP was completely destroyed. After this damage, a conventional repair was implemented at a higher cost than the CFRP repair.

3 PRESTRESSED CFRP TENDONS

3.1 Long-Term Testing

Seven 4.4 m long CFRP prestressed concrete beams were fabricated in 1995 and tested over a period of 13 years. The beams were T-shaped with a flange breath of 500 mm and an overall depth of 300 mm (Braimah et al. 2003, Saiedi et al. 2013). Four 8 mm diameter CFRP rods in each beam were pretensioned to either 50 or 70 % of the ultimate strength of the rods. The concrete had a 28 day compressive strength of 40 MPa, and the CFRP rods had a guaranteed strength of 2300 MPa with an elastic modulus of 150 MPa.

Four of these beams were studied for long-term deformations under sustained load at room temperature for a three year period from 1997 to 2000 (Braimah et al. 2003). The other three beams were tested under similar loading conditions but at low temperature (-27 °C) for six months as shown in Figure 5. The differences in temperature exposure did not appear to affect the deformations under sustained loading, and the increases in deflection were typically less than 1.0 mm compared to initial deflections due to the short-term loading of approximately 15 mm (Saiedi et al. 2013).

3.2 Fatigue Performance

Unbonded (Braimah et al. 2006) and bonded (Saiedi et al. 2011) CFRP prestressed concrete beams were tested under fatigue loading for up to 3 million cycles. The geometry of the bonded beams was the same as described in section 3.1, and one of the beams was tested under cyclic loading at low temperature (-28 °C) while the other two were tested at room temperature. All the CFRP prestressed beams survived 3 million cycles. However, a similar steel prestressed beam subjected to the same cyclic loading regime failed in fatigue after only 185,000 cycles. Unbonded CFRP prestressed beams did not perform as well under cyclic loading because the tendons fractured at the anchor (Braimah et al. 2006). However, one of the CFRP rods survived 2 million cycles of loading and thus unbonded CFRP rods may be able to achieve adequate fatigue performance if anchor failures can be avoided.

3.3 Field Application

A parking garage in Toronto (Figure 6(a)) required rehabilitation because of corrosion of the steel prestressing strands. The strands were unbonded and thus two corroded strands were removed and replaced with 12 mm diameter CFRP rods (MacDougall et al. 2011). The rods had a guaranteed strength of 2068 MPa with a modulus of elasticity of 124 GPa as specified by the manufacturer. The span for the strand replacement was 17.9 m long but the CFRP rods could only be shipped with a maximum length of 12 m. Therefore the CFRP rods were mechanically spliced in the middle as shown in Figure 6(b). The two rods were then stressed to the required prestress load level of 145 kN. Unfortunately, a problem occurred with setting the anchors and the final prestress load levels were only 40 kN in one rod and 113 kN in the other. Subsequent analysis showed that these prestress levels were satisfactory for serviceability requirements in the parking garage and follow up testing demonstrated a new method for setting the anchors that could avoid the anchor set problems encountered in the field (MacDougall et al. 2011). These tendons have now been in service for almost 10 years without any signs of deterioration.

(a) (b) (c)

Figure 6. Parking garage post-tension tendon replacement in Toronto, Ontario. (a) Garage (b) Splicing the CFRP rods (c) Stressing the CFRP rods.

4 CONCLUSIONS

CFRP prestressing systems for strengthening existing concrete beams and for new construction were described. These systems were inspired by pioneering research by Prof. Meier at EMPA. Long-term and fatigue tests were conducted and both systems generally displayed strong performance. The weak link with both systems was related to anchorage. As such, the fatigue life of unbonded CFRP prestressed beams was limited by fatigue failure at the rod to anchor junction. For strengthening with CFRP prestressed sheets, the fatigue life was reduced by exposure to freeze-thaw cycles. Two successful field applications were conducted: a bridge in Winnipeg was successfully strengthened with prestressed CFRP sheets and corroded prestressing strands were replaced with CFRP rods in a parking garage in Toronto. The CFRP rods in the latter project have performed successfully in service for almost 10 years.

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6 REFERENCES

Abdelrahman, A.A., G. Tadros, and S.H. Rizkalla, 1995, Test model for the first Canadian smart highway bridge. *ACI Structural Journal*, 92(4): 451–458.

Abdelrahman, A.A., and S.H. Rizkalla, 1997, Serviceability of Concrete Beams Prestressed by Carbon Fiber Reinforced Plastic Bars. *ACI Structural Journal*, 94(4): 447-457.

Aslam, M., P. Shafigh, M.Z. Jumaat, and S.N.R. Shah, 2015, Strengthening of RC beams using prestressed fiber reinforced polymers – A review. *Construction and Building Materials*, 82: 235-256.

Braimah, A., M.F. Green, and K.A. Soudki, 2003, Long-Term Behaviour of CFRP Prestressed Concrete Beams. *PCI Journal*, 48(2): 98-107.

Braimah, A., M.F. Green, and T.I. Campbell, 2006, Fatigue Behaviour of Concrete Beams Post-Tensioned with Unbonded Carbon Fiber Reinforced Polymer Tendons. *Canadian Journal of Civil Engineering*, 33(9): 1140-1155.

Currier, J., C. Dolan, and E. O'Neil, 1995, Deflection Control of Fiber Reinforced Plastic Pretensioned Concrete Beams. *Proceedings of FRPRCS-2*, Ghent, Belgium, August, 413-420.

Czaderski, C., and M. Motavalli, 2007, 40-year-old full-scale concrete bridge girder strengthened with prestressed CFRP plates anchored using gradient method. *Composites Part B (Engineering),* 38: 878–886.

El-Hacha, R., 2000, Prestressed CFRP Sheets for Strengthening Concrete Beams at Room and Low Temperatures. *PhD Thesis*, Queen's University, Dec.

El-Hacha, R., and K. Soudki, 2013, Prestressed near-surface mounted fibre reinforced polymer reinforcement for concrete structures – a review. *Canadian Journal of Civil Engineering*, 40: 1127-1139.

Fam, A.Z., S.H. Rizkalla, and G. Tadros, 1997, Behavior of CFRP for Prestressing and Shear Reinforcement of Concrete Highway Bridges. *ACI Structural Journal*, 94(1): 77-86.

Ford, J., 2004, Effects of Freeze/Thaw Cycling on the Fatigue Behaviour of Prestressed Concrete Beams Strengthened with Prestressed CFRP Sheets. *M.Sc (Eng.) Thesis*, Queen's University, ON, Canada.

Grace, N.F., 2000, Response of continuous CFRP prestressed concrete bridges under static and repeated loadings. *PCI Journal*, 45(6): 84–101.

Grace, N.F., T. Enomoto, A. Abdel-Mohti, Y. Tokal, and S. Puravankara, 2008, Flexural behavior of precast concrete box beams post-tensioned with unbonded, carbon-fiber-composite cables. *PCI Journal*, 53(4): 62-82.

Keller, T., 2003, Strengthening of Concrete Bridges with Carbon Cables and Strips. *Proceedings FRPRCS-6*, Singapore, 1331-1340.

Kim, Y.J., 2006, Strengthening Concrete Structures with Prestressed CFRP Sheets: Laboratory and Numerical Investigations to Field Application. *PhD Thesis*, Queen's University, Sept.

Kim, Y.J., M.F. Green, G.J. Fallis, R.G. Wight, and R. Eden, 2006, Damaged Bridge Girder Strengthening. *Concrete International*, *American Concrete Institute (ACI)*, 28(11): 47-52.

Kim, Y.J., R.G. Wight, and M.F. Green, 2008, Flexural Strengthening of RC Beams with Prestressed CFRP Sheets: Using Nonmetallic Anchor Systems. *ASCE Journal of Composites for Construction*, 12(1): 44-52.

MacDougall, C., M.F. Green, and L. Amato, 2011, CFRP Tendons for the Repair of Post-Tensioned, Unbonded Concrete Buildings. *ASCE Journal of Performance of Constructed Facilities*. 25(3): 149-157.

Matthys, S., and L. Taerwe, 1998, Long-Term Behaviour of Concrete Slabs Pre-Tensioned with AFRP or Prestressing Steel, Durability of FRP Composites for Construction, pp. 95-106.

Meier, U., 1987, Proposal for a Carbon Fibre Reinforced Composite Bridge across the Strait of Gibraltar at its Narrowest Site. *Proceedings of the Institution of Mechanical Engineers, Part B: Management and engineering manufacture*, 201(2): 73-78.

Meier, U., 1995, Strengthening of structures using carbon fibre/epoxy composites. *Construction and Building Materials.* 9: 341–351.

Mertol, H. C., S.H. Rizkalla, P. Scott, J.M. Lees, and R. El-Hacha, 2006, Durability and fatigue behavior of high-strength concrete beams prestressed with CFRP bars. *ACI Special Publication SP245-1: Case Histories and Use of FRP for Prestressing Applications*, American Concrete Institute, 1–20.

Michels, J., J. Sena-Cruz, C. Czaderski, and M. Motavalli, 2013, Structural strengthening with prestressed CFRP strips with gradient anchorage. *Journal of Composites for Construction*, 17(5): 651-661.

Mufti. A.A., M-A Erki, and L.G. Jaeger, 1991, *Advanced Composite Materials with Application to Bridges: State-of-the-Art Report.* Canadian Society for Civil Engineering, Montreal, 297 p.

Rizkalla, S., and G. Tadros, 1994, First Smart Bridge in Canada, *Concrete International*, *American Concrete Institute (ACI)*, 16(6): 42-44.

Rizkalla, S., and G. Tadros, 2003, FRP for Prestressing of Concrete Bridges in Canada. *ACI Special Publication 215*, 75-90.

Saiedi, R., A. Fam, and M.F. Green 2011, Behavior of CFRP-Prestressed Concrete Beams under High-Cycle Fatigue at Low Temperature. *ASCE Journal of Composites for Construction*, 15(4): 482-489.

Saiedi, R., M.F. Green, and A. Fam, 2013, Behavior of CFRP-Prestressed Concrete Beams under Sustained Load at Low Temperature. *ASCE Journal of Cold Regions Engineering*, 27(1): 1-15. 16.

Stöcklin, I., and U. Meier, 2001, Strengthening of Concrete Structures with Prestressed and Gradually Anchored CFRP Strips. *Proceedings of FRPRCS-5*, Cambridge, UK, 6–18 July.

Wight, R.G., M.F. Green, and M.A. Erki, 2001, Strengthening Reinforced Concrete Beams with Prestressed CFRP Sheets. *ASCE Journal of Composites for Construction*, 5(4): 214-220.

Zou, P.X.W., and S. Shang, 2007, Time-Dependent Behaviour of Concrete Beams Pretensioned by Carbon Fibre-Reinforced Polymers (CFRP) Tendons. *Construction and Building Materials*, 21(4): 777-788.