EXPERIMENTAL FIRE BEHAVIOUR OF PRECAST CFRP PRETENSIONED HPSCC SLABS

Citation for published version:
Maluk, C, Terrasi, GP, Bisby, L, Stutz, A & Hugi, E 2014, 'EXPERIMENTAL FIRE BEHAVIOUR OF PRECAST CFRP PRETENSIONED HPSCC SLABS'. in 7th international Conference on Fiber Reinforced Polymer (FRP) Composites in Civil Engineering (CICE 2014). Vancouver.

Document Version:
Author final version (often known as postprint)

Published In:
7th international Conference on Fiber Reinforced Polymer (FRP) Composites in Civil Engineering (CICE 2014)

EXPERIMENTAL FIRE BEHAVIOUR OF PRECAST CFRP PRETENSIONED HPSCC SLABS

Cristian MALUK
PhD Candidate (Fire and Structures), The University of Edinburgh, UK
c.maluk@ed.ac.uk

Giovanni P. TERRASI
Head, Mechanical Systems Engineering Laboratory, EMPA, Switzerland
giovanni.terrasi@empa.ch

Luke A. BISBY
Arup Professor of Fire and Structures, The University of Edinburgh, UK
luke.bisby@ed.ac.uk

Alex STUTZ
Research Engineer, Mechanical Systems Engineering Laboratory, EMPA, Switzerland
alex.stutz@empa.ch

Erich HUGI
Head, Fire Resistance Testing Laboratory, EMPA, Switzerland
erich.hugi@empa.ch

ABSTRACT: Optimized concrete elements have been developed using high-performance, self-consolidating, fibre-reinforced concrete (HPSCC) reinforced with high-strength, lightweight, non-corroding pre-stressed carbon fibre reinforced plastic tendons. This new type of thin-walled precast carbon FRP (CFRP) pretensioned HPSCC slab has been used in building façades and is under consideration for a range of other applications in buildings. However, it is well known that the bond strength between both steel and FRP reinforcements and concrete deteriorates at elevated temperature, and that HPSCC has a comparatively high risk of heat-induced concrete spalling. Reductions in bond strength, the occurrence of heat-induced concrete spalling, and their impacts on the load-bearing capacity of precast CFRP pretensioned HPSCC slabs during fire are not well understood. This paper gives insights into the fire behaviour of precast CFRP pretensioned HPSCC slabs by evaluating the influence of concrete mixture, slab thickness and the presence of local reinforcement (CFRP grids) in the prestress transfer zones. Selected results and analysis of a large scale fire resistance test on five HPSCC slabs are presented in this paper. It is shown that the occurrence of heat-induced concrete spalling resulted in sudden failure of the specimens, and that in cases where no spalling occurred failure was due to loss of bond strength.

1. Introduction

Driven by the need for more durable and sustainable concrete structures; careful selection, design, and optimization of both the concrete mixes and the reinforcing materials used are now commonplace within the precast concrete industry. Concrete elements incorporating high-performance, self-consolidating concrete (HPSCC) and novel reinforcing and prestressing materials, such as carbon-fiber-reinforced polymer (CFRP) tendons are now being produced. An example of this is the use of precast CFRP pretensioned HPSCC members for façade beams and columns in building envelopes (Terrasi et al., 2012). The combination of CFRP and HPSCC along with an appropriate interface between them (i.e. an epoxy-bonded sand-coating on the CFRP) allow minimisation of the weight of prestressed elements by reducing concrete cover and wall thickness while providing excellent serviceability (corrosion resistance, high stiffness and fatigue strength). However, the performance of these HPSCC precast elements in fire is not well known (Maluk et al. 2011) and must be better understood before they can be used with confidence in load-bearing applications where structural fire resistance is required.

It is widely perceived that FRP-reinforced concrete elements have lower fire resistance than equivalent conventional steel-reinforced elements. However, comparatively few large-scale fire tests under load have ever been performed on FRP-reinforced or prestressed concrete elements; little is known about the true response of such elements in standard fire resistance tests. A limited number of fire resistance tests on FRP-reinforced or prestressed concrete elements have been reported in the literature; unfortunately, however necessarily given the diversity of available FRP reinforcing or prestressing products, each study has used a specific FRP material thus making it difficult to draw generalized conclusions. To understand the relative importance of the foregoing issues (and others such as heat-induced concrete spalling and reductions in bond strength) for CFRP prestressed HPSCC concrete elements, a large scale fire resistance test on five loaded CFRP prestressed HPSCC slabs was performed.

The test specimens used a high performance, self-consolidating concrete (HPSCC) of strength class C90 (minimum 150mm cube strength after 28 days of 90 MPa). Detailed information on the HPSCC mixtures is given in Table 1. Polypropylene (PP) monofilament fibres 3 and 6 mm long (32 µm cross-section diameter) were included for mixes 342 and 142, respectively, in an attempt to avoid explosive heat-induced concrete spalling. PP fibre doses of 1.2 and 2.0 kg per cubic metre of concrete were included in mixes 142 and 342, respectively. After casting, the test specimens were kept under a polyethylene sheet for 2 days and then left to cure under ambient conditions until testing at an age of 5.5 months. Round CFRP tendons, 5.4 mm diameter (pultruded and quartz sand-coated) were used for pretensioned prestressed reinforcement. The tendons have a carbon fiber volume fraction of 62%, a nominal tensile strength of 2000 MPa, an elastic modulus of 150 GPa, and an ultimate strain of 1.33%. The low density, excellent stress-corrosion resistance, and low creep and relaxation (Uomoto, 2001) of CFRP are well known, making unidirectional CFRP tendons particularly suitable as prestressed reinforcement for concrete (Burgoyne, 1997).

2. Aim of the Study

Results from an earlier set of similar fire resistance tests performed between 2009 and 2010 showed that the failure mode of precast CFRP pretensioned HPSCC slabs is highly influenced by accumulated heat-induced concrete spalling (Terrasi et al., 2012). For the few tested slabs for which no spalling occurred during these prior tests, early failure (about 30 minutes from the start of the test) was driven by loss of bond between the tendons and the concrete within the prestress transfer zone induced by the appearance of longitudinal splitting cracks and/or degradation of bond strength due to softening of the tendons' epoxy-bonded sand coating (Terrasi et al., 2012).

The current study aimed to experimentally assess specific aspects of the fire resistance design of precast CFRP pretensioned HPSCC slabs. Issues of anchorage of the CFRP tendons were of primary interest; this is the reason for inclusion of CFRP grids within the specimens' anchorage zones and of various doses of PP fibres for spalling mitigation (see below). Five large scale specimens were tested simultaneously with fire exposure from below following a standard cellulosic time-temperature curve (CEN, 2012). The influence of the following design parameters was evaluated:

- concrete mixture and PP fibre dose to prevent spalling (mix 342 and 142) (refer to Table 1);
- overall slab thickness (45 and 60 mm), and concrete cover to the concentric prestressing; and
- the presence of CFRP grids to prevent splitting cracking within the prestress transfer zone.

Table 1 – Concrete mix compositions and slump flow measurements.

Mix Label	Water/ (cement + microsilica + fly ash)	Cement (20% microsilica)	Fly ash	Limestone aggregate (0-8 mm)	Super-plasticizer	Dose of PP fibres	Slump flow (CEN, 2010)
	[-]	[kg/m^3]	[kg/m^3]	[kg/m^3]	[% of cement]	[kg/m3]	[mm]
142	0.31	469.0	120.0	1668.9	1.75 %	1.2	785
342	0.31	474.5	120.0	1675.2	1.69 %	2.0	830

3. Experimental Program

Since no clear influence of an unheated overhang length in excess of 160 mm was seen in fire resistance tests performed between 2009 and 2010 (Terrasi et al., 2012), it was decided to keep a constant unheated overhang length of 195 mm for all slabs. The overall length of the slabs was 3355 mm with an exposed length of 2960 mm. Mechanical service loads were applied in a simply-supported four-point bending arrangement, with end supports (rollers) placed 155 mm from the slabs' ends.

All tendons were located at the slabs' mid-depth with a tolerance of ±2 mm to obtain a nominally concentric prestressing. Slabs were 45 or 60 mm thick (see Table 2), corresponding to clear concrete covers to the prestressed CFRP reinforcement of 19.5 mm 27 mm respectively, and 200 mm wide. Lateral concrete cover at the slab edges was 22 mm in all cases with tendon-to-tendon clear spacing of 44 mm. Slabs were prestressed with four CFRP tendons identical to those used for the slabs tested between 2009 and 2010 (Terrasi et al., 2012) and stressed initial prestress of 1,000 MPa.

Slabs for which no spalling occurred during prior fire resistance tests performed between 2009 and 2010 suffered from relatively early failure driven by loss of tendon bond strength in the anchorage zone. CFRP grids were therefore placed at the prestress transfer zone of some slabs (see Table 2), both above and below the prestressed CFRP tendons, in an attempt to improve the bond strength of some of the tested slabs by preventing the splitting cracking that had been observed in the prior tests. These CFRP grids had a transversal and longitudinal spacing of 46 and 41 mm respectively with a design tensile elastic modulus of elasticity was 234 GPa in both directions.

The applied mechanical service load (simply-supported four-point bending) during the test was defined to to achieve decompression at the tension fibre within the constant moment region; this corresponds to a typical design service load condition for a CFRP prestressed façade element in a real building (Terrasi et al., 2012). The applied load was calculated considering the age dependency of the prestressing losses due to elastic shortening, shrinkage and creep effects, resulting in applied loads (per point) of 25.0 and 38.4 kg for slabs 45 and 60 mm thick respectively. It is noteworthy that the sides of the slabs were fully insulated during testing so that thermal exposure was on their bottom surfaces only. The mechanical and thermal response of the tested slabs was recorded with thermocouples inside the furnace and embedded in the slabs (through-thickness at midspan and within the prestress transfer zone) and displacement gauges measuring midspan vertical displacement and draw-in of the CFRP tendons.

Table 2 – Test matrix for specimens for the large-scale fire resistance test.

Slab #	Concrete Mixture	Slab depth [mm]	CFRP grid	Time-to-failure	Failure mechanism
1	342	45	No	42' 01''	Loss of bond
2	342	45	Yes	12' 37''	Spalling
3	342	60	Yes	22' 10''	Spalling
4	142	45	Yes	50' 27''	Loss of bond
5	142	60	Yes	93' 04''	Loss of bond

4. Results and Analysis

The main findings of this study are related to the occurrence of heat-induced concrete spalling and to loss of bond strength of the precast CFRP pretensioned HPSCC slabs. Thus, the following sections briefly present the results and analysis associated with these two heat-induced phenomena.

4.1. Heat-induced Concrete Spalling

Failure of slabs #2 and #3, both cast from the same concrete batch (mix 342), was driven by the occurrence of a single explosive heat-induced concrete spalling event at minute 12 and 22, respectively (refer to Table 2). Immediately after spalling, the slabs failed suddenly. A snapshot from the video sequence recorded during testing shows the exact moment at which spalling occurred for Slab #3 (Figure

1) and shows the violence with which pieces of concrete were expelled from the furnace. Slab #2 suffered early failure at minute 12 due to a single explosive spalling event while Slab #1, which was virtually identical to Slab #2, failed due to loss of bond strength at minute 42 without significant spalling being observed (refer to Table 2). Whilst a full analysis of the reasons for this cannot be included in the current paper, through-thickness temperature measurements showed a more rapid temperature increase within Slab #2 compared with Slab #1 (both were 45 mm thick); this is thought the be associated with the occurrence of spalling and due to slight non-uniformity of thermal exposure within the furnace. Likewise, Slab #3, which also suffered from spalling, showed more rapid temperature increase at midspan.

Slabs #4 and #5, both cast from the same batch (mix 142), showed a similarly rapid through-thickness temperature increases at midspan to those measured for slabs #2 and #3 but did not experience spalling. This suggests that for an equivalent through-thickness temperature increase (i.e. thermal exposure), the risk of heat-induced concrete spalling for slabs cast with mix 142 is lower than for slabs casted with mix 342, and further suggesting that the shorter 6 mm PP fibres are more effective in spalling mitigation than the 3 mm fibres, even at a considerably lower dose (1.2 versus 2.0 kg/m^3).

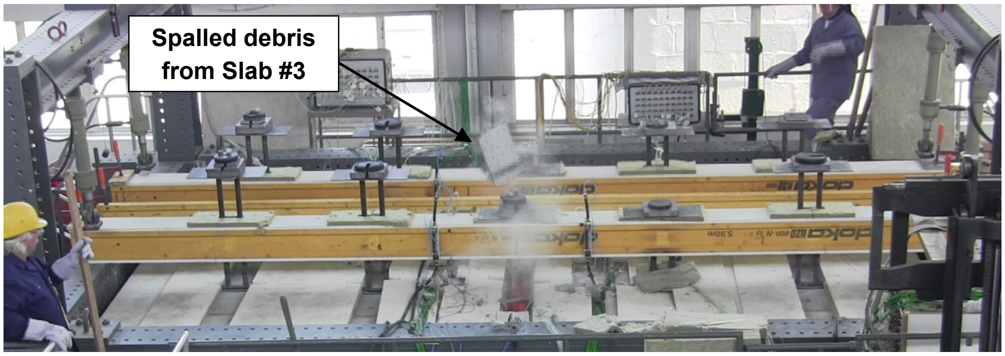

Fig. 1 – Testing Furnace, Explosive Spalling and Imminent Failure of Slab #3 at 22’ 10’’.

4.2. Loss of Bond Strength

The failure mechanism of slabs #1, #4, and #5 was driven by loss of bond strength within the prestress transfer zone which resulted in structural failure at minute 42, 50, and 93, respectively (refer to Table 2). Loss of bond strength for CFRP prestressed HPSCC structural elements in fire resistance tests has previously been shown to be driven by thermo-mechanical bond degradation, thermo-mechanically induced longitudinal splitting cracks, or a combination of both (Terrasi et al., 2012). Figure 2 shows midspan deflection versus heating time for slabs which failed due loss of bond, as well as photographic evidence of the first observed longitudinal splitting cracks at the slabs’ unexposed surfaces. Midspan deflection measurements showed an increase in the rate of deflection at the time when these splitting cracks were observed, as shown in Figure 2. The midspan deflection at an early stage of the test is governed by the well known thermal bowing of the test specimens, however the observed increase in the rate of midspan deflection appears to be linked to degradation of the bond strength and the observed splitting cracking.

To analyse the loss of bond strength and its influence on the failure mechanism observed for slabs #1, #4, and #5, the temperature at the lower edge of a central CFRP tendon measured at midspan and at 200 mm from the end of the slab (around the end of the unheated overhang) was measured. For all slabs an increase in the rate of midspan deflection was observed at the moment that the temperature at the lower edge of a central CFRP at midspan was in the range of 300°C. The temperature at this moment 200 mm from the end of the slab was only around 70°C for the 45 mm thick slabs (slabs #1 and #4), and 120°C for the 60 mm thick slab (Slab #5). It is noteworthy that the thermocouples at the lower edge of the CFRP tendon measure the temperature of the concrete at the surface of the tendon rather than the temperature inside the tendon. At the moment that the first longitudinal splitting crack at the unexposed surface was observed, the temperature at the lower edge of a centre CFRP tendon was between 320-390°C. thermo-mechanical modelling is currently underway in an effort to understand the significance of these temperatures for splitting cracking.

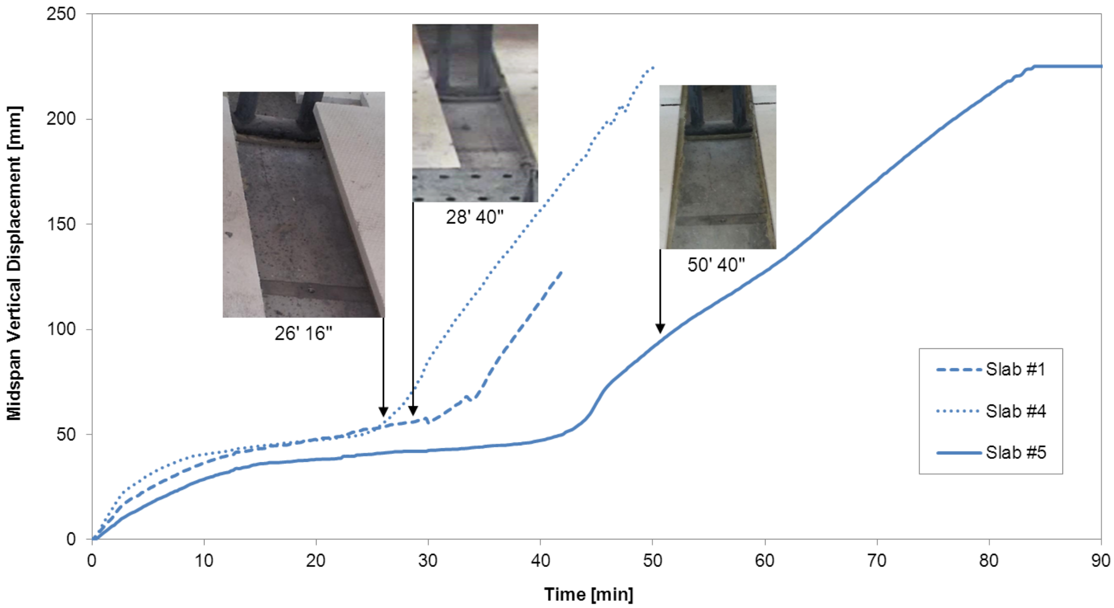

Fig. 2 – Midspan Deflection Measurements and Photographic Evidence of the First Observed Longitudinal Splitting Crack at the Unexposed Surface for Slabs #1, #4, and #5 (refer to Table 2).

Slab #4 (45 mm thick) and Slab #5 (60 mm thick), both of which had CFRP grids in their prestress transfer zones, failed when midspan temperature at the lower edge of a centre CFRP tendon was about 600°C. Slab #1, which had no CFRP grids, failed when midspan temperature at the lower edge of a centre CFRP tendon was about 450°C. This indicates a possible increase in bond strength at elevated temperature provided by the presence of CFRP grids at the prestress transfer zones. Figure 3 shows a bottom view (i.e. view from inside the furnace) of Slab #4 at the moment of failure.

Fig. 3 – Failure of Slab #4 at 50’ 27’’ Due to Loss of Bond Strength Capacity (refer to Table 2).

5. Conclusions

The following conclusions can be drawn on the basis of the test results briefly described in this paper:

- Comparison of the temperature measurements recorded for tested slabs #1, #2, and #3 evidenced the influence of time-history of through-thickness temperature in the occurrence of heat-induced concrete spalling. Although specimens were tested simultaneously, and exposed to the same time-history of temperature inside the furnace (CEN, 2012) diverse time time-history of through-thickness temperature was recorded for the five slabs tested. While heat-induced concrete spalling is traditionally recognized as a stochastic phenomenon, thermal exposure (i.e. time-history of through-thickness temperature) is rarely analysed in past and current studies; it appears to have played a role in the tests described in this paper.
- After a thorough assessment of the thermal exposure experienced by the five tested slabs (however not fully presented in this brief paper), test results showed that the risk of heat-induced concrete spalling for slabs casted with mix 142 (1.2 kg/m^3) is lower than for slabs casted with mix 342 (2.0 kg/m^3). This may be due to the longer 6 mm length of the PP fibres used in this mix. It is noteworthy

that modern design guidelines (e.g. CEN, 2004), solely prescribe the inclusion of 2 kg/m^3 of monofilament PP fibres as the required method to 'avoid' the occurrence of heat-induced concrete spalling, with no particular length of PP fibres being specified.

- Whilst during this study no attempt was made to individually identify the influence of thermo-mechanical bond degradation versus thermo-mechanically induced longitudinal splitting cracks in the loss of bond strength of precast CFRP pretensioned HPSCC slabs tested, test results confirmed that at a combination of both mechanisms is relevant to some degree.
- Irrespective of all design parameters assessed in this study, loss of bond strength started when the temperature at the lower edge of a central CFRP tendon at midspan was in the range of 300°C. This demonstrates the potential triviality of prescribing an unheated overhang length for the fire resistance design of precast CFRP pretensioned HPSCC slabs (Terrasi et al., 2012). The precise reasons for this are not yet known and thermo-mechanical modelling is currently underway to inform this issue. The authors suspect that a combination of longitudinal thermal conduction (along the tendon) and differential thermal expansion (transverse to the tendon) is responsible for this observation.
- The presence of CFRP grids within the prestress transfer zones showed an increase in the time-to-failure of the tested slabs which failed due to loss of bond strength. While slabs with CFRP grids failed when midspan temperature at the lower edge of a centre CFRP tendon was about 600°C, this occurred at 450°C for the slab without CFRP grids in the prestress transfer zone.

6. Acknowledgements

The authors would like to thank SACAC Schleuderbetonwerk AG, EMPA, and The University of Edinburgh, and in particular to Lukas Bäurle, Thomas Hofer, Marcel Steiner, Angelo Demont, and Mauricio Fuentes. This research was partially funded by EMPA, the BRE Centre for Fire Safety Engineering at The University of Edinburgh, and The Royal Society of Edinburgh. Arup and the Royal Academy of Engineering are gratefully acknowledged for their ongoing support of Luke Bisby.

7. References

BURGOYNE CJ, "Rational Use of Advanced Composites in Concrete", *Proceedings of the 3th International Symposium of Non-Metallic (FRP) Reinforcement for Concrete Structures (FRPRCS-3)*, Sapporo, 14-16 October 1997, pp. 75-88.

CEN, "Design of Concrete Structures, Part 1.2: General Rules – Structural Fire Design (EN 1992-1-2)", *European Committee for Standardization*, 2004, 100pp.

CEN, "Testing Fresh Concrete, Part 8: Self-compacting Concrete – Slump-flow Test (EN 12350-8)", *European Committee for Standardization*, 2010, 14pp.

CEN, "Fire Resistance Tests, Part 1: General Requirements (EN 1363-1)", *European Committee for Standardization*, 2012, 56pp.

MALUK C, BISBY L, TERRASI G, and GREEN M, "Bond Strength Degradation for CFRP and Steel Reinforcing Bars in Concrete at Elevated Temperature", *Innovations in Fire Design of Concrete Structures (ACI SP 279), American Concrete Institute*, 2011, 36pp.

MALUK C, BISBY L, and TERRASI G, "Effects of Polypropylene Fibre Type on Occurrence of Heat-induced Concrete Spalling", *Proceedings of the 3rd International Workshop Concrete Spalling due to Fire Exposure*, September 2013, 8pp.

SMITH K and ATKINSON T. "Factors to Consider in Using PP Fibres in Concrete to Provide Explosive Spalling Resistance in the Event of a Fire". *Shotcrete – Elements of a System*, 2010, pp. 261–268.

TERRASI G, BISBY L, BARZBEZAT M, AFFOLTER C, and HUGI E, "Fire Behavior of Thin CFRP Pretensioned High-Strength Concrete Slabs, *Journal of Composites for Construction*, Vol. 16, No. 4, August 2012, pp. 381-394.

UOMOTO T, "Durability Considerations of FRP Reinforcement", *Proceedings of the 5th International Symposium of Non-Metallic (FRP) Reinforcement for Concrete Structures (FRPRCS-5)*, Cambridge, 16-18 July 2001, pp. 17-32.