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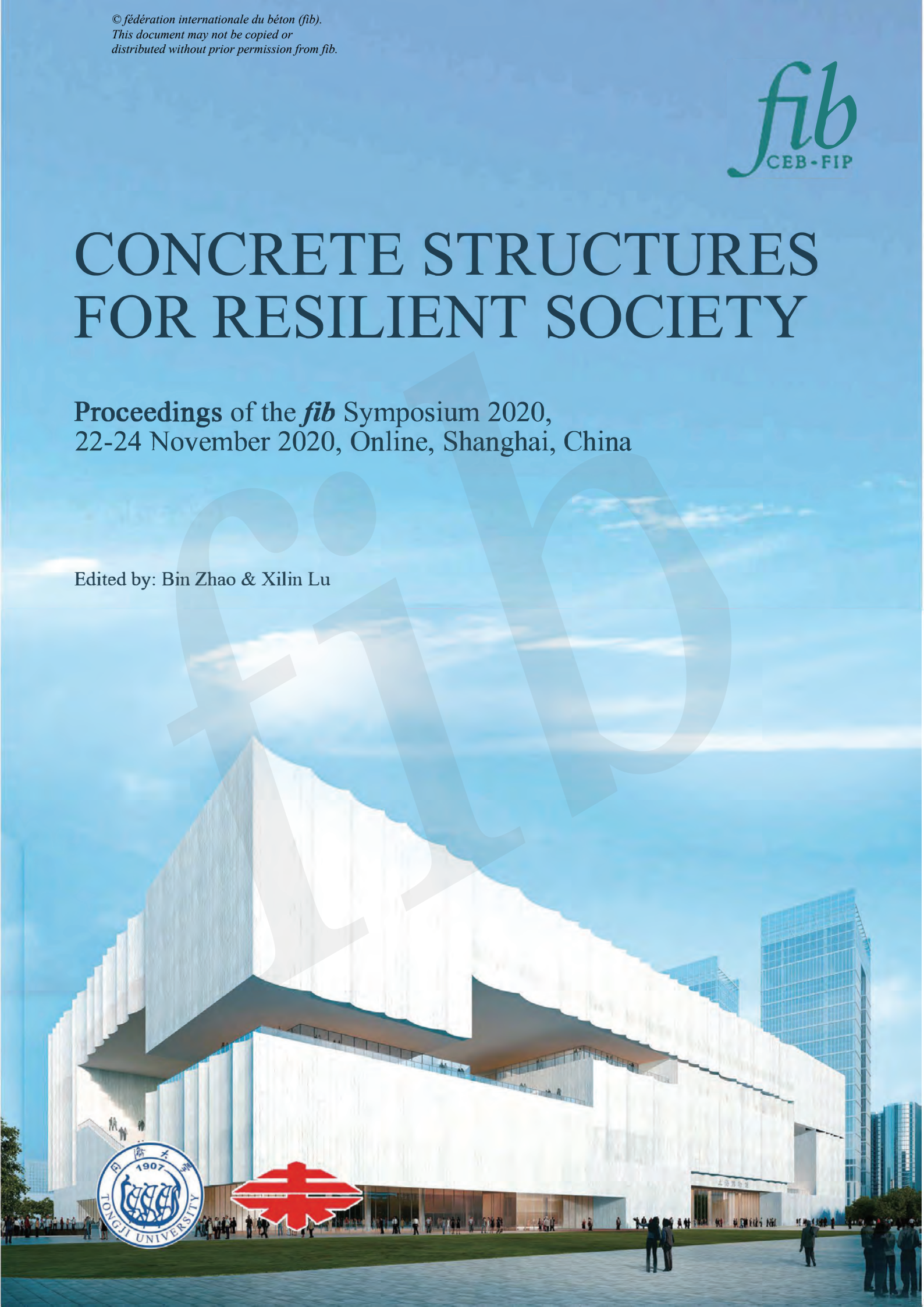
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# CONCRETE STRUCTURES FOR RESILIENT SOCIETY

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## BEHAVIOR OF BONDED ANCHORS IN UNCRACKED AND CRACKED CONCRETE AT HIGH TEMPERATURE

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### Abstract

Post-installed bonded anchors are commonly used in steel-to-concrete connections that demand high load-carrying capacities and flexible and/or unplanned anchoring locations. While formulations of polymer-based bonded anchors have continued to advance in their temperature-resistant properties, all polymers possess an inherent sensitivity in load-carrying capacity to temperatures near and above glass transition.

Protocols for determining fire performance of post-installed bonded fastening products are described in EOTA TR 020 for bonded fasteners and EAD 330087 (2018) for post-installed reinforcement (PIR). No fire criteria are currently provided in EAD 330499 (2019) for bonded fasteners or in any American anchor assessment documents. Beyond the limitation that TR 020 (2005) cannot be used as the basis for a European Technical Assessment, descriptions in TR 020 permit a degree of interpretation that can significantly influence the evaluated performance of bonded anchors under fire conditions. Therefore, there is a need to improve the fire assessment of bonded anchors in uncracked and cracked concrete by recommending clearer and more specific criteria that can be placed into anchor assessment documents.

This paper presents an experimental study on bonded anchors using an epoxy resin in cracked concrete exposed to high temperature. Reference confined pull-out tests were conducted on bonded anchors in cracked (0.3 mm crack width) and uncracked concrete at ambient temperatures in accordance with existing European guidelines. Tests were then conducted on bonded anchors in cracked and uncracked concrete exposed to high temperature with an electrical heating system. The results were analysed to understand the thermal and mechanical influence of a crack running along the embedment depth of the anchors at ambient and elevated temperatures. This experimental study provides a database for future development of testing and assessment requirements for bonded anchors exposed to high-temperature fire conditions.

**Keywords:** Bond, anchor, fastener, crack, fire, resin, adhesive, thermal distribution.

### 1. Literature review

Over the years, many types of anchorage systems have been developed and tested. Post-installed anchors are increasingly used in the field of construction thanks to their easy and rapid installation in pre-existing structural and non-structural elements for retrofitting as well as strengthening of existing structures (ACI 318-11, 2011). Post-installed bonded anchors transfer loads to the concrete bearing element by chemical bond and friction, producing bond stresses that are nearly uniformly distributed along the embedment depth (Kumar, 2009).

The behaviour of bonded anchors is influenced by many factors (e. g. geometry, installation procedure, moisture, material properties of the adhesive and the adherent and temperature...) (Petit et al., 2005), (Eligehausen et al., 2007), (Zhang et al., 2016), (Muciaccia et al., 2019). The mechanical properties of adhesive resins are particularly temperature-dependant (Reis, 2012). When exposed to fire, structural



members are subjected to heavy thermal loading inducing thermal gradients in a short period of time. The increase of temperature degrades the material properties of concrete (EN 1992-1-2, 2008), (ACI 318-14, 2014), steel (EN 1993-1-2, 2005) and resin (Sorathia et al., 1997), reducing the load-bearing capacity of the connection.

Studies have shown that different types of adhesive resins exhibit varying levels of sensitivity to temperature increase. Epoxy resins in particular are more sensitive to temperature than polyester mortars (Ribeiro et al., 2004). The glass transition temperature ( $T_g$ ) of the polymer quantifies the temperature effect on polymeric materials. The adhesive bond shows a reduction in stiffness and ultimate capacity when its temperature exceeds  $T_g$  (Pinoteau et al., 2013). Temperature increases to values below the glass transition temperature enhance the mechanical properties of the resin due to the continuation of the cross-linking reaction between the mother resin and the hardener. Studies on Post-installed reinforcement (PIR) showed that when bond temperature of loaded anchors exceeds  $T_g$ , changes of physical state occur leading to a stress redistribution along the embedment length of the anchors (Lahouar et al., 2017). Other studies on PIR showed that the heating rate of the adhesive bond is of importance (Pinoteau et al., 2013), where they demonstrated that high heating rates lead to thermal gradients along the steel member and therefore to a stress redistribution of bond stress.

Anchors may fail in different failure modes at ambient temperatures (Eligehausen et al., 2006), (EN 1992-4, 2018). Under fire, the pull-out failure mode may occur more frequently than other failure modes due to the high sensitivity of the adhesive to temperature increase and rapid degradation of its mechanical properties. Therefore, it is most interesting to evaluate the bond capacity of bonded anchors in accidental situations such as fire exposure.

The guidelines in EOTA TR 020 (2005) for determining fire performance of anchors were integrated in the European Assessment Document EAD 330232 (2016) for mechanical anchors. Their integration in the European Assessment Document 330499 (2019) for bonded fasteners is still in progress. However, no American assessment document provides protocols for this particular problem. Furthermore, the limitations of the EOTA TR 020 (2005) for the case of bonded anchors were investigated by several authors (Reichert and Thiele, 2017) and (Al-Mansouri et al., 2019). The existing assessment protocol prescribes a steel fixture for load transfer to anchors. The steel fixture is directly exposed to fire for the assessment of anchors in uncracked concrete. The allowance of insulating material to protect the fixture from direct exposure to fire in the case of anchors in cracked concrete raises questions. Indeed, (Reichert and Thiele) signalled that tests on bonded anchors in cracked concrete according to EOTA TR 020 (2005) using insulating material around the fixture should be avoided and Al-Mansouri et al (2019) showed that insulating material around the fixture protects the fixture and the bonded anchors from fire leading sometimes to twice the resistance compared to the case with no insulation around the fixture.

The existing assessment documents for anchors in concrete at ambient temperature give clear guidelines for determining the ratio of the load-bearing capacity between anchors in cracked concrete and anchors in uncracked concrete for concrete classes between C20/25 to C50/60. In general, for common size bonded anchors with small and medium size anchors, the ratio of bond strength for anchors in cracked concrete to uncracked concrete is around 70%.

This paper presents an experimental study to investigate the bond behaviour of bonded anchors at high temperature in cracked concrete. First, reference tests were conducted in uncracked and cracked concrete (0.3 mm crack width) at ambient temperature (20°C) using the European Assessment Document for bonded fasteners (EAD 330499, 2019). Then, tests on bonded anchors in uncracked and cracked concrete were conducted at high temperature to capture the reduction of pull-out strength due to crack existence. Heating was done using radiant panels capable of radiating at a surface temperature up to (400°C) at the surface of the panels. The anchors were directly exposed to heating up to a certain thermal gradient along the embedment depth of the anchor with no load applied on anchors. Then, the heating system was removed and a confined tension test was immediately conducted on the anchor to determine the pull-out capacity of the anchor. The results of different series of tests with different heating durations (2 hours, 3 hours and 4 hours) were assessed and the ratio of bond resistance in cracked concrete to uncracked concrete was determined from the mean value of bond strength.

## 2. Experimental study

This section describes the testing procedure using radiant panels as a heating system and the ratio of the pull-out capacity for bonded anchors in cracked concrete to uncracked concrete. Test results at ambient and high temperature allowed to determine if the reduction due to crack existence at ambient temperature changes due to temperature increase. Indeed, the current guidelines in EOTA TR 020 (2005) consider that the values of fire tests on anchors in uncracked concrete can be taken without reduction for use in cracked concrete.

The goal of this work was to check if the reduction from uncracked to cracked changes at high temperature (Figure 1). Reichert (2017) investigated the reduction of strength of bonded anchors loaded in tension under fire due to crack existence compared to uncracked concrete. This work, although done on a limited number of tests, proves that there is a reduction due to crack existence under fire and that the current status of the guidelines allowing adoption of the values of fire tests in uncracked concrete for the case of cracked concrete should be revoked. However, this work did not investigate the evolution of this reduction with temperature increase, and the ratio of bond strength between uncracked and cracked concrete is calculated from power trend tendency curves based on a limited number of fire tests.

The principle of the research done in this paper (as summarized in Figure 1) is the following: the reduction of bond strength at ambient temperature from uncracked to cracked concrete  $\alpha$  can be found by conducting a series of tests according to the EAD 330499 (2019) for bonded fasteners. At high temperature, such as in the case of fire (or any high temperature short term heating scenario), a reduction of bond strength  $\beta$  in uncracked concrete can be found from ambient to high temperature. The question arising is whether the reduction of bond strength at high temperature from uncracked to cracked concrete  $\gamma$  is different from  $\alpha$ . If this is the case, then the reduction factor  $\delta$  for bond strength in cracked concrete from ambient to high temperature is different from  $\beta$ . If not, then the reduction  $\gamma$  does not change at high temperature and the reduction  $\alpha$  can be taken from tests at ambient temperature for the reduction from uncracked to cracked concrete at high temperature.

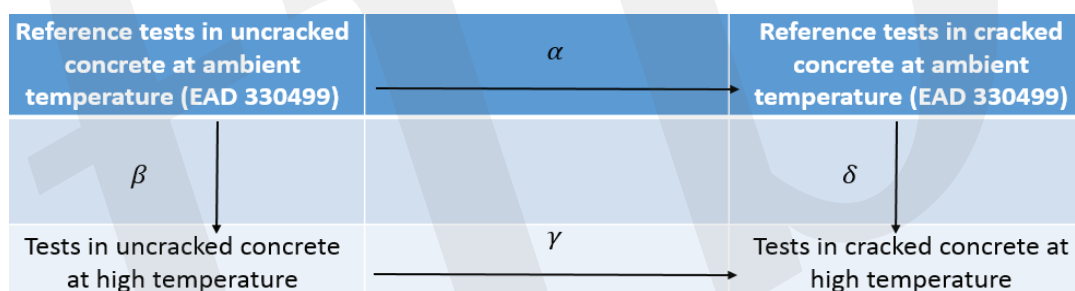


Figure 1. Reduction factors of bond strength from uncracked to cracked concrete at ambient and high temperature

### 2.1. Reference tests at ambient temperatures

Series of 5 confined tension tests were conducted on bonded anchors in uncracked and cracked concrete ( $\Delta w = 0.3$  mm) using an adhesive epoxy resin (Hilti HIT-RE 500 V3) according to the European Assessment Document for bonded fasteners (EAD 330499, 2019).

The concrete slabs had a reinforcement degree of approximately 0.8%. Slab dimensions were (1.5 m length  $\times$  0.5 m width  $\times$  0.2 m thickness). Figure 2 shows a cross section (0.5  $\times$  0.2 m) in the slab with the bonded anchor installed at  $4d$  for reference tests. A concrete class of C20/25 was used for the slabs. The compressive strength of concrete was tested on a series of 3 cubes (15  $\times$  15  $\times$  15 cm) and 3 cylinders ( $\phi$ 16 cm – L32 cm) at 28 and 256 days (date of testing). The concrete compressive strengths were  $f_{c,28} = 35.5$  MPa,  $f_{ck} = 32.1$ ,  $f_{c,256} = 38$  MPa and  $f_{ck,256} = 35.7$  MPa.

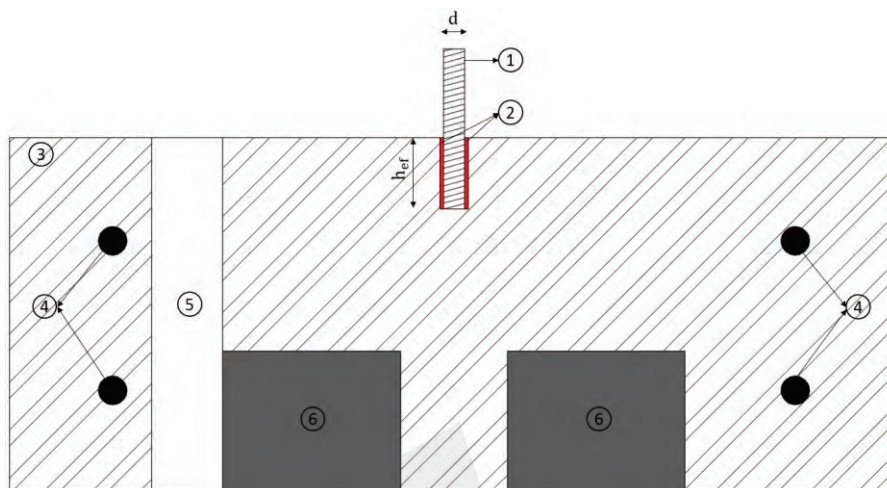


Figure 2. Cross section of the slab with: (1) threaded rod, (2) adhesive resin, (3) concrete slab, (4) HA16 reinforcement bars, (5) hole for wedges and (6) thin steel plates for crack orientation.

The diameter of the threaded rods used for tests was  $d = 12$  mm (M12 rods) made of carbon steel with a steel grade of 10.9. An embedment length of approximately  $h_{ef} = 4d$  was adopted for the reference tests. This length was chosen to avoid steel failure of the rod and obtain pull-out failure of the anchor because the study focuses on the behaviour of the bond. An adhesive layer around the rod of 2 mm thickness was adopted. Anchors were installed in cracked concrete after creation of cracks. The hole cleaning procedure in the MPII (Manufacturer's Product Installation Instructions) using compressed air and a specific brush was adopted. The anchors were left to cure at the curing time defined by the manufacturer.

Hairline cracks were initiated prior to installation of anchors using wedges (Figure 3). Wedges were installed inside the concrete slab and crossed the entire section of the slab. The diameter of the wedge before expansion is 40 mm. The advantage of using wedges is that they ensure a homogeneous crack along the section of the concrete slab (around the cross section). Crack width was measured using displacement sensors placed on the upper side of the slab prior to cracking. Crack displacement sensors were placed on one side of the anchor and measured the displacement of a metallic ring placed around the anchor with the anchor in its centre. The crack displacement sensor was fixed on one side of the crack and the metallic ring was fixed on the other side of the crack (Figure 4).

Wedges were expanded by applying a pressure that leads to the required opening of cracks. The crack displacement sensor measured the displacement of the slab on one side of the crack to the other which corresponds to the width of the crack ( $\Delta w$ ). Special measures were taken to ensure vertical-straight-like cracks along the section. These measure consisted in placing (prior to casting of concrete) adhesive tape around the reinforcement bars at the area where the cracks have to be created and the use of steel plates at the bottom of the slab to orient the cracks in a favourable path.



Figure 3. Wedges used for cracking concrete with: (1) lower side of the slab, (2) thin steel plate, (3) wedges and (4) hairline crack.



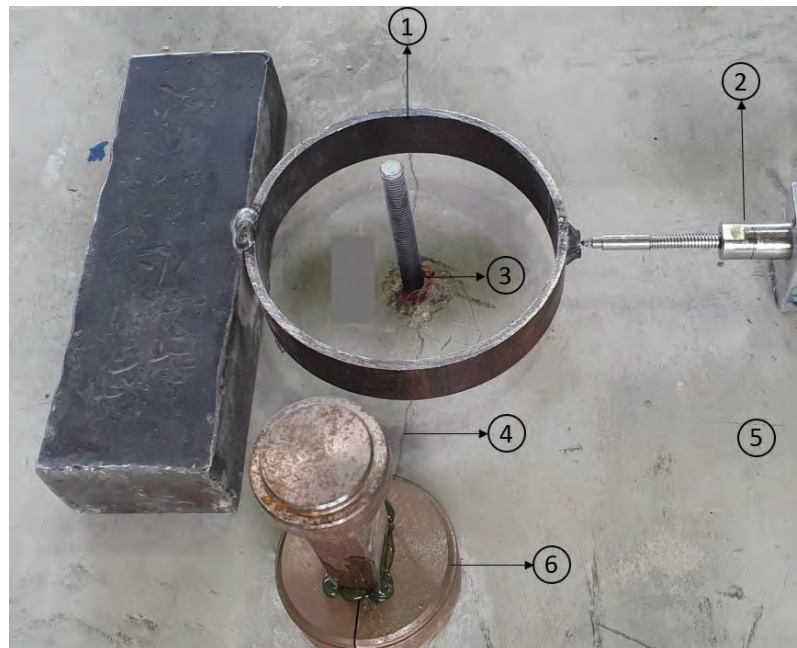


Figure 4. Crack width measurement with: (1) metallic ring, (2) displacement sensor, (3) bonded anchor, (4) crack, (5) upper side of the slab and (6) wedges.

Each slab had a total of 3 cracks with approximately 350 mm spacing between the cracks. In each crack one M12 bonded anchor was installed at an embedment depth of  $h_{ef} = 100 \text{ mm} \approx 8.33d$  with an adhesive layer of 2 mm around the rod (Figure 5). Other anchors were installed in uncracked concrete at the same embedment depth with enough spacing to prevent mechanical and thermal interaction between neighbouring anchors.

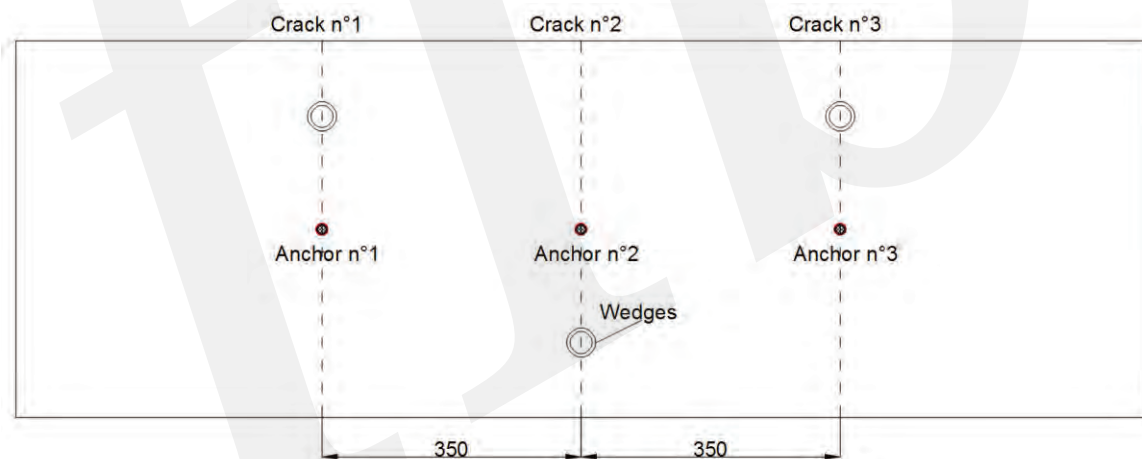


Figure 5. View of the test slab with the position of anchors in cracked concrete

The results of confined tension tests at ambient temperature on bonded anchors are given in details in Figure 6. The ratio of bond strength between bonded anchors in cracked concrete and uncracked concrete is 68%. This ratio is close to the usual ratio of 70%.

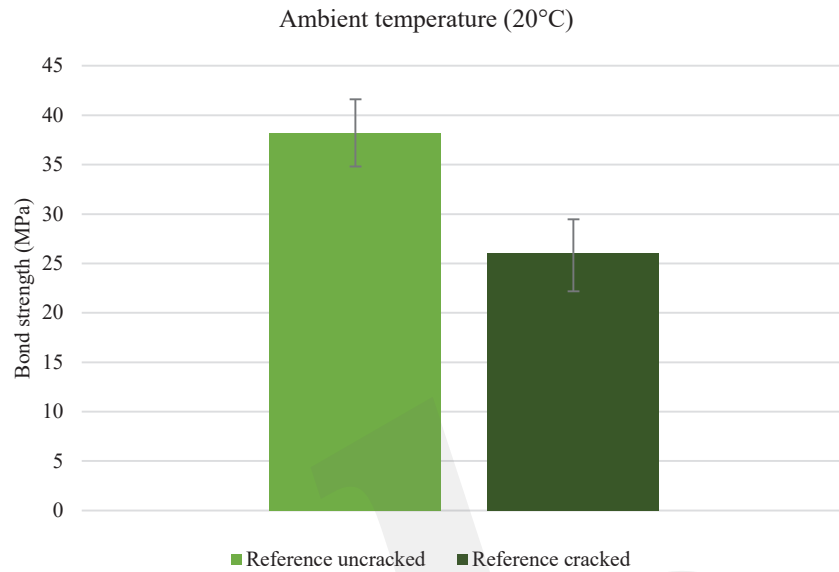


Figure 6. Results of pull-out tests on bonded anchors in uncracked and cracked concrete

## 2.2. Tests at high temperature

In order to assess if the ratio of bond strength between cracked and uncracked concrete changes at high temperature, tests in cracked and uncracked concrete on bonded anchors were conducted using electrical heating. The heating system consisted of radiant panels capable of radiating at a surface temperature (surface of the panels) of approximately 450°C. It should be noted that the position of radiant panels is alterable but was fixed for all tests in this paper. This device was developed internally in CSTB to conduct tests on concrete elements with a relatively slow heating rate compared to a standard ISO fire. Heating is applied on the exposed surface of the slab by radiation only without convection. The heating system is capable of covering a slab of the same dimensions as used for the reference tests ( $1.5 \times 0.5 \times 0.2$ ). The panels are situated on the upper side of the heating system. They consist of small radiant units distributed homogeneously around the surface of the heating system (Figure 7). Figure 8 shows a photo of the heating system on top of a test slab. The sides of the heating system were insulated with a rock wool based material to provide optimal heating inside and limit energy loss.

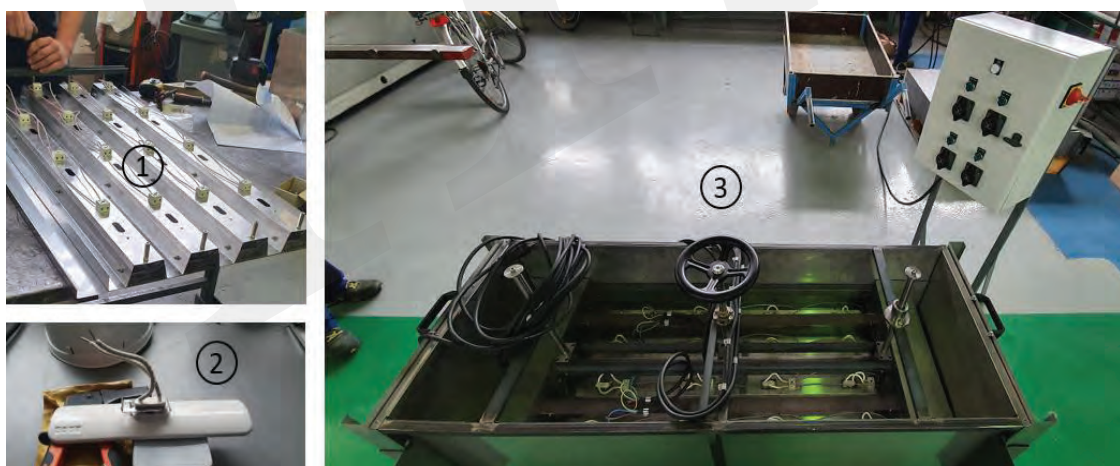


Figure 7: Electrical heating system with: (1) radiant panels, (2) radiant units and (3) complete heating system.





Figure 8. Heating system on top of a test slab in the fire resistance laboratory at CSTB.

The cracks were opened at 0.3 mm width prior to thermal heating. No crack measurement was ensured during heating. The slab along with the anchors on the upper side were heated up during 2, 3, and 4 hours. Multiple series of confined tension tests were done for each heating time.

Test results in Figure 9 show that a reduction of bond strength from uncracked to cracked concrete is maintained at high temperature. The ratio of bond strength from uncracked to cracked concrete was found to be 69% for 2 hours of heating, 66% for 3 hours of heating and 71% for 4 hours of heating. At 2 hours of heating, 13 tests were conducted in uncracked concrete and 6 in cracked concrete. Test results at 3 hours of heating had a higher standard deviation because the series of tests consisted of 4 tests in uncracked and 4 tests in cracked concrete. At 4 hours of heating, 17 tests were conducted in uncracked concrete and 6 in cracked concrete.

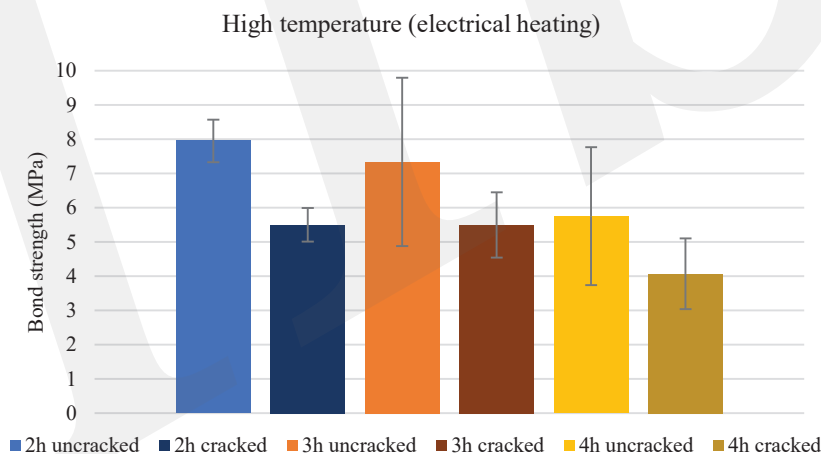


Figure 9. Results of pull-out tests on bonded anchors in uncracked and cracked concrete at high temperature

### 3. Conclusions

This paper presented an experimental investigation of the pull-out behavior of bonded anchors (epoxy resin) in uncracked and cracked concrete at high temperature (using electrical heating). First, reference tests were done at ambient temperature to find the ratio of bond strength between cracked and uncracked concrete (generally around 70%). Then, tests at high temperature were conducted to assess if this reduction changes with temperature increase. Tests were conducted for different heating times (2 hours,

3 hours and 4 hours). The results at high temperature show that the same ratio is also found at high temperature. This result confirms that the current state of the guidelines for fire tests on bonded anchors in cracked concrete must be revised. The reduction due to crack existence at high temperature should be considered and fire test results on bonded anchors in uncracked concrete should not be used for cracked concrete. The reduction can also be taken from reference tests at ambient temperatures.

The results of this experimental work can establish the basis for a new assessment method of bonded anchors in cracked concrete under fire. The behavior under constant load might vary from the behavior with the testing method used in this work (heating followed with pull-out test) due to the creep phenomenon and the slow heating rate compared to standardized fires. Also, The phenomena occurring in concrete under fire might vary from those occurring under slow rate radiative electrical heating. Therefore, the authors will pursue this research in the future by means of fire tests on bonded anchors in cracked concrete under sustained load on several types of adhesives to confirm the findings of this paper.

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