PROJECT: Fire Behaviour of Self-Prestressed Concrete Slabs Reinforced with Carbon Fibre Reinforced Polymer Tendons

Joint PhD Thesis project at The University of Edinburgh and Empa

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Background:

Novel precast concrete elements were developed by Empa in 2013-2015, utilizing high-strength, self-consolidating concrete (fire resistant or expanding SCC) in which prestress is introduced by high-strength and modulus, lightweight, and non-corroding carbon fiber reinforced polymer tendons (UHM CFRP tendons). These precast FRP pretensioned HPSCC panels are intended as e.g. load-bearing panels for concrete building facades [Terrasi, G.P., J. of Materials Science Research, Vol. 2, No. 1, 2013]. It is known that the bond strength between both steel and FRP reinforcing tendons and concrete deteriorates at elevated temperature and that high strength concrete tends to an explosive spalling failure mode when subjected to a fire [Terrasi, G.P., Bisby, L., Barbezat, M., Affolter, C., Hugi, E., J. Comp. Constr. 2012.16:381-394.]. The bond strength reductions in fire, their impacts on the load-bearing capacity of prestressed concrete structures, and the spalling behavior of high-strength concrete remain poorly understood and are the researched topics in this project.

Objectives:

The goals of this thesis are to improve the understanding of the fire behavior of thin-walled CFRP self-prestressed SCC slabs and to define design criteria to reach enough fire resistance for their application in building interiors (e.g. more than 60 minutes of exposure to an ISO 834 design fire scenario).

Methods:

The above objectives require the development of a spalling resistant expanding concrete. Accordingly, the first stage of the proposed thesis will be dedicated to understanding the spalling mechanisms of the current Empa expanding SCC and the subsequent development of a spalling resistant expanding SCC of strength class C75 or higher. Initial experiments in August 2015 (RAEng DVF award to Bisby/Terrasi) showed that Empa's current expanding SCC spalls rapidly when centrally precompressed and subjected to an incident radiant heat flux simulating an ISO 834 fire (a layer-wise spalling begins after approx. 10 minutes). Therefore new spalling-resistant SCC mix designs will be studied using different additives (e.g. polypropylene microfibers, super absorbent polymer spheres, and combinations thereof, see [Lura and Terrasi, Cement and Concrete Composites. 2014 .49: 36-42]) and characterized by first concrete spalling evaluation tests in a simpler Empa apparatus [Weber B. et al., 3rd Int. Workshop on Concrete Spalling due to Fire Exposure, Paris, MATEC Web of Conf 6, 03004 (2013)]. Thereafter, in this first project stage, a series of 45 mm thick, 200 m wide, and 0.5 m long self prestressed SCC slabs will be investigated for spalling. The slabs will be produced by· the PhD student during his/her first Empa stay and will be prestressed by two sand coated UHM CFRP reinforcing tendons. Control slabs that are conventionally prestressed by the same UHM CFRP tendons will be produced using a spalling resistant SCC, see [Lura and Terrasi, Cement and Concrete Composites. 2014 .49: 36-42]. An experimental fire test series on thin-walled slabs will then be performed in The University of Edinburgh's new H-TRIS testing system, by exposing them to a radiant heat flux equivalent to:

- an ISO 834 furnace test (in this second phase of the spalling resistant material development)
- a hydrocarbon fire (after spalling resistance in an ISO 834 fire scenario has been achieved)
- a smouldering fire (after spalling resistance in an ISO 834 fire scenario has been achieved)

The mechanical loading condition of the 0.5 m long slabs will be given by the internal prestress (2 CFRP tendons with diameter of 5.3 mm, originally stressed through SCC expansion at approximately 1000 MPa) without additional external loading; therefore the slabs will be supported by an unloaded frame. Prestress will be measured by bonding strain gauges on the high modulus CFRP tendons.

The University of Edinburgh's novel H-TRIS fire test method has already been successfully used in the recent past for studying the propensity for heat-induced spalling of conventional high strength seif compacting concrete [Maluk, C., Bisby, L., Terrasi, G.P., Constr. Build. Mats 2015]. Rather than taking the traditional approach of controlling the gas temperature inside a fire testing furnace, the H-TRIS test method permits direct and independent control of the thermal boundary condition; it does this by controlling the time-history of incident radiant heat flux, at the exposed surface of a test specimen [Maluk, C. , PhD thesis at The University of Edinburgh, 2014]. H-TRIS uses a mobile array of propane-fired radiant panels, along with a mechanical linear motion system and a rotary stepper motor (see Figure 1 below). The linear motion system can be programed to actively control the relative position between the radiant panels and the exposed surface of a test specimen, thus varying incident heat flux at the test sample.

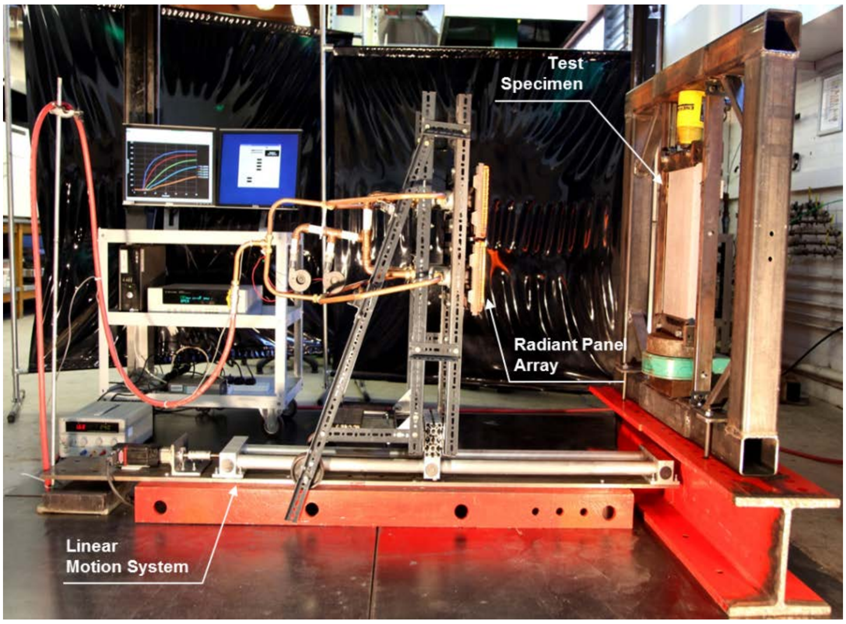

Figure 1: The University of Edinburgh's H-TRIS testing system [Maluk, C., PhD thesis, 2014 Supervisor Professor Luke Bisby]

The second stage will commence after satisfactory spalling resistance has been achieved by the used self compacting concretes (either the novel expanding one and/or the one described in [Lura and Terrasi, Cement and Concrete Composites. 2014 .49: 36-42]. In this phase experiments will be designed to understand the high temperature bond behavior between the UHM CFRP tendons and the novel prestressed SCCs. The experiments will be again performed in the novel H-TRIS fire testing facility of the University of Edinburgh. Longer slabs will be considered in this case.

On the reinforcement side, a series of transient elevated temperature tensile strength tests on Empa's new UHM CFRP reinforcing tendons were performed in Edinburgh in June 2015 (in the frame of an RAEng DVF award to Bisby/Terrasi) and showed that the new quartz-sand coated CFRP tendons perform better than most CFRP tendon products on the market. Literature [Bisby L., CICE 2012] shows that at temperatures between 250°(and 400°(, most carbon/epoxy CFRP composites lose about half of their original tensile strength: The novel Empa UHM CFRP tendons have a design tensile strength of 1400 MPa, their failure temperature at a service stress of 50% of the design tensile strength is 409°((standard deviation of 4 tests of only 8.27 M Pa).

Therefore the experiments should be set-up considering:

- a need to monitor the CFRP tendons' draw-in at the slab ends by linear potentiometers;
- temperature monitoring by applying thermocouples (Type K) at the cold surface and on the CFRP tendons, in particular for monitoring the temperature in their anchorage zones at the slabs' ends;
- lateral displacement measurement (i.e. thermal bowing) during heating;
- high resolution digital camera(s) to perform digital image correlation (DIC) to observe concrete cracks developing at the cold surface; and
- thermal imaging of the exposed surface to better understand the uniformity of heating.

The main objective of these experiments is to gain deeper understanding of the underpinning mechanisms of bond failure of the CFRP prestressing tendons in the different fire scenarios studied and different SCC-mixes used (e.g. ISO 834, hydrocarbon fire or smouldering fire). The softening of the coating layer on the tendons' surface and of the epoxy matrix in the tendons' cross section plays a relevant role herein. In addition we are particularly interested to monitor/comprehend the formation of longitudinal splitting cracks of the concrete cover along the prestressing tendons [Terrasi, G.P., Bisby, L., Barbezat, M., Affolter, C., Hugi, E., J. Compos. Constr. 2012.16:381-394.]. The superposition of the tensile splitting stresses present in the prestress transfer zone and the thermal tensile stresses in the concrete cover near the slab's support (due to the transition from the heated region of the slab to the unheated support region) are hypothized to play a major role in the crack formation. Additional thermal tensile stresses in the concrete cover in this area caused by differential thermal expansion between the concrete and the CFRP tendon transverse to the fiber direction may also play a prominent role.

To complement this, the complex thermomechanical stress field when heating the CFRP prestressed slabs should be analyzed with a thermo-mechanical finite element model.

This part of the study should finally lead to the definition of design criteria that allow to guarantee prestress transfer and bond at elevated temperatures for the novel prestressed CFRP SCC material systems studied (see the main objectives).