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ABSTRACT

Novel structures are emerging utilizing high performance, self-consolidating, fibre-reinforced concrete (HPSCC) reinforced with high-strength, lightweight, and non-corroding prestressed reinforcement. One example of this is a new type of precast carbon fibre reinforced polymer (CFRP) pretensioned HPSCC panel intended as load-bearing panels for building envelopes. As for all load-bearing structural members in building applications, the performance of these members in fire must be understood before they can be used with confidence. In particular, the bond performance of CFRP prestressing reinforcement at elevated temperatures is not well known. This paper examines the fire performance of these new types of structural elements, placing particular emphasis on the bond performance of CFRP and steel wire prestressing reinforcement at elevated temperatures. The results of large-scale fire tests and transient high temperature tensile and bond-pullout tests on CFRP and steel prestressing bars embedded in HPSCC cylinders are presented and discussed to shed light on the fire performance of these structural elements.

INTRODUCTION

Current trends in construction are forcing the development of more durable and sustainable concrete structures. Careful selection, design, and optimization of both the concrete mixes and the reinforcing materials used are now commonplace. One result of this has been the emergence of structural elements incorporating optimized, high-performance, self-consolidating, fibre-reinforced concrete (HPSCC) and novel reinforcing and prestressing materials such as carbon fibre reinforced polymer (CFRP) tendons, which are high-strength, creep resistant, lightweight, non-corroding, and magnetically invisible. One example of such an element is precast CFRP pretensioned HPSCC members used as load-bearing panels for building envelopes (Figure 1). However, the performance of these HPSCC precast members in fire is not well known and must be understood before

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Title: Bond Strength Degradation for Prestressed Steel and Carbon FRP Bars in High-Performance Self-Consolidating Concrete at Elevated Temperatures and in Fire

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ABSTRACT

Novel structures are emerging utilizing high performance, self-consolidating, fibre-reinforced concrete (HPSCC) reinforced with high-strength, lightweight, and non-corroding prestressed reinforcement. One example of this is a new type of precast carbon fibre reinforced polymer (CFRP) pretensioned HPSCC panel intended as load-bearing panels for building envelopes. As for all load-bearing structural members in building applications, the performance of these members in fire must be understood before they can be used with confidence. In particular, the bond performance of CFRP prestressing reinforcement at elevated temperatures is not well known. This paper examines the fire performance of these new types of structural elements, placing particular emphasis on the bond performance of CFRP and steel wire prestressing reinforcement at elevated temperatures. The results of large-scale fire tests and transient high temperature tensile and bond-pullout tests on CFRP and steel prestressing bars embedded in HPSCC cylinders are presented and discussed to shed light on the fire performance of these structural elements.

INTRODUCTION

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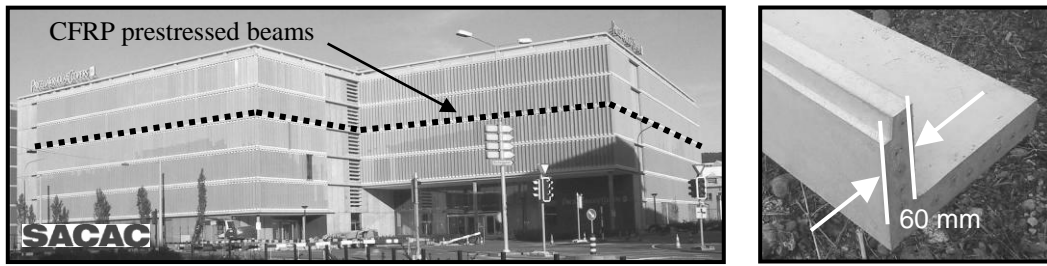G Terrasi & E Hugi, EMPA Dübendorf, Zurich, Switzerland.

Figure 1. Use of precast CFRP pretensioned HPSCC members in a building envelope [3].

they can be used with confidence. The bond between both steel and FRP reinforcing bars (prestressed and non-prestressed) and concrete deteriorates at elevated temperature. Indeed, for FRP reinforcement, bond strength reductions are thought to be a limiting factor for the fire-safety of FRP reinforced or prestressed concrete [1], although the precise magnitude of bond strength reductions and their impacts on the load-bearing capacity of heated reinforced (or prestressed) concrete structures have not been studied and remain unknown. The tensile strength of steel & CFRP is also reduced by exposure to elevated temperatures; the reductions are well known for steel tendons [2] but remain largely unknown for CFRP tendons.

To address all of the above issues, an ongoing study is underway which includes: (1) large-scale furnace tests on CFRP prestressed HPSCC panels, (2) transient tensile strength tests on CFRP prestressing tendons, (3) transient bond pullout tests on CFRP tendons and steel prestressing wires, and (4) micro-mechanical characterization of the CFRP tendons. The goal in all cases is to better understand the response of CFRP prestressed HPSCC panels and to determine the factors that should be considered in their fire-safe design and application.

LARGE SCALE FIRE TESTS

Seven large scale fire tests were performed on CFRP prestressed HPSCC slabs in a floor furnace at EMPA (ISO 834 Fire). Figure 2 shows schematics of the specimens and test setup, and Table I provides details of the experimental program.

Initial scoping tests (not presented) performed on small scale slabs [4] indicated that loss of bond between the FRP tendons and the concrete was a governing factor in determining the fire resistance of the CFRP prestressed slabs. Bond failure occurred at bond line temperatures near the glass transition temperature of the CFRP's epoxy matrix ($T_g = 121°C$ for these CFRP tendons). Thus, the testing programme included slabs with unheated overhangs (of varying length) at each end to provide a cold anchorage region during fire testing. The smallest anchorage

TABLE I. FIRE TEST POGRAMME AND SELECTED RESULTS (REFER TO FIGURE 2)

| No.	Age (mths)	Tendon type	Prestress (MPa)	Cover c (mm)	Thickness t (mm)	Overhang (mm)	Failure time	Failure mode
4	9.3	CFRP	1200	19.8	45	160	26'12"	spalling → crushing
7	8.8	CFRP	1200	20.3	46	280	34'36"	spalling → crushing
8	8.4	CFRP	1200	28.3	62	280	24'12"	spalling → crushing
5	8.4	CFRP	1200	27.8	61	160	47'00"	spalling → crushing
9	9.3	CFRP	1200	34.8	75	280	1h00'24"	spalling → crushing
6	9.3	CFRP	1200	34.8	75	160	1h31'36"	spalling → crushing
40	1.0	Steel	1200	34.8	75	160	29'00"	spalling → crushing
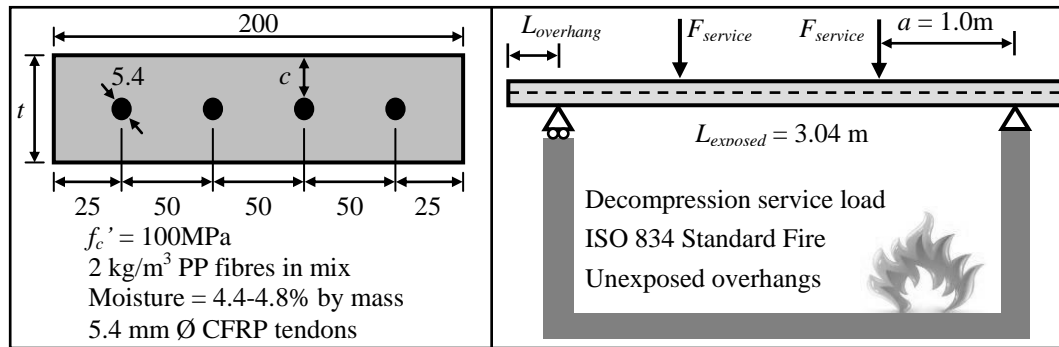
Figure 2. Details of fire test specimens and fire test setup.

length (160mm) represented the room temperature prestress development length for a tendon stress of 1200MPa, as determined from previous testing. The slab thickness, and hence the cover to the reinforcement, varied between 45mm and 75mm. The 100MPa concrete incorporated $2kg/m^3$ of short polypropylene (PP) fibers and had a high moisture content at the time of testing (4.4-4.8%). The load in the central span corresponded to a typical service load condition [3]. One slab used 6mm Ø cold-drawn steel prestressing wire stressed to 1200MPa.

The fire resistance of the slabs varied between 24min and 91min, with the thicker slabs generally achieving higher fire endurances. The notable exception was the steel prestressed slab, which suffered severe spalling early in the test (likely due to its very young age at the time of testing). This test is being repeated in May 2010 to properly account for the differences in slabs' age at the time of testing. Despite including PP fibers in the mix, the dominant failure mode was sudden collapse due to accumulated HSPCC spalling, which reduced the slabs' cross-sections until they failed in bending due to crushing of the remaining concrete under the service load. Spalling was first localized in the shear and bending span (i.e. near the supports where the bending moment is low and the exposed face of the slab is most precompressed). It is widely known that concrete's propensity for spalling is increased by compressive stress, so the location of first spalling is unsurprising.

Longitudinal splitting cracks were observed on the exposed and unexposed surface prior to failure for both 45mm thick slabs and, to a smaller extent, for the 60mm slabs. These were possibly caused by thermal incompatibility between the CFRP tendons and the HPSCC. Most 75mm slabs displayed single longitudinal cracks. Significantly, tendon slip versus time measurements showed no evidence of slip increases during the tests, indicating that the anchorage length of 160mm was sufficient to prevent bond failure. Tendon temperatures recorded in the fire exposed spans during these tests indicated that the tensile strength of the CFRP was maintained at temperatures above 330°C. Full details of these tests will be presented elsewhere [4]. Nevertheless, it appears that a fire resistance of 30min is achievable for these slabs when a concrete cover of 35 mm or more is used and a 160mm cold anchorage is provided.

TENSILE & BOND STRENGTH AT ELEVATED TEMPERATURE

The tensile strength of both steel and CFRP prestressing tendons can be expected to be reduced at elevated temperatures. For cold-drawn steel prestressing
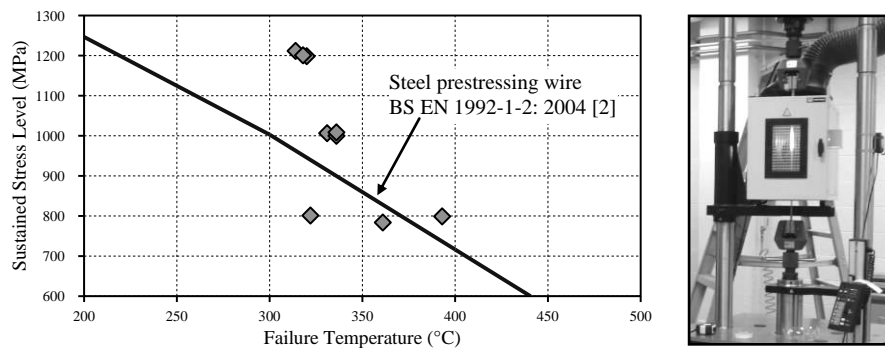
Figure 3. Results of transient tensile tests on CFRP tendons at high temperature.

tendons the relationship between temperature and tensile strength is relatively well established and is available, for example, in the Eurocodes [2]. The effects of elevated temperature on the specific strength of the CFRP tendons used in the current study are not known. Thus, a series of nine transient high temperature tensile tests was performed on the CFRP tendons at sustained stress levels between 800MPa and 1200MPa (a realistic stress range for pretensioning applications). The tendons were stressed to sustained loads of approximately 800, 1000, or 1200MPa and then heated, at 10°C/min, to failure. The anchorages were protected from high temperature. The results of these tests are given in Figure 3, along with the yield stress reduction curve recommended by the Eurocode [2] for Class A cold-drawn prestressing steel. It is evident that the performance of the CFRP tendons is similar to steel prestressing in terms of retention of tensile strength at elevated temperature, and that CFRP tendons stressed to 1000MPa can be expected to fail at about 330°C.

Past research on the bond performance of FRP and steel reinforcing bars at high temperatures has often been performed by heating a pullout sample without any load applied and then loading it to failure once a target temperature is reached [5, 6]. This is not representative of conditions in a prestressed concrete structure in a real fire, where materials are heated under sustained load (hence the transient procedure used for the tensile tests described above). Furthermore, in pretensioned prestressed elements there is considerable bond strength demand throughout the structure's lifetime needed to develop and maintain the required prestressing forces. It seems likely that sustained stresses are likely to be much more important than short terms loads for CFRP tendons at elevated temperature, since the tendon's epoxy matrix may undergo considerable creep deformation under sustained load at elevated temperature. Thus, in the current research bond pullout testing has been performed by applying a sustained load to a predefined bonded length and then heating the bond line at a prescribed rate until failure occurs; this is more representative of the state of stress within a real FRP prestressed structural element during a fire. Although the stress conditions in a reinforced concrete element differ greatly from those produced in a pullout test [7], this type of test has been widely adopted in the assessment of bond performance of steel reinforcing bars in concrete. The pullout test setup adopted in the current study is shown in Figure 4.

A total of 18 pullout specimens were tested, nine with CFRP tendons and nine with steel prestressing wire. Round, sand-coated unidirectional CFRP tendons supplied by SACAC, Switzerland were used in the pullout tests (identical to those used in the large scale tests described previously). The tendons' design ultimate
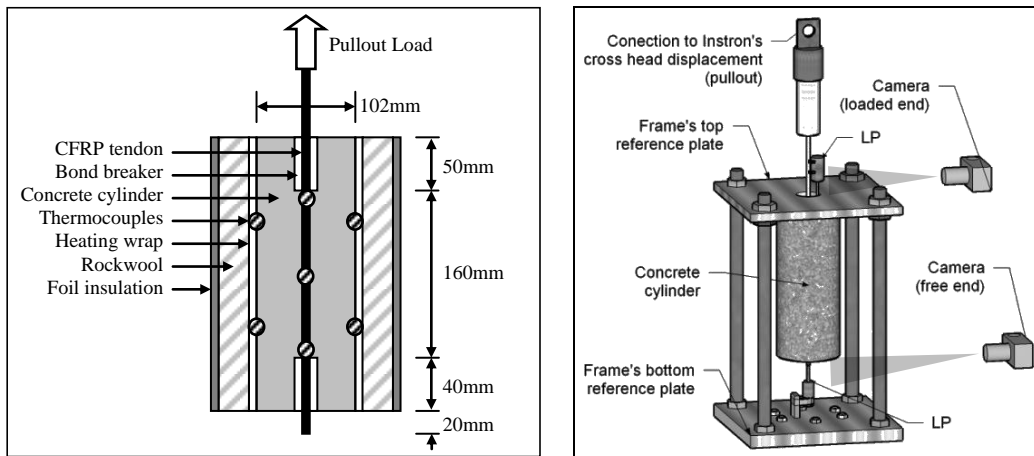
Figure 4. Schematic of pullout test specimens and experimental setup for pullout tests.

tensile strength is 2000MPa, with an elastic modulus of 150GPa, a linear-elastic tensile stress-strain response to failure, and an ultimate strain of 1.33%. The maximum prestress level for the CFRP tendons is governed by anchorage issues during stressing and is currently 1200MPa. To compare the bond performance of the CFRP tendons against conventional steel prestressing wire, 6mm Ø steel wire produced by NEDRI Spanstaal BV, specifically for prestressing applications, was also studied (identical to that used in Slab 40 in Table I). The wire's design yield strength is 1592MPa (0.2% offset) and its modulus is 210GPa.

The relatively high cost of CFRP tendons necessitates a correspondingly high quality of concrete. A high performance self-consolidating concrete (HPSCC) was designed for a strength of 90-100MPa at 28 days. 2kg/m3 of short PP fibres were included in the concrete to simulate the concrete mix used in the fire tests.

The pullout samples were 102mm Ø concrete cylinders with total length of 250mm. The moulds were designed in such way that the tendons/wires were placed vertically and axisymmetrically. The tendons/wires were debonded over a portion of their embedded length at the top and bottom of the cylinders to: (1) allow for the bonded length to be equal to the prestress transfer length of the CFRP prestressing tendons (160mm); (2) prevent localized artificial confinement of the bonded length due to compressive load on the concrete at the loaded end; and (3) promote an axisymmetric heat transfer condition along the bonded length and assure a uniform bond line temperature. Special consideration was given to the accuracy of the measurements of bar slip at both the loaded and free ends of the specimens. A unique digital image correlation analysis was used to measure slip [8] (Figure 4).

The behaviour of the specimens during heating turned out to be far more complex than expected, resulting in three distinct types of bond tests:
1. Regular pullout test (RPOT): Specimens were loaded at room temperature under displacement control until pullout failure occurred.
2. Regular prestress and heated pullout test (Regular PHPOT): Specimens were loaded at room temperature to a prescribed load under load control and then heated under sustained load until pullout occurred.
3. Extended PHPOT: Identical to regular PHPOTs except that bond stress was insufficient to produce failure of the bond interface on heating. After 230mins at steady state temperature the load was increased until failure.

The prescribed sustained loads were taken as increasing percentages of the average strength of RPOT tests: for CFRP tendons these were 15, 30, 38, 45, 53, 60 and 68% and for steel prestressing wires they were 37, 46 and 55%.

Steel Pullout Test Results

A summary of the test results for all of the pullout tests is presented in Table II. Steel RPOT samples failed by tensile rupture of the steel wire at the loaded end (i.e. the bond failure capacity was greater than the tensile failure capacity of the wire). The average RPOT failure load of $\tau_{ave, s}$ = 16.6MPa was used to define subsequent test loads.

Extended PHPOTs executed on steel pullout samples were stressed to 37% and 46% of $\tau_{ave, s}$. Under $0.37\tau_{ave, s}$ the samples were heated to a bond line temperature of about 162°C and were then loaded to failure of the bond interface, which occurred at an average bond stress of 12.6MPa. Under $0.46\tau_{ave, s}$ the samples were heated to about 166°C and were then loaded to failure of the bond interface, which occurred at an average bond stress of 13.2MPa.

Regular PHPOTs on steel tendons were at a sustained stress of $0.55\tau_{ave, s}$. In these cases failure occurred by transverse splitting failure of the concrete cylinder in less than six minutes of heating when the average bond stress was being maintained at 9.1MPa and the bond line temperature had not yet increased. Failure of these tests was likely the result of the concrete's tensile strength being exceeded due to the summation of the mechanical stresses produced by the pullout conditions and the thermal stresses produced by the steep thermal gradient in the concrete.

The results show that the bond performance of steel prestressing wire in concrete is influenced by a number of parameters, notably including transverse splitting cracking of the concrete. However, on the basis of the current results it appears that the bond between the steel wires and the concrete was reduced by up to 30% at a temperature of 166°C. Considerable additional research is needed before meaningful conclusions can be drawn. Such research appears to be warranted.

TABLE II. PULLOUT TEST PROGRAMME AND SELECTED RESULTS

Test	Prestressing Condition			Failure Condition					Residual bond strength (MPa)
	Bond stress (MPa)	Tensile stress (MPa)	Pullout load (kN)	Bond stress (MPa)	Tensile stress (MPa)	Pullout load (kN)	Temperature Bar (°C)	Blanket (°C)	
CFRP RPOT	-	-	-	5.3	633	14.5	21	24	4.1
CFRP RPOT	-	-	-	4.4	524	12.0	20	24	2.9
CFRP 15%	0.7	87	2.0	3.9	461	10.6	166	182	2.3
CFRP 30%	1.5	175	4.0	5.1	601	13.8	166	182	2.2
CFRP 38%	1.8	218	5.0	4.3	513	11.8	164	185	2.3
CFRP 45%	2.2	262	6.0	-	-	-	109	169	0.65
CFRP 53%	2.6	306	7.0	-	-	-	102	155	0.89
CFRP 60%	3.0	349	8.0	-	-	-	95	148	0.92
CFRP 68%	3.3	393	9.0	-	-	-	21	76	-
Steel RPOT	-	-	-	16.6	1774	50.2	22	24	-
Steel RPOT	-	-	-	16.6	1772	50.1	21	24	-
Steel 37%	6.1	648	18.3	11.8	1257	35.5	164	184	-
Steel 37%	6.1	648	18.3	13.5	1434	40.6	160	178	-
Steel 46%	7.6	810	22.9	12.8	1365	38.6	170	192	-
Steel 46%	7.6	810	22.9	13.7	1460	41.3	162	179	-
Steel 55%	9.1	972	27.5	-	-	-	31	155	-
Steel 55%	9.1	972	27.5	-	-	-	25	118	-
Steel 55%	9.1	972	27.5	-	-	-	25	105	-

CFRP Pullout Test Results

CFRP RPOT samples failed by slipping at the bond interface between the sand coating on the CFRP tendons and the tendon. After failure occurred, pullout continued at a constant slip rate and a residual bond strength capacity of 66-77% of the peak load was measured. The average RPOT failure load was $\tau_{ave, f} = 4.9$MPa.

Extended CFRP PHPOT samples were prestressed to 15, 30 and 38% of $\tau_{ave, f}$. In all cases the samples were heated to a bond line temperature of about 170°C and were then loaded to failure, which occurred at an average bond stress of about 4.4MPa. Again, after failure ocurred pullout continued and a residual bond strength of 44-58% was measured. The residual bond strengths observed in Extended PHPOTs on CFRP were consistently larger than the bond stresses at which the bond interface failed *during* heating in Regular PHPOTs at higher stress levels. This suggests a time dependency of bond strength related to the duration of loading at a given stress level, likely related to the time-temperature-stress dependent creep properties of the polymer coating at the surface of the CFRP tendons.

Regular PHPOTs on CFRP were prestressed to 45, 53, and 60% of $\tau_{ave, f}$. These samples failed during heating with decreasing failure temperatures observed as the sustained bond stress level increased. Figure 5 shows a plot of loaded end slip versus bond line temperature for these three tests, where the correlation between bond stress, temperature, and slip initiation is clear. For regular PHPOTs, pullout continued after the initial bond failure as the loading frame attempted to maintain the load, and a residual strength of about 29-35% of the bond stress at which the tendons were prestressed was observed. The Regular PHPOTs on CFRP at 68% of $\tau_{ave, f}$ failed soon after heating began. This was likely initiated by a small slip produced by longitudinal thermal expansion of the concrete during initial heating.

On the basis of the pullout tests on CFRP tendons, it appears that the bond between CFRP tendons and concrete is damaged by exposure to temperatures in the range of 90-120°C. Significantly, the glass transition temperature (T_g) for the epoxy matrix used in the fabrication of these tendons was measured at EMPA by DMTA as 125°C (as T_g-onset, the temperature above which the polymer softens and suffers a reduction in strength and stiffness of several orders of magnitude). This idea is supported by previous research studying the bond strength of Glass FRP bars used as non prestressed reinforcement for concrete structures [1]. However, considerable additional testing is needed to fully understand the complex interactions between time, stress, temperature, and strength that eventually lead to bond failure.
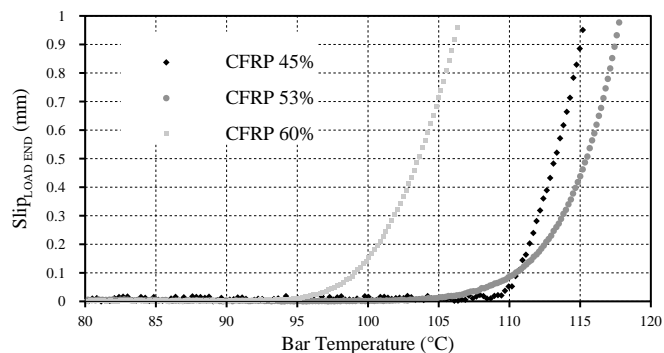
Figure 5. Loaded end slip versus bar temperature for Regular PHPOTs on CFRP tendons.

SUMMARY & CONCLUSIONS

Several conclusions can be drawn on the basis of the data presented herein:
- The HPSCC concrete used in these elements experienced considerable spalling, which eventually led to structural failure during large scale furnace tests. This was despite the concrete containing 2kg/m^3 of short PP fibres. Additional research to mitigate spalling is badly needed. When CFRP anchorage is maintained, CFRP prestressed concrete can perform as well or better than steel prestressed concrete in fire, achieving fire resistances of 30mins or more.
- Loss of bond (anchorage) is potentially a governing factor for CFRP prestressing tendons in concrete at elevated temperatures. It appears that temperatures in range of the T_g of the tendon's epoxy matrix (used also for the bond enhancing sand coating) are critical for maintaining anchorage.
- For the CFRP tendons used in the current study, greater than 50% of the design ultimate tensile strength was maintained at temperatures exceeding 330°C. This is similar to values widely quoted for cold-drawn steel prestressing but can only be relied on if a cold anchorage zone is provided.
- Many aspects of bond performance at elevated temperature (for both FRP tendons and steel prestressing wires) remain poorly understood and require additional investigation.

ACKNOWLEDGEMENTS

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