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INFLUENCE OF TESTING CONDITIONS ON THERMAL DISTRIBUTION AND RESULTING LOAD-BEARING CAPACITY OF BONDED ANCHORS UNDER FIRE

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Abstract

This paper aims to experimentally apply the existing method for evaluating the pull-out capacity of mechanical anchors under fire, to bonded anchors. Due to the absence of sufficient guidelines for evaluating bonded anchors directly exposed to fire, this experimental work studies the influence of the existing evaluation method on the prediction of the bond resistance and failure time. Different testing conditions and possible configurations for anchors in buildings are explored. The studied influencing parameters are: presence of fixtures, insulation of fixtures, thickness of the concrete bearing element, diameter of the anchor, concrete/steel temperature. The influence of each parameter on the predicted bond resistance and failure time, determined with a design method based on resistance integration is studied. Results show that parameters such as concrete element thickness and attaching metallic fixtures on anchors have a negligible influence on the predicted load-bearing capacity and failure time. However, adopting concrete temperature instead of anchor steel temperature in the resistance integration method, and putting insulation around fixtures may lead to a false estimation of the load-bearing capacity and failure time.

Keywords: bond, resin adhesive, bonded anchor, pull-out, fire tests, thermal distribution.

1. Introduction:

One of the techniques used in the field of construction consists in anchoring steel elements in concrete by using adhesive resins for structural purposes. This technique allows for an easy and rapid installation of anchors in pre-existing structural elements. Installed anchors can be loaded in tension and/or in shear situations. Chemically bonded anchors can either ensure a junction between two structural elements such as post-installed rebars, in this case they are not directly exposed to fire due to concrete cover, or they can be directly exposed to fire such as chemically bonded threaded rods which are studied in the work presented in this paper. The advantages of these bonded anchors are their ease of implantation and their high load-bearing capacity at ambient temperature for deep embedment depths. However, when exposed to an accidental increase of temperature such as a fire, these structural elements show a rapid decrease in bond resistance.

Chemically bonded anchors can be bonded using polyester, vinylester and epoxy resins [1]. Research studies on the influence of temperature on the elastic modulus and flexural strength of polymer mortars using a thermostatic chamber have shown that the deformation and strength decrease of mortars are temperature dependent [2]. These studies have also shown that for a temperature range from room temperature up to 60 °C, temperature effect is limited. However, for temperatures above 60 °C, the decrease of mortar strength becomes drastic. Other research studies on adhesive-joints for a temperature range from -60 °C up to 200 °C have shown that stress/strain properties of polymer adhesives change a lot with temperature. Many studies have focused on the contrast of structural performance of connectors at ambient and elevated temperatures [3]. At high temperatures, the strain capability of these adhesives is high whereas their load capacity is low [4]. It was also shown that epoxy mortars are more sensitive to temperature than polyester mortars [5]. Moreover, mechanical properties of resins have been found to be highly susceptible to resin type and reinforcement employed as well as their quantities in the bearing structural element [2]. Glass transition is considered as the limiting factor of the state of a polymer and as an indicator of durability [6].

The design and assessment of the structural integrity of anchors under fire are defined in EOTA TR 020 [7]. This document defines the guidelines to perform fire tests on anchors in order to establish the bond resistance vs. exposure time relationship. This relationship gives the duration of fire-resistance for a certain applied load.

However, pull-out assessment of bonded anchors under fire is not mentioned in this technical report [8]. Bonded anchors are only covered for steel failure, whereas steel resistance could be greater than bond resistance under fire. Furthermore, no guideline exists for the design of bonded anchors under fire while a reliable method exists for the design of bonded rebars at high temperature.

The resistance integration method is based on the good knowledge of temperature profiles along the embedment depth of the anchor. The obtained temperature profiles are used then to establish the relationship between bond resistance and temperature by dividing the anchor into little segments. Each segment gives a certain resistance as a function of temperature using tests described in EAD 330087-00-0601 [9]. This finally allows plotting the relationship between bond resistance and exposure time. The resistance integration method presented promising results for pull-out failure under fire of chemically bonded post-installed rebars indirectly exposed to fire in the works of Pinoteau et al. [10] and Lahouar et al. [11], [12]. Furthermore, this method was also adopted in the numerical work of Lakhani and Hofmann [13] to determine the pull-out strength of bonded anchors directly exposed to fire.

Experimental parametric studies on different types of resins have shown that a maximum adhesive shear strength is reached for a resin thickness of 2 mm around the rod. Beyond this value the shear strength decreases until a certain value which remains constant. Moreover, increasing the embedment depth leads to an increase in the tension capacity of the anchor until a certain point beyond which the capacity remains constant [14].

Studies conducted by means of pull-out tests on adhesive joints [15] and on cast-in and post-installed rebars [16], have shown that the performances of chemical bonds and steel/concrete connections are comparable at ambient temperature. Studies have shown that the mechanical behavior is very similar with a slight advantage for bond resistance over cast-in rebars. However, at high temperature, such as in a building fire scenario, mechanical properties of adhesive resins assuring the connection between steel and concrete decrease rapidly due to temperature gradients and the increase of temperature along the member. This capacity reduction is faster in the case of bonded anchor systems using polymeric mortars, which can cause safety issues [13]. Thus, a good design of these bonded anchors under fire is needed to ensure the safety of lives and properties in burning buildings.

The European technical report EOTA TR 020 [7] covers the evaluation of mechanical anchors under fire for different failure modes. Possible failure mechanisms for bonded anchors under tensile loads are: a) concrete cone failure (manifested either as the characteristic cone failure or concrete splitting), b) steel failure, c) combined failure (concrete cone failure + bond failure at the adhesive-concrete interface + possibly tensile failure at the lower part of the adhesive) and d) bond failure of the anchor [17]. However, the European technical report EOTA TR 020 [7] covers the evaluation of bonded anchors under fire only for steel failure mode. Failure of bonded anchors may occur for pull-out more frequently than other failure modes during fire exposure due to the rapid degradation of mechanical properties of the resin. Thus, for safety reasons, it is the most decisive failure mode for bonded anchors under fire. Therefore, it is most interesting to evaluate bonded anchors by performing pull-out tests under fire to predict bond capacity in accidental situations such as a building under fire [18].

The required testing method to determine the fire-resistance of bonded anchors under fire and the obtained data must allow subsequent classification. This classification must be based on fire-resistance duration of tested bonded anchors. For this duration, the performances of tested anchors for a standard fire exposure scenario need to satisfy specific criteria. Thus, the method described in Part 1 of ISO 834 [19] was adopted in the work presented in this paper.

Studies on anchor rods and polyester base adhesives were conducted by Paterson [20] with 10 mm diameter rods and 75 mm effective depth. These studies have shown that pull-out failure of anchors exposed to standard fire is within 10-15 min of fire and the anchor temperature is between 330-440 °C, for temperatures measured near the fixture (between bolts assuring the connection between the fixture and the rod). Paterson also alerted that under fire the adhesive anchor may reach failure earlier than the structural element in which it is installed and thus creating a major issue putting the life of occupants at risk.

The mechanical properties of adhesive resins at high temperature were investigated by Pinoteau [21]. His work highlighted that the glass transition temperatures (T_g) of the used epoxy products ranged between 80 °C and 130 °C and their tension capacity became lower than 2.5 MPa above 140 °C. Furthermore, Lahouar et al. [22] showed that temperature profiles of bonded anchors vary depending on the adopted test procedure for evaluating their pull-out capacity at high temperature. Indeed, Lahouar et al. studied two approaches: by applying a constant

tensile load to the anchor before heating and keeping it while progressively heating the specimen until failure (constant load tests), and by stabilizing bond temperature then applying pull-out (stabilized temperature test). Their theoretical work allowed obtaining stress profiles for a thermal distribution along the embedment depth of the anchor using experimental entry data from the characterization of the anchor. Researchers have shown that the stress distribution along the embedment depth of adhesive anchors cannot be considered uniform for long embedment depths (larger than $7.5 \cdot d$) [23-25].

In order to get a better understanding of the load-bearing behavior of chemical anchor systems under fire, the research project “Bonded anchors in case of fire” conducted by Reichert & Thiele [8] studied a combination of different types of fire tests and simulations. This project demonstrated that the existing guidelines of fire tests on bonded anchors are not clear till today. The Technical report TR 020 [7] contains no regulation for the evaluation of chemical anchor systems. Test execution and evaluation have to be determined thereby.

Similar testing conditions in EOTA TR 020 [7] were studied by Lakhani and Hofmann [13] by means of finite element numerical modeling. These conditions were applied on an anchor rod with 12 mm of diameter and 110 mm of embedment depth. The differences between the thermal distribution of the configuration where the anchor in itself was exposed to fire (acting as heat transfer path) and the configuration where the anchor was insulated (along with a fixture) were large. The pull-out capacity obtained from the thermal distribution highlighted a drastic reduction in case of unprotected anchors (without fixture and insulation). This large difference may lead to a pull-out failure for non-insulated anchors which would occur faster than the failure for insulated anchors.

The influence of existing testing conditions in EOTA TR 020 [7] for bonded anchors under fire on the precision of failure prediction using the resistance integration method is highlighted in the work presented in this paper. Pull-out fire tests were carried out on several possible configurations of bonded anchors in concrete beams submitted to elevated temperatures. Temperature profiles along the embedment depth of bonded anchor during fire were thus measured. These profiles are the thermal data needed for the resistance integration method in order to predict bond strength vs. exposure time of anchors. EAD 330087-00-0601 [9] allows predicting bond resistance vs. temperature relationship for bonded rebars at high temperature. In this paper, tested bonded anchors were threaded rods installed with an epoxy resin. Fasteners were installed according to the manufacturer’s indications (hole diameter, cleaning method, injection system...etc.). The rods were directly exposed to fire. In order to obtain a good prediction of the resistance of these bonded anchors under fire, the integration method requires a good knowledge of temperature profiles along the embedment depth of the anchor during fire. Knowing precisely the temperature profiles allows a precise prediction of failure time for an applied load. Due to the lack of European guidelines to perform pull-out fire tests for bonded anchors, the only applicable evaluation method for non-uniform temperature profiles along the embedment depth is the one for mechanical anchors cast-in concrete without resin [7].

Many parameters of testing conditions may influence temperature profiles. Hence, it is difficult to precisely calculate the bond resistance vs. fire exposure time relationship which affects the precision of the predicted failure time for a given load. The influence of the following parameters was explored by conducting fire tests under a standard ISO 834 fire:

- Anchor’s diameter and adopting concrete temperature instead of steel temperature in the resistance integration method.
- Thickness of the concrete beam in which the anchor was installed.
- Existence of a fixture on the anchor.
- Insulation of fixtures.

In this paper first, the existing testing method for the evaluation of pull-out strength of mechanical anchors is presented. Then, pull-out fire tests were conducted using the same method on chemically bonded anchors. Furthermore, a parametric study was conducted to determine the influence of each parameter on the predicted bond strength and failure time by conducting fire tests without pull-out.

2. Testing procedure and design method

This section describes the existing experimental method for the determination of pull-out resistance duration under fire for bonded anchors in non-cracked concrete. It also recalls a design method (the resistance integration

method), for the determination of bond strength of these anchors under fire. Furthermore, it presents a first application of this method on experimental data exploited from pull-out fire tests. This application is based on thermal profiles along the embedment depth of the anchor as entry data for the resistance integration method.

2.1. Existing procedure for assessing the structural integrity of anchors under fire

According to EOTA TR 020, part 4 [7], tests have to be carried out according to the general rules for structural fire design in [26]. For fire tests on bonded anchors, pull-out failure is more decisive in general conditions than other failure modes such as concrete cone and steel failure [13]. In order to favor pull-out and avoid other failure modes, the degree of reinforcement and the concrete element thickness must respect certain precautions [7].

According to EOTA TR 020 (Fig. 1), a fixture has to be attached to the anchor to transfer the tensile load from a tension member. The fixture must ensure a steel stress of 2-4 N/mm² in the flanges of the fixtures. This is due to the fact that the loading system is connected to the fixtures via the flanges. Fixture dimensions have to be chosen depending on load categories. However, the tension member linked to the fixture is not described in this technical report. Fire tests have to be carried out according to the general requirements of the determination of fire-resistance of different structural elements in EN 1363-1:1999-10 [27]. In order to perform pull-out fire tests, EOTA TR 020 [7] requires insulation around the fixture. Only details in Fig. 2 are presented in the technical report. This insulation in the case of bonded anchors may hugely influence thermal distribution leading to lower temperature profiles and a significant delay in failure time.

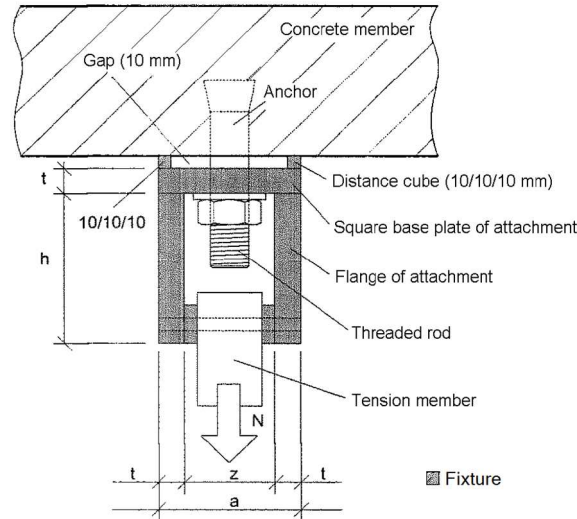
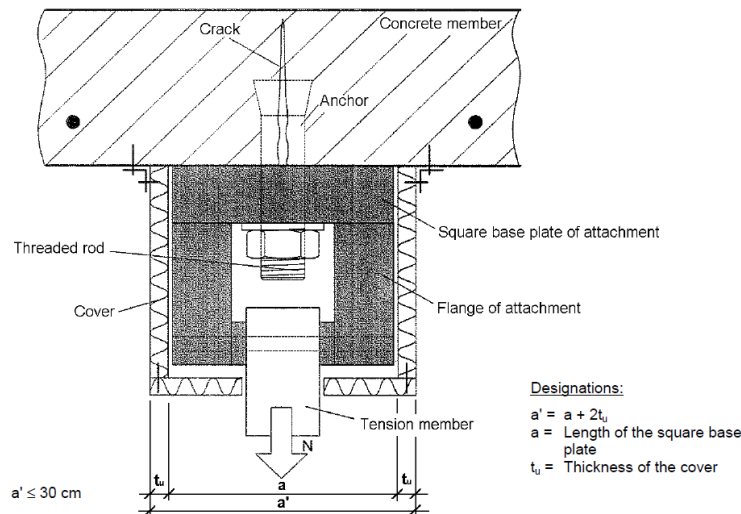


Fig. 1. Test set-up for the determination of steel failure test under fire in EOTA TR 020



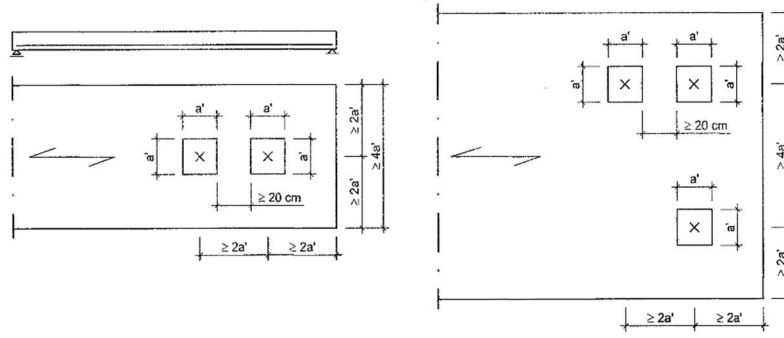


Fig. 2. Test set-up for the determination of the characteristic resistance under fire exposure to pull-out failure [7]

2.2. Design method for the determination of the pull-out resistance of bonded anchors under fire

Pinoteau [21] [10], Lahouar [12] [28] and Reichert & Thiele [8] proposed a method for the determination of the load capacity of anchors at a given time during fire exposure. The resistance integration method was used to determine the pull-out capacity of bonded anchors under fire. The thermal data necessary for the resistance integration method was obtained using various methods, one of which was experimental pull-out fire tests at constant load on bonded anchors installed in cylindrical concrete specimens according to EAD 330087-00-061 [9]. The cylindrical tested specimens were heated laterally. Concrete surface and extended parts of anchors were not heated directly, thus obtaining an acceptable uniform temperature profile along the embedment depth. In these works, bond resistance vs. temperature relationship was obtained by pull-out tests according to [9]. This relationship served later to predict the bond resistance vs. fire exposure time for non-uniform temperature profiles during fire tests. This was obtained by dividing the anchor into discrete elements (Fig. 3). By making the hypothesis that every discrete element has a uniform temperature, the bond resistance of each element is obtained from the bond resistance vs. temperature relationship. By integrating the bond resistance of the discrete elements, the total load resistance is obtained for a given time (equation in Fig. 3).

This prediction method works very well for post-installed rebars in concrete, while an anchor directly exposed to fire has a more aggressive thermal diffusion. However, it is reasonable to say that the non-uniform temperature profiles of anchors directly exposed to fire can be used to calculate the bond resistance vs. fire exposure time. Hence, to predict failure time as long as the resin is not subjected to fire directly. This confirms that temperature profiles must be well known at every time during fire test in order to obtain good failure prediction.

The resistance of the anchor is calculated according to Eq. 1:

$$N_{Rd,fire} = \pi \cdot d \cdot \int_0^{l_v} f_{bd,fire} \cdot k(\theta(x)) \cdot dx \quad \text{Eq. 1.}$$

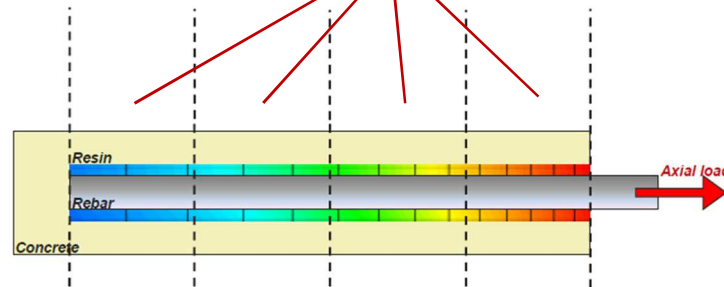


Fig. 3. Principle of the resistance integration method

Where: $N_{Rd,fire}$ is the fire design load resistance (kN).

d is the diameter of the anchor (mm).

$f_{bd,fire}$ is the design bond resistance at ambient temperature (N/mm²).

$k(\theta)$ is a reduction factor that depends on temperature.

l_v is the length of the anchor (mm).

The advantage of this design method is that it can be applied on different configurations of pull-out fire tests which provide the thermal data of the bond. The configurations presented in EOTA TR 020 [7] do not cover pull-out for bonded anchors without insulation. Whereas, in the event of a real fire inside a building or on a building site, an anchor may be subjected directly to the thermal exposure while being subjected to tensile loads. This could cause failure more rapidly than for insulated cases [13]. Moreover, anchors could exist in thinner concrete elements. Boundary conditions of this problem influence temperature profiles along the anchor. Many shapes of fixtures could be applied on anchors where some may cover completely the anchor insulating it from a direct thermal exposure to fire.

The design method was experimentally validated in this paper. This was done using failure time obtained from loaded tests and the predicted time obtained from the resistance integration method.

2.3. Details of the experimental application for validating the design method

Fire tests were carried out on concrete beams of 230 mm of width and 1500 mm of length and different beam thicknesses (150 mm, 180 mm and 300 mm). Concrete beams were carved from slabs reinforced with HA10 rebars. The obtained beam sections were reinforced with different degrees of reinforcement according to the number of rebars in each section. The carving procedure ensured at least two rebars in the section of each beam so that the surface exposed to fire could resist to cracking and thermal expansion. A typical cross section of one of the concrete beams is shown in Fig. 4. In these beams, some bonded anchors were equipped with coax thermocouples to measure temperature profiles along the embedment depth. ISO 834 fire was applied using a gas furnace at CSTB with the following dimensions: 1,4 m length, 1 m width and 1,05 m height. A loading system was put in place for the three loaded tests (Fig. 5). The loading system used hydraulic jacks powered by hydraulic pumps, applying a downward mechanical load on a system of tubes surrounding the concrete beam. Metallic tubes transferred the applied load to fixtures connected to the anchor facing the inside of the furnace. Tube dimensions were 40 mm x 40 mm x 400 mm. Dimensions described in EOTA TR 020 [7] were adopted for the fixtures.

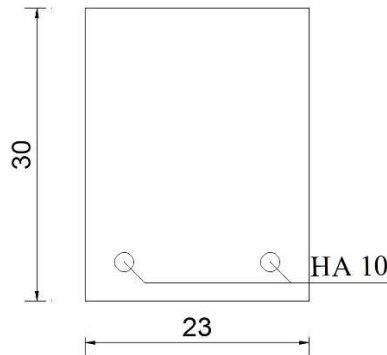


Fig. 4. Typical cross section of one of the concrete beams

In order to ensure a one-dimensional heat-transfer inside the beams and along the bond, the lateral faces of the beams were insulated using a glass wool based material (50 mm thickness). The bonded anchors were fastened using a polymer based resin. In order not to influence the bond surface between adhesive resin and steel of the rod, no thermocouples were positioned on the mechanically loaded anchors. This would result in a decrease of adherence between resin and steel leading to a false measurement of bond resistance. In order to measure temperature profile along the embedment depth without influencing the bond of the anchor, another unloaded anchor rod was instrumented with at least 4 thermocouples and installed in the same beam as the loaded one (Fig. 6 and Fig. 7). This aimed to emulate the same temperature profile in the loaded anchor. The instrumented anchor did not interact mechanically with the loaded one, because it was not loaded. Thus, choice of 150 mm distance was taken between the loaded anchor (centered above the furnace) and the unloaded anchor.

As recommended in EOTA TR 020 [7] and in order to reuse the metallic parts transferring the load to the fixture and the tension member, insulating material was put in place to protect the steel of the loading system from reaching failure before pull-out.

It is required to take a minimum of 2 mm of resin around the anchor diameter. Fire tests were performed on 2 beams at a time. The furnace was left at least one day to cool before performing the next test.

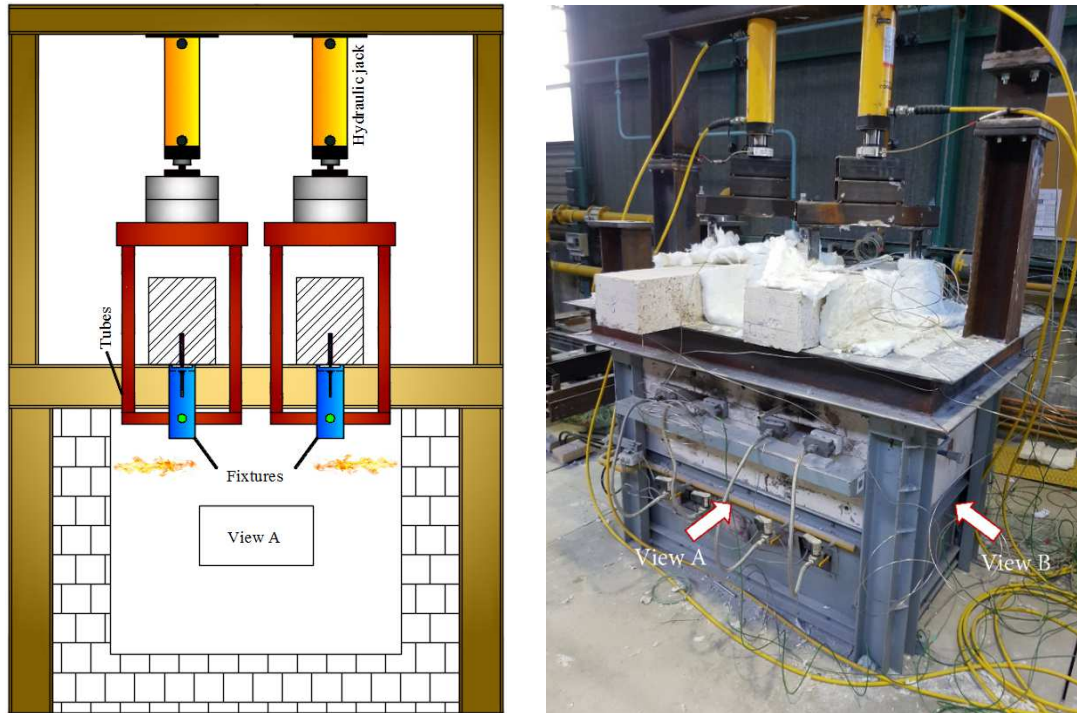


Fig. 5. View A (left) and photo (right) showing the gas furnace and the loading system

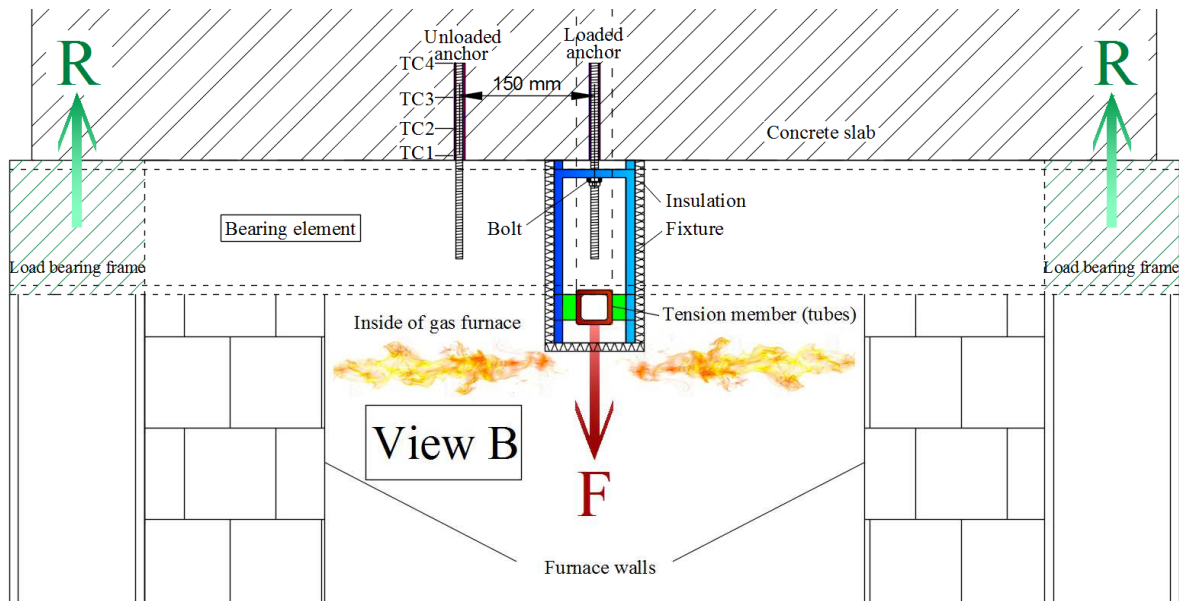


Fig. 6. View B of the gas furnace and the loading system

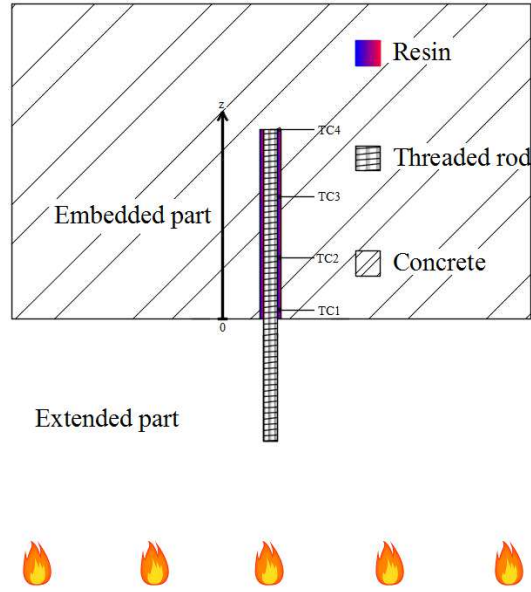


Fig. 7. Positioning of thermocouples along the embedment depth of unloaded anchors.

The composition of the C20/25 concrete used for the manufacture of beams is presented in [Table 1](#).

Designation	Origin	Quantities (kg/m ³)
G 0/8 Sand Siliceous-Limestone	Bouaffles (27) (Morillon-Corvol factory)	880
G4/14 Gravel RC Labrosse	Labrosse (77)	792
G4/20 Gravel RC Labrosse	(Sablères de la Seine factory)	88
CEM II/B-LL 32.5R CE CP2 NF	Calcia (Couvrot factory)	320
Water	-	227

Table 1. Composition of concrete used for the manufacture of beams

Threaded rods of grade-8.8 were used. The details of the threaded rods are presented in [Table 2](#).

Major diameter (mm)	Minor diameter (mm)	Pitch diameter (mm)	Pitch (mm)	Thread angle	Helix angle	Tensile strength (MPa)
8	7.188	6.647	1.25	60°	3.17°	800-980
12	10.863	10.106	1.75	60°	2.93°	

Table 2. Details of threaded rods provided by the manufacturer of the resin

In order to reach a maximum bond strength for the three different rod diameters (8 mm, 12 mm and 16 mm), the adopted thickness for the adhesive material was 2 mm as recommended by the manufacturer of the resin.

The adhesive resin presents a bond stress up to 25 MPa at ambient temperature for threaded rods with diameters below 16 mm. Resin properties at high temperatures according to EAD 330087-00-0601 [9] are presented in [Fig. 8](#).

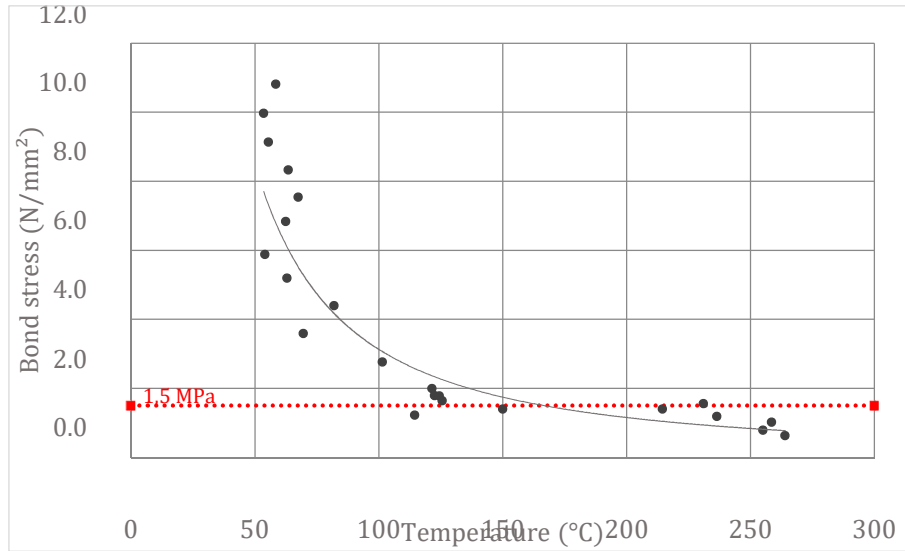


Fig. 8. Bond stress vs. Temperature relationship of the used polymer resin

The furnace satisfies the requirements for fire resistance studies in the international standard ISO 834 [19]. Therefore, thermal exposures are uniform on all samples. Temperature profiles were used as entry data to calculate the bond stress vs. temperature and bond stress vs. fire exposure time curves in order to predict the same failure time. Pre-existing data was available on the tested resin by performing pull-out tests according to EAD 330087-00-0601 [9] for the characterization of the mechanical properties of adhesives at high temperature (Fig. 8).

The resistance integration method used to calculate bond failure and failure time is based on temperature profiles measured experimentally. In this paper, load application was only used to validate the prediction obtained from the resistance integration method. The parametric study of the influence of the loading system did not need load application but only temperature profiles to compare failure between different test configurations.

The work on loaded tests went as following: First, temperature profiles at all times of fire exposure are obtained by performing fire tests. Then, bond stress vs. temperature relationship is plotted allowing, thanks to the discretization of the anchor, to attribute a resistance as a function of temperature to each discrete element. Finally, the load-bearing capacity of the anchor is obtained by integrating the resistances of all the discrete elements obtaining the resistance of the anchor at all times of fire exposure. The bond resistance vs. fire exposure time curve can be plotted and a comparison can be done between the applied load and load-bearing capacity of the anchor (Fig. 9).

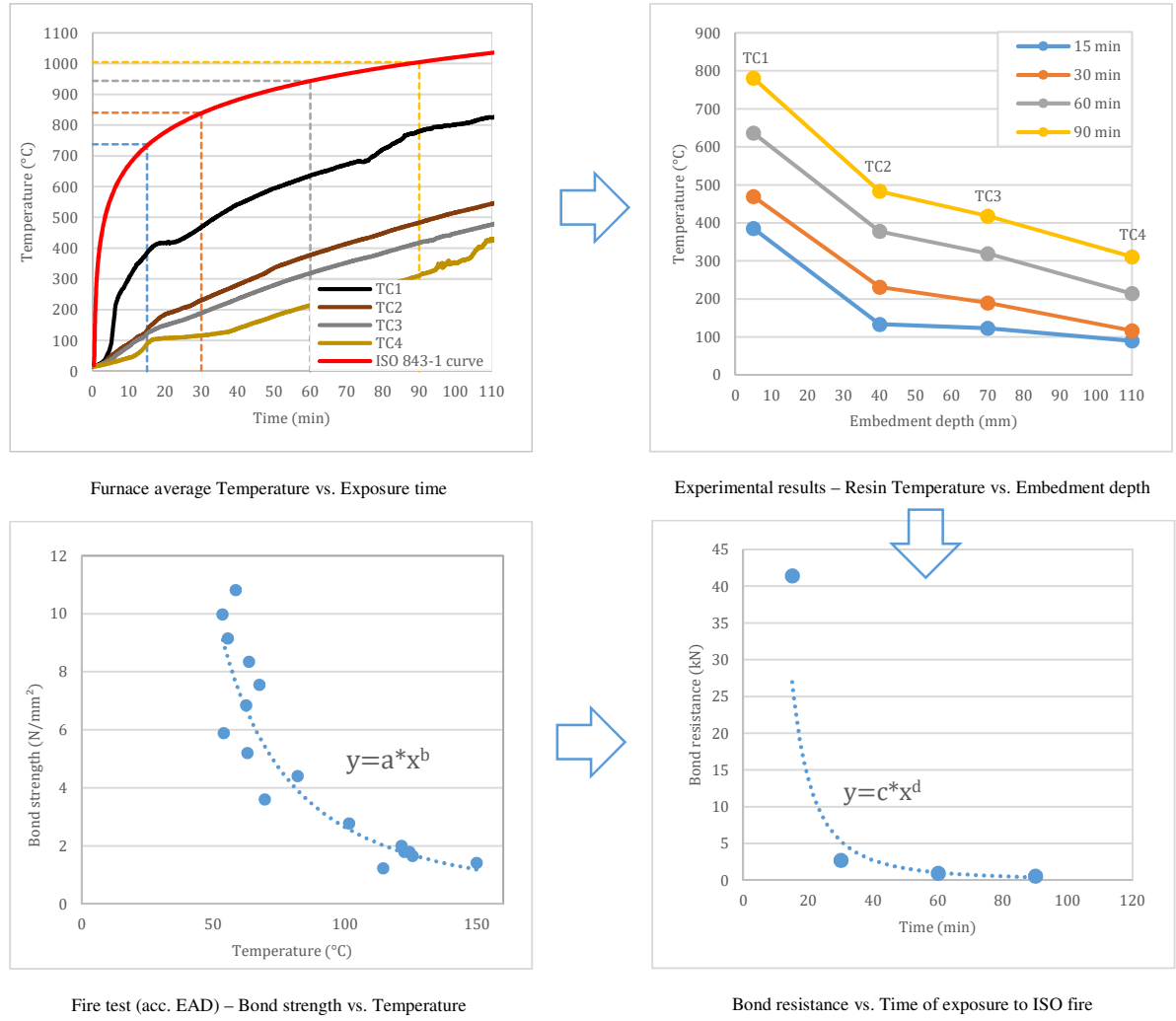


Fig. 9. Steps of the resistance integration method

The conducted loaded fire tests are summarized in Table 3.

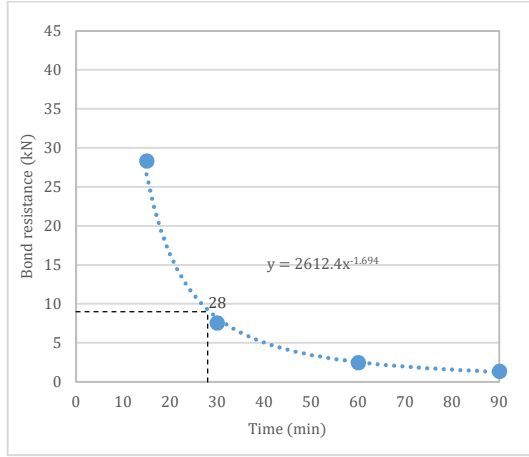
Fire type	Test n°	Bond geometry			Beam dimensions (m)	Load (kN)	Experimental failure time (min)	Predicted failure time (min)
		Ø (mm)	h _{eff} (mm)	N° of TC	Length × width × thickness			
ISO 834	1	12	110	8	1.5 × 0.23 × 0.18	9	29	28
	2	12	110	4	1.5 × 0.23 × 0.18	1.8	60	48
	3	8	70	4	1.5 × 0.23 × 0.18	0.75	75	96

Table 3. Details of mechanically loaded pull-out fire tests

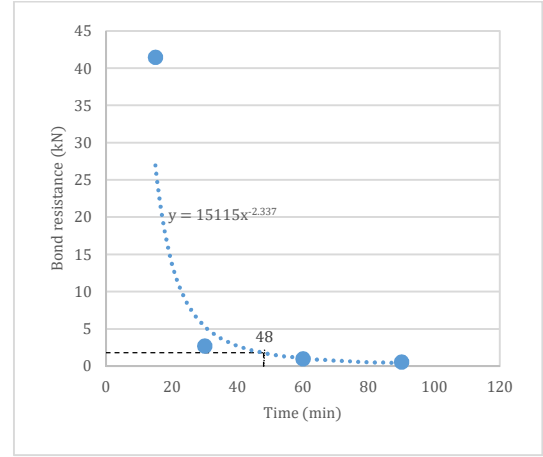
Three fire tests were performed with one loaded and one unloaded anchor per beam to validate this method. Tests were conducted on beams with 180 mm of thickness. The 1st test was loaded at 8.7% of the load-bearing capacity at ambient temperature and reached failure at 29 min while the estimated failure time using the resistance integration method was 28 min. The 2nd test was loaded at 1.7% of the load-bearing capacity at ambient temperature and reached failure after 60 min while the estimated failure time was 48 min. The 3rd test was loaded at 1.7% of the load-bearing capacity at ambient temperature as well, and reached failure after 75 min while the estimated failure time was 96 min (Fig. 10).

These load levels were chosen in order to compare the precision of failure prediction of bonded anchors under high and low load levels. Fig. 8 shows the bond stress vs. temperature relationship of the adopted adhesive resin. According to this relationship, failure temperature for low load levels presenting a bond stress below 6% of the load-bearing capacity at ambient temperature may vary significantly for a very minimal increase in bond stress. Thus, the 1st anchor was loaded under a bond stress larger than 1.5 MPa, and the remaining two loaded tests were conducted for bond stress below 6% of the load-bearing capacity at ambient temperature. Only one test was

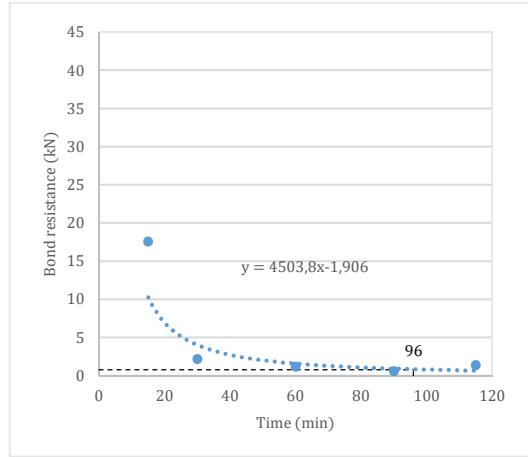
conducted per series. The repeatability of these tests could not be shown. The presented results and predictions are only indicative of the adopted experimental protocols and research practices detailed in this study.



Bond resistance vs. Time for the first case with a load of 9 kN and a failure time of 28 min



Bond resistance vs. Time for the second case with a load of 1.8 kN and a failure time of 48 min



Bond resistance vs. Time for the third case with a load of 0.75 kN and a failure time of 96 min

Fig. 10. Bond resistance vs. Time relationship for the loaded tests

Fig. 11 shows an illustration of pull-out failure of loaded bonded anchors after fire tests. The pull-out of the anchor clearly manifested at the steel/adhesive interface.



Fig. 11. Illustration of pull-out failure at the steel/resin interface of loaded bonded anchors under fire

It is concluded that for high load levels, the predicted time has a higher accuracy than for low load levels ($\leq 6\%$ of the reference bond stress at ambient temperature). A comparison between average temperatures of anchors shows that failure at low load levels is reached for a temperature at which the adhesive resin doesn't resist or has minimal resistance due to the degradation of its mechanical properties. It is supposed that large differences

obtained for low load levels are due to the poor knowledge of temperature profiles. The hypothesis that temperature profiles of unloaded anchors are similar to those of loaded anchors in (Fig. 6) gives uncertain results for failure time prediction. This requires further investigation in order to determine the influence of the loading system on thermal distribution and the precision of the prediction method.

3. Thermal influence of different parameters of pull-out fire tests

Studies on other types of anchors in concrete at high temperatures have shown that anchor geometry and thermal boundary conditions of test setup have a significant influence on the prediction of the anchor's resistance [29]. Concrete beams in which the anchors were installed were subjected only to their weight and to thermal loading due to fire exposure. Each test was composed of two concrete beams on top of the furnace. In each beam, two bonded anchors were installed. The configuration of these anchors varies from one test to another according to the tested parameter. During these parametric thermal tests, bonded anchors were not subjected to pull-out loads. Thermal data obtained from temperature profiles along the embedment depth of anchors served to determine the bond resistance vs. fire exposure time by using the resistance integration design method presented earlier.

In order to assess the thermal influence of test configurations described in TR 020 [7], additional tests were conducted without mechanical loading. Tested bonded anchors were instrumented with 4 thermocouples per rod (Fig. 7).

Table 4 describes the positioning of thermocouples in the tested specimens.

TC n°	TC position
1 to 4	Embedment depth of the anchor
5 - 6	Bolt tightening the fixture
7 - 8	Exposed surface of the concrete beam
9 - 10	Flange of the fixture at mid-height
11	Unexposed surface of the beam

Table 4. Positioning of thermocouples

Temperatures of fixtures at mid-height, bolt tightening the fixture on the threaded rod, and applied ISO 834 fire were recorded in order to ensure the same testing conditions for compared anchors. Thermocouples from TC5 to TC11 were protected with a thin, small layer of insulation at the measuring head of the thermocouple in order to measure the surface temperature instead of that of the radiation of the furnace or of surrounding ambient gas.

EOTA TR 020 [7] provides very little information on how to perform these tests. The application of the existing method of performing pull-out fire tests requires the study of its influence and limitations on thermal distribution. The limitation of the existing method is that in a real fire case scenario, the load may be applied on the bonded anchor without any insulation or fixtures (Configuration 1 in Fig. 12). Furthermore, the influence of different configurations on the precision of the method is linked to the difference between temperature profiles due to the presence of the parts of loading system that consist of fixtures (Configuration 2 in Fig. 12) and insulation around fixtures (Configuration 3 in Fig. 12).

Conducted thermal investigation tests are summarized in Table 5. Some tests were conducted several times for repeatability purposes. Details are presented in the following sections.

Fire type	Test n°	Test configuration	Anchor geometry		Concrete element dimensions (m)
			\varnothing (mm)	h_{eff} (mm)	
ISO 834	4	1	8	60	$1.2 \times 0.45 \times 0.10$
	5	1	12	60	$1.2 \times 0.45 \times 0.10$
	6	1	16	60	$1.2 \times 0.45 \times 0.10$
	7	2	8	70	$1.5 \times 0.23 \times 0.15$
	8	2	8	70	$1.5 \times 0.23 \times 0.18$
	9	2	8	70	$1.5 \times 0.23 \times 0.30$
	10	2	12	110	$1.5 \times 0.23 \times 0.18$
	11	2	12	110	$1.5 \times 0.23 \times 0.18$
	12	3	12	110	$1.5 \times 0.23 \times 0.30$

Table 5. Details of thermal investigation fire tests

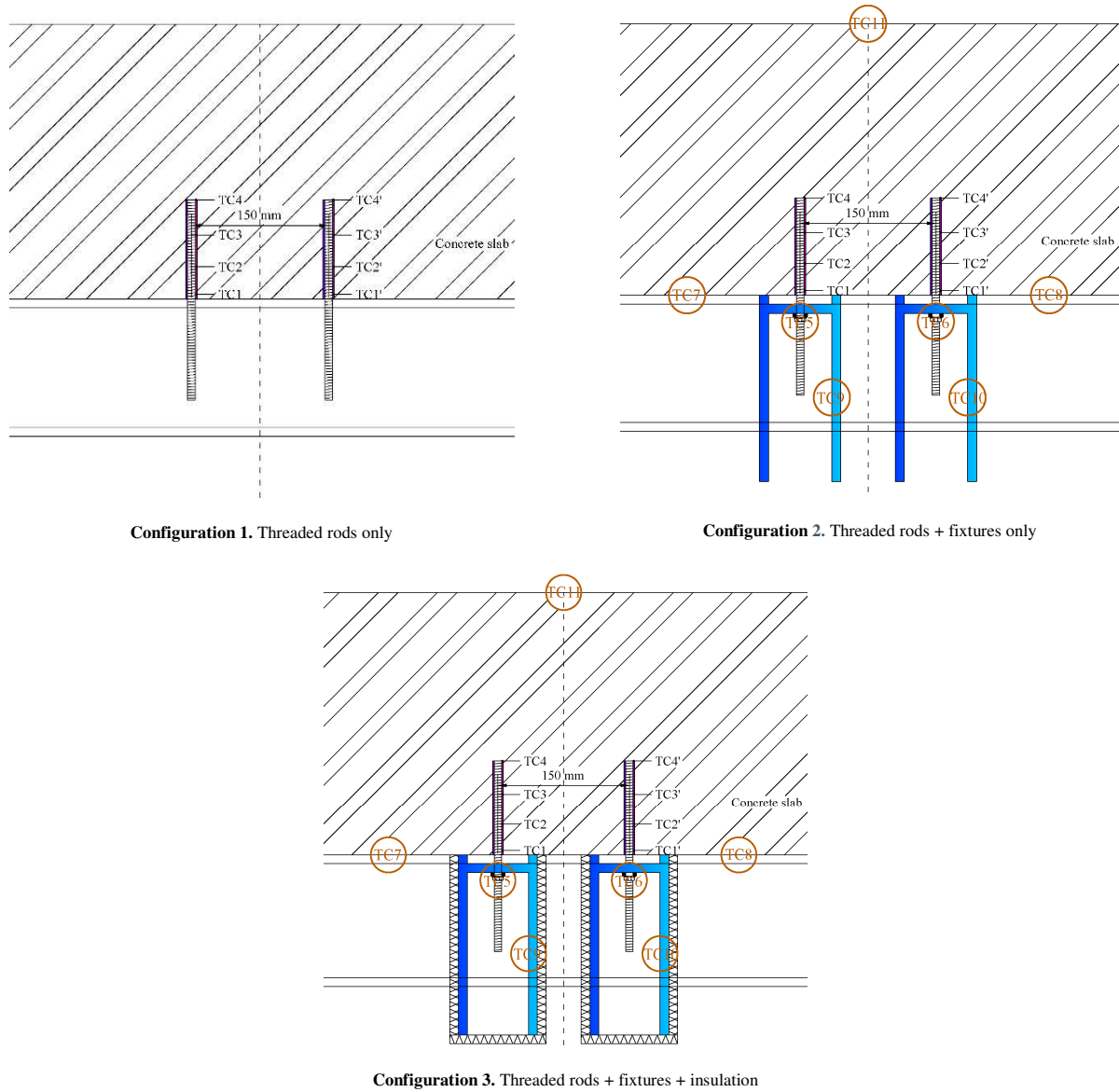


Fig. 12. Positioning of thermocouples in different configurations of unloaded fire tests.

3.1. Influence of anchor diameter and adoption of steel/concrete temperature in the resistance integration method

In order to determine the influence of anchor diameter on thermal distribution, three anchors with different diameters (8 mm, 12 mm and 16 mm) were installed with 60 mm embedment depth in a slab with the following dimensions: 1.2 m × 0.45 m × 100 mm. The anchors had the same configuration as presented in [Configuration 1](#) in [Fig. 12](#). The anchors were directly exposed to fire without any insulation or fixtures. Cast-in coax thermocouples were positioned along the thickness of the slab. These thermocouples were placed on a steel wire tightened in place on its upper and lower sides with wooden boards before pouring the concrete.

[Fig. 13](#) shows the temperature of thermocouples vs. fire exposure time for each rod. For the M16 rod, thermocouples were positioned at 5, 19, 29 and 60 mm of the embedment depth. For the M12 rod, thermocouples were positioned at 7, 17, 31 and 55 mm of the embedment depth. For the M8 rod, thermocouples were positioned at 5, 12, 28 and 59 mm of the embedment depth. Afterwards, data from [Fig. 13](#) were used to plot temperature profiles for specific exposure times (i.e. 15, 30, 60 and 90 min). A reduction of the temperature of thermocouples was noticed from TC1 to TC4 in all cases. This is due to the increase of distance between the thermocouple and the fire exposed surface. Indeed, as shown in [Fig. 6](#), TC1 is the closest to the fire exposed

surface and TC4 is the furthest. Sudden fluctuations in Fig. 12 are due to the movement of insulation around the beams during fire tests. A rapid homogenization of furnace temperature is noticed.

The relationship between temperature profiles vs. the embedment depth is then obtained in Fig. 14.

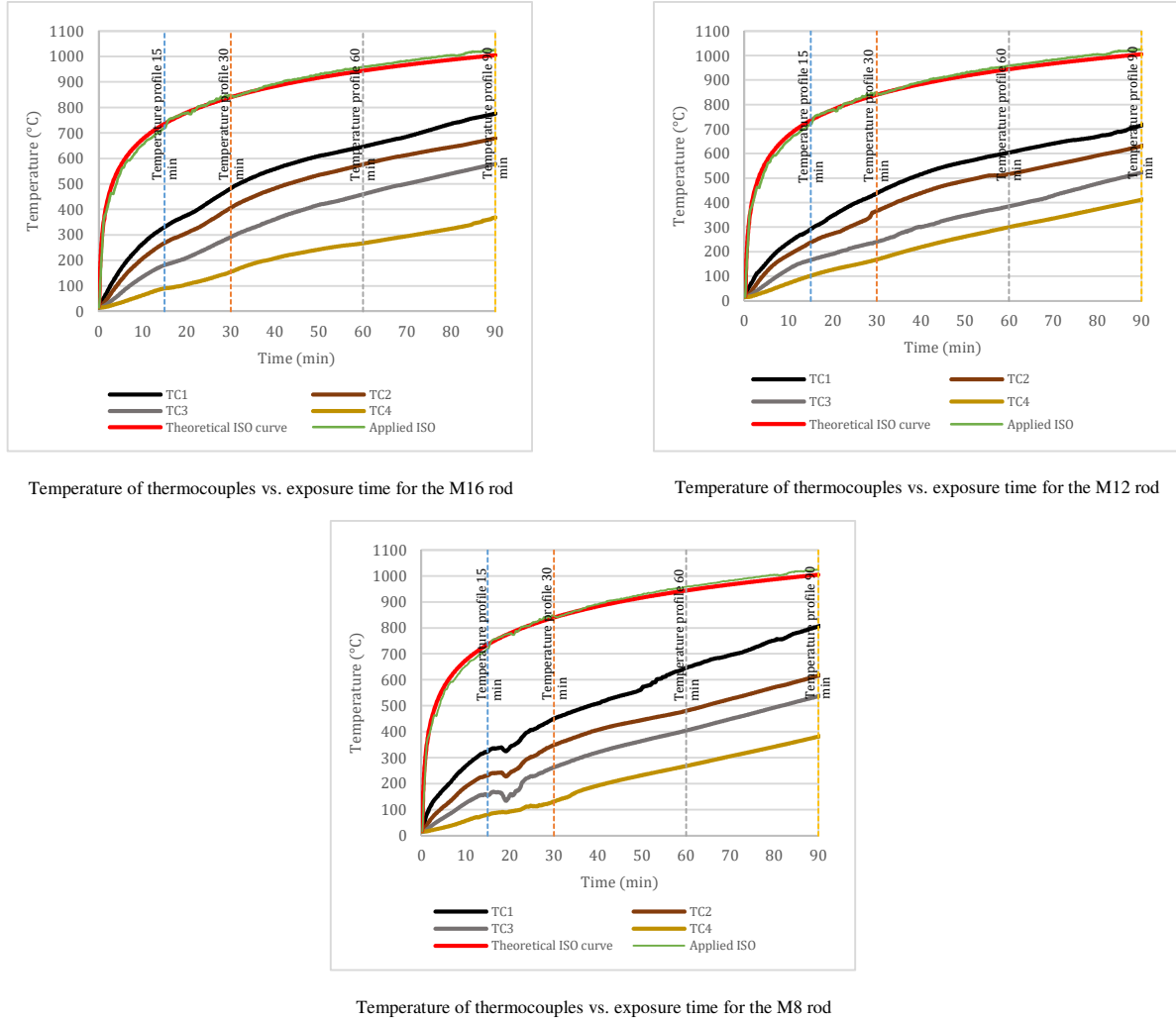


Fig. 13. Temperature of thermocouples vs. exposure time for three different diameters of threaded rods

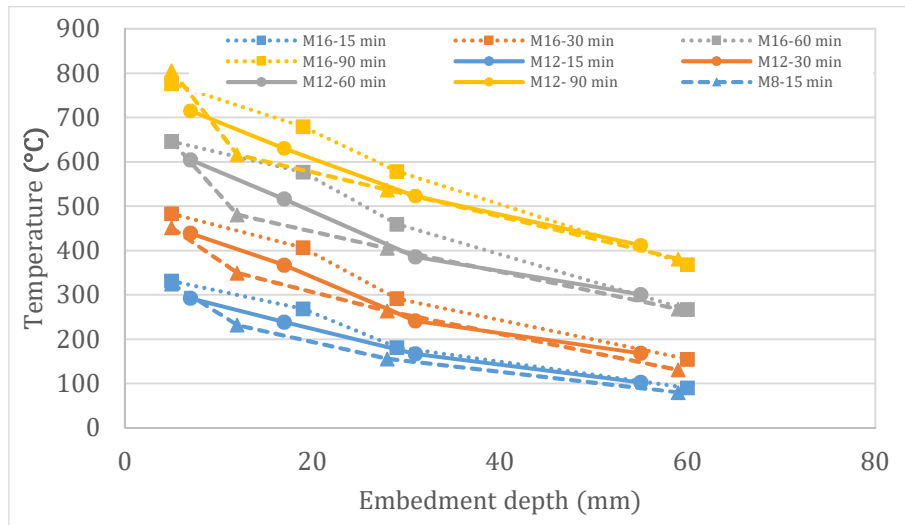


Fig. 14. Comparison of thermal profiles along the anchor for three different anchor diameters (Configuration 1 in Fig. 12)

The comparison in Fig. 14 shows that a bigger diameter gives a slightly higher temperature at the same point of observation. The difference of temperature between the smallest and the biggest diameter is 9% after 90 min of fire exposure and only near the exposed area (10 to 20 mm from the exposed surface). This difference of temperature profiles between different diameters increases with fire duration. It also decreases towards the bottom of the embedment length.

The temperature profiles plotted in Fig. 14 show that the bigger the diameter of the rod is, the higher the temperature is, especially near the exposed surface. Only points in the figure (thermocouples at four different depths) were measured. Temperature profiles are plotted by connecting the points using straight lines. This could be explained by the fact that for anchors with bigger diameters, steel quantity is larger, which increases the effect of heat transfer through the steel rod.

In order to quantify the influence of this parameter, the resistance integration method was applied to the three cases. For a stress of 0.43 MPa (same as loaded anchor n°2 and 3) applied to the three cases, the predicted failure times were 51 min for the M8 rod, 64 min for the M12 rod, and 43 min for the M16 rod. This does not necessarily mean that a larger diameter leads to a faster failure, because a larger diameter increases the bond surface around the rod. This could mean that for a given stress, there is an optimal diameter/embedment depth ratio leading to the best resistance vs. time curve.

The previous fire test, with cast-in thermocouples along the thickness aimed also to compare the temperature along the concrete thickness and the steel of the anchor. The anchor with a diameter of 12 mm was considered for comparison. The comparison was studied along the first 60 mm of the test.

Fig. 15 shows that the temperature profile measured at the steel-resin interface gives higher temperatures than the temperature of concrete for the first 15-20 min, except for the part of the rod near the exposed surface. The steel of the anchor tends to homogenize the temperature along the embedment depth. This explains why steel temperature is higher than concrete temperature in the deep part of the anchor after 15-20 minutes. Steel at the beginning of the fire test is hotter than concrete near the exposed side then the curves of temperature vs. depth for both materials cross at a certain moment. This point of crossing advances towards the unexposed side with fire exposure. This is due to the fact that steel behaves as a temperature vector compared to concrete.

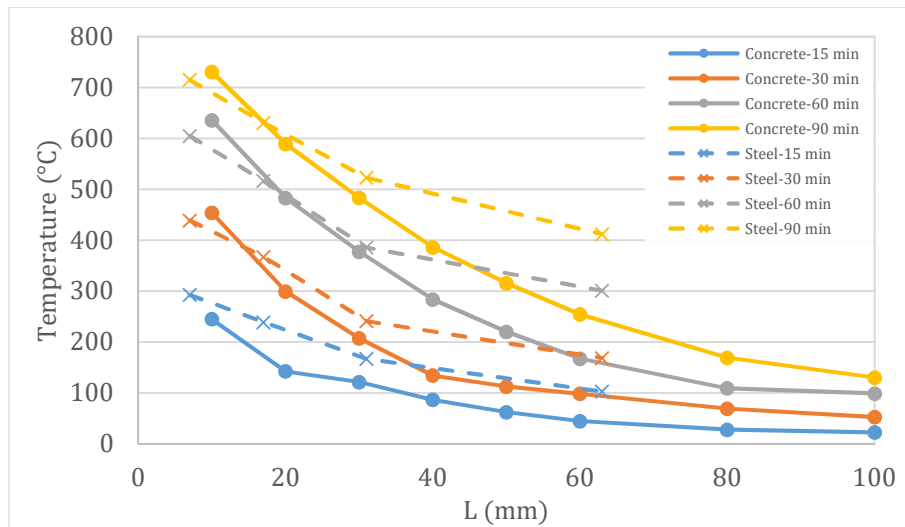


Fig. 15. Comparison between the thermal gradient of the beam and the temperature profile of the anchor (Configuration 1 in Fig. 12)

The resistance integration method was applied to the first 60 mm of concrete and steel of Fig. 15 to calculate the bond resistance of the anchor vs. fire exposure time, for a bond stress of 0.43 MPa (same as loaded anchor n°2 and 3) for example presented in Fig. 16.

In the work of Pinoteau [21] and Lahouar [30] on rebars in concrete, the effect of steel was not taken into account to calculate thermal profiles along the bond. Concrete temperature in the same position was adopted instead. This may be valid for steel cast in concrete because the thermal diffusion occurs via concrete. In the case

of an anchor directly exposed to fire, the thermal attack occurs via the steel of the anchor and the concrete of the beam simultaneously.

In the results presented in Fig. 16, there is a 27% difference in the ratio between the resistance calculated based on concrete temperature and the resistance calculated based on steel temperature for low load levels ($\leq 6\%$ of the load-bearing capacity at ambient temperature) for bond stress. This difference is not negligible. The dependence on concrete temperature instead of steel temperature in the resistance integration method for bonded anchors directly exposed to fire may lead to a false estimation of failure for both low and high load levels.

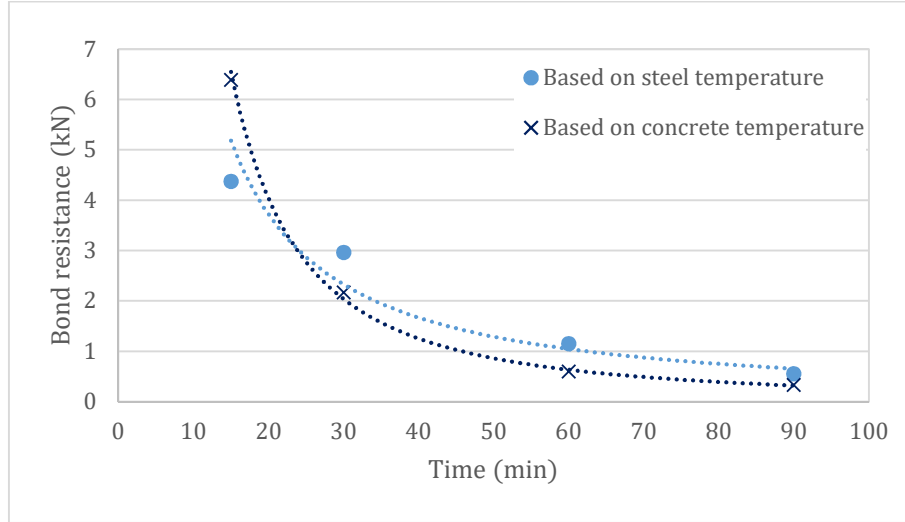


Fig. 16. Comparison between resistance integration based on concrete/steel temperature

3.2. Influence of concrete element thickness

The thickness of the tested concrete beam plays a role in influencing the temperature profiles. In order to assess this influence of the change in boundary conditions for the unexposed surface, three different beam thicknesses were tested: 150 mm, 180 mm and 300 mm. The temperature of the unexposed surface was recorded using copper disks thermocouples. Fig. 17 shows that the temperature of the unexposed surface is inversely proportional to the thickness of the beam. This result can be explained by the fact that thinner beams have higher temperature gradients along a shorter thickness and hence they homogenize temperature along the thickness faster than thicker beams.

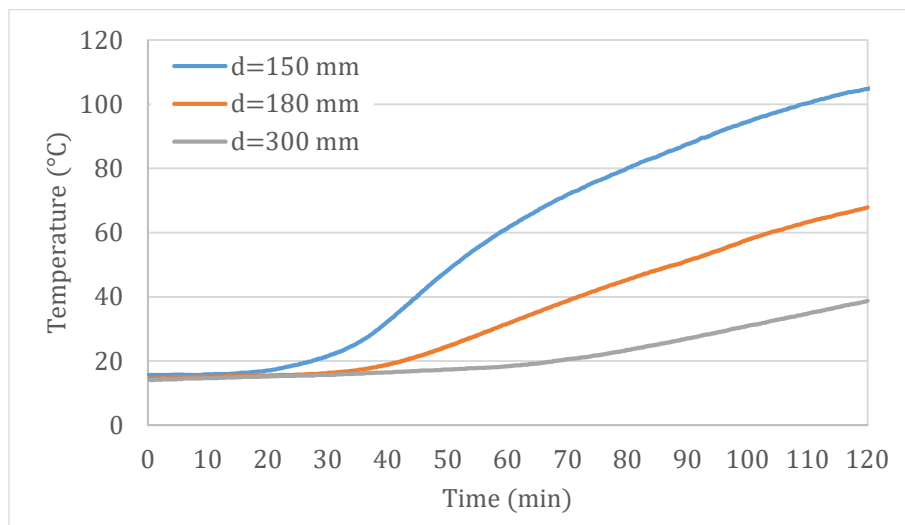


Fig. 17. Comparison between the temperatures of the unexposed surface vs. Fire exposure time for different beam thicknesses

The same comparison was done for temperature profiles for two threaded rods with a diameter of 8 mm and an embedment depth of 70 mm in two different beams with a thickness of 180 and 300 mm. The anchors had the same configuration as that presented in [Configuration 1 in Fig. 12](#). For the rod installed in a 180 mm beam, thermocouples were positioned at 5, 25, 40 and 70 mm of the embedment depth with a margin up to ± 3 mm. For the rod installed in a 300 mm beam, thermocouples were positioned at the same distances of the embedment depth with a margin up to ± 2 mm. [Fig. 18](#) shows a comparison between temperature profiles vs. embedment depth for both cases. A thinner beam shows a higher temperature profile for the same diameter and the same embedment depth, but the differences are rather small. However, this slight difference seems to decrease towards the

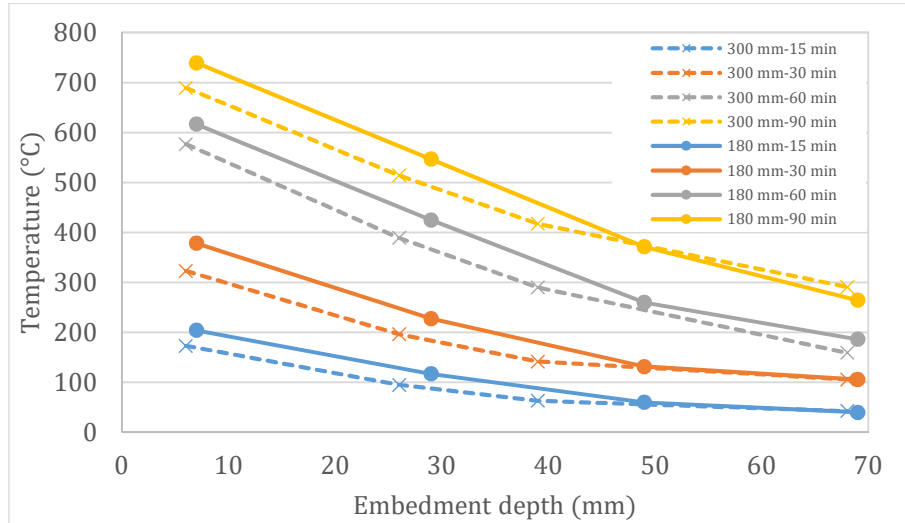


Fig. 18. Comparison between temperature profiles vs. Embedment depth for two anchors in different beam thicknesses ([Configuration 1 in Fig. 12](#))

In order to quantify the influence of this parameter, the resistance integration method was applied on both cases. For a stress of 0,43 MPa (same as loaded anchor n°2) applied on both cases, the predicted failure times were 75 min for the anchor installed in a 180 mm beam, and 71 min for the anchor installed in a 300 mm beam. This means that thicker slabs result in a slightly faster failure for low load levels. For this small difference, the influence of beam thickness is most likely negligible for both low and high load levels.

3.3. Influence of fixtures

In EOTA TR 020 [7] only fixtures are represented with details. Due to the absence of requirements, inside a building an anchor may be exposed to fire without having steel plates attached to it, leading to a thermal transfer via the rod directly. Anchors with and without the existence of fixtures were tested.

[Fig. 19](#) shows temperature profiles vs. the embedment depth for two anchors with a diameter of 12 mm in beams with a thickness of 300 mm, with and without fixtures ([Configurations 1 and 2 in Fig. 12](#)). The anchor without fixture had 8 thermocouples whereas the anchor with fixture had 4 thermocouples along the embedment depth. A slight difference is observed between the two cases. The difference decreases after 90 min of fire exposure. This could be caused by the homogenization of fixture temperature with furnace temperature. The existence of fixtures interferes with the thermal transfer mode and limits it to conduction. In the absence of fixtures, thermal transfer is mostly done by radiation. [Fig. 19](#) shows that the temperature difference between the profiles of configurations 1 and 2 decrease with time, which is linked to the kinetics of the heating inside the furnace.

[Fig. 20](#) shows temperature evolution of thermocouples vs. fire exposure time for both cases with and without fixture.

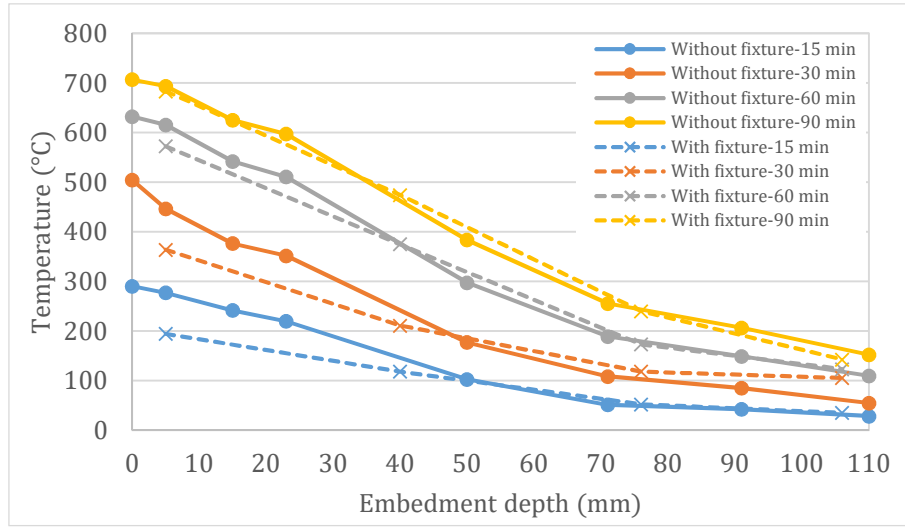


Fig. 19. Comparison between temperature profiles vs. Embedment depth for anchors with/without fixture (Configurations 1 and 2 in Fig. 12)

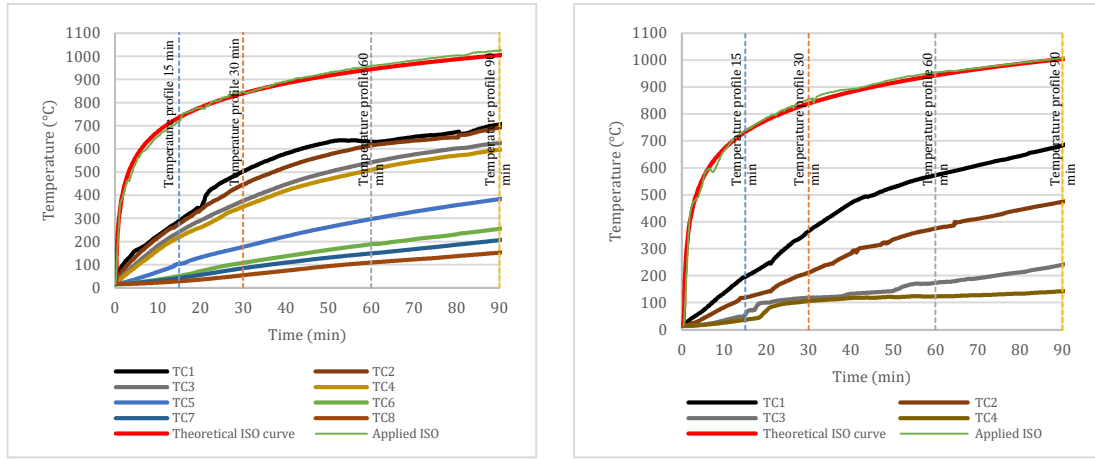


Fig. 20. Temperature evolution of thermocouples for test configurations 1 (left) and 2 (right) of Fig. 12

In order to quantify the influence of this parameter, the resistance integration method was applied on both cases. For a stress of 0.43 MPa (same as loaded anchor n°2) applied on both cases, the predicted failure times were 74 min for the rod without fixture, and 80 min for the rod with fixture. This means that the existence of the fixture delays failure for low load levels. However, for a stress of 2.17 MPa (same as loaded anchor n°1), the predicted failure times were 27 min for the rod without fixture, and 28 min for the rod with fixture.

Fig. 21 shows that the existence of fixtures has a slight influence on failure time prediction for high load levels. The difference between the precision of results for low and high load levels, despite of its negligence, could be attributed to the fact that for high load levels, the fitting curve of the bond stress vs. time relationship varies very little on the abscissa (time axis) during the first 30 min due to its slope. However, for low load levels, even the slightest difference between the fitting points (in this case at 30 min) can cause a significant change of slope at the end of the curve causing a noticeable difference of failure time between the two cases.

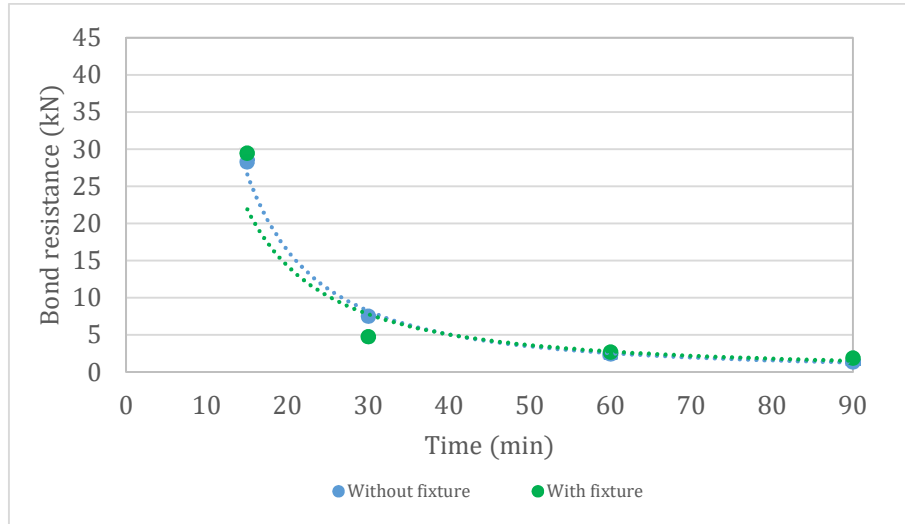


Fig. 21. Bond resistance vs. Time relationship for anchors with/without fixture

3.4. Influence of insulation

Insulation of the steel parts is required to perform pull-out tests in EOTA TR 020 [7]. It was also necessary to prevent the steel parts of fixtures from reaching failure before the anchor. In order to assess the influence of insulation around fixtures, four beams with a thickness of 300 mm were tested. Each beam had 2 bonded anchors, with a diameter of 12 mm (Configuration 3 in Fig. 12). Fig. 22 shows insulation around fixtures with 50 mm of glass wool before testing.

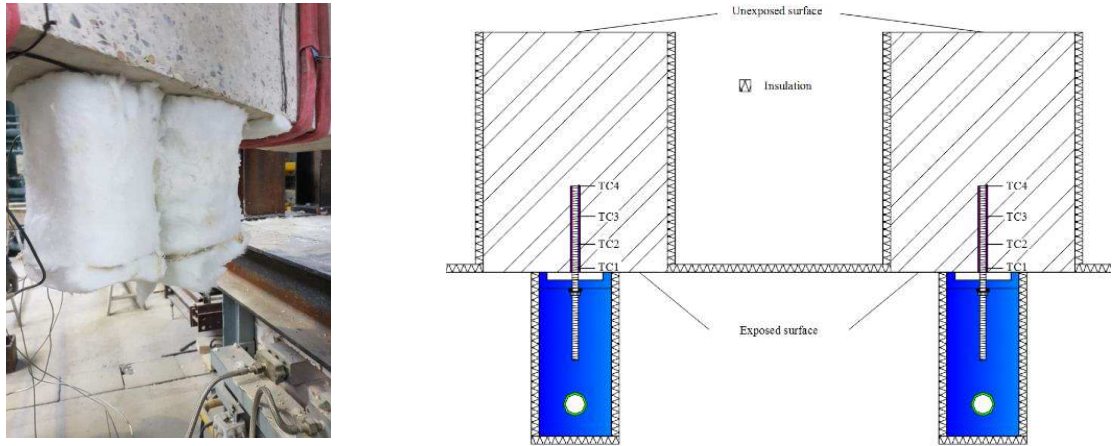


Fig. 22. Insulation of the fixtures and the lateral sides of beams (view B defined in Fig. 6)

Results presented in Fig. 23 show a significant reduction in temperature profiles for the insulated case, compared to the non-insulated case (Configurations 2 and 3 in Fig. 12). Fig. 24 shows that insulation also affects parts located inside the fixture. For example: the temperature of the bolt ensuring the connection between the fixture and the anchor is reduced by almost 500 °C after one hour of heating in the insulated case. Temperature at mid-height of the fixture's flange is also reduced by almost 400 °C after the same time of heating. This confirms that the thermal diffusion is reduced significantly due to insulation around fixtures.

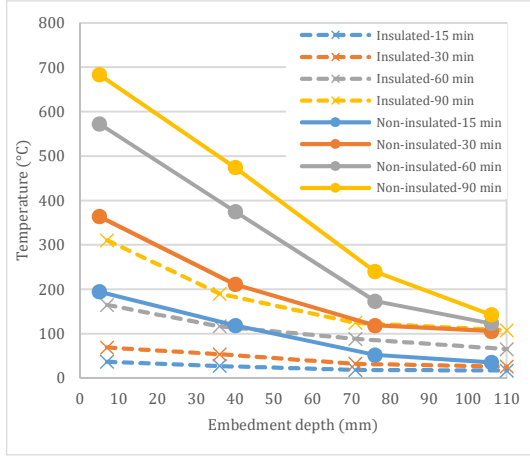


Fig. 23. Comparison between temperature profiles vs Embedment depth for insulated/non-insulated anchors (Configurations 2 and 3 in Fig. 12)

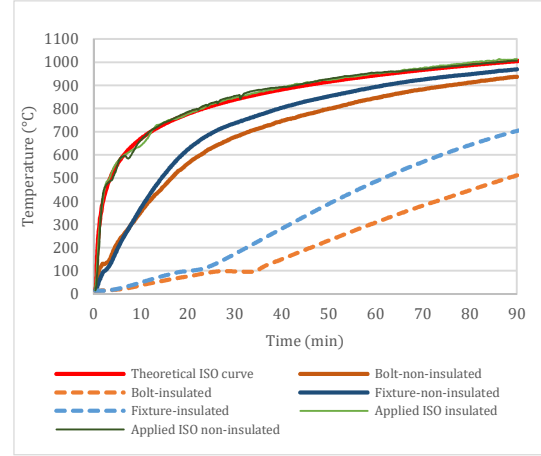


Fig. 24. Comparison between bolt temperature (TC5-TC6) and fixture temperatures (TC9-TC10) for insulated/non-insulated anchors

Fig. 25 shows temperature evolution of thermocouples vs. fire exposure time for insulated and non-insulated fixtures.

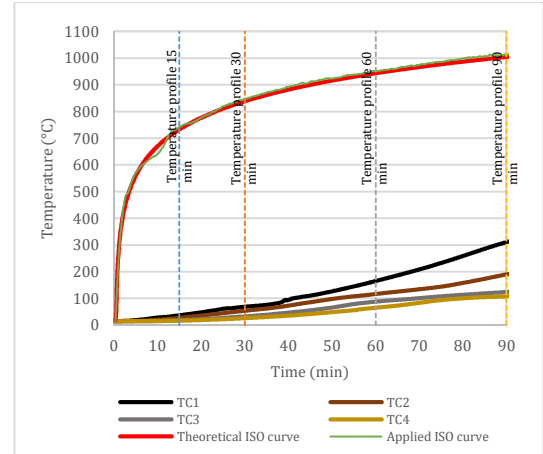
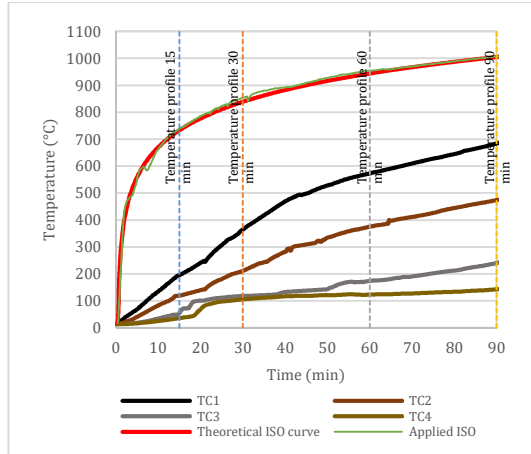


Fig. 25. Temperature evolution of thermocouples for test configurations 2 (left) and 3 (right)

In order to quantify the influence of this parameter, the resistance integration method was applied on both cases. For a stress of 0.43 MPa (same as loaded anchor n°2) applied on both cases, the predicted failure times were 80 min for the case without insulation, and 160 min for the case with insulation. For a stress of 2.17 MPa (same as loaded anchor n°1), the predicted failure times were 28 min for the case without insulation around the fixture, and 69 min for the case where the fixture was insulated with glass wool. This means that insulation delays predicted failure significantly for both low and high-load levels.

Table 6 summarizes all the results for unloaded thermal investigation tests on bonded anchors in concrete under fire.

Tested parameter	Test configuration	Anchor geometry		Concrete element dimensions (mm)	Supposed applied stress (MPa)	Estimated failure time (min)
		Ø (mm)	h _{eff} (mm)			
Anchor diameter	1	8	60	1.2 × 0.45 × 0.10	0.43	51
		12	60			64
		16	60			43
Concrete element thickness	2	8	70	1.5 × 0.23 × 0.18	0.43	75
				1.5 × 0.23 × 0.30		71
Fixture existence	1	12	110	1.5 × 0.23 × 0.30	0.43	80
					2.17	28
	2				0.43	74
					2.17	27
Insulation around fixtures	1	12	110	1.5 × 0.23 × 0.30	0.43	80
					2.17	28
	3				0.43	160
						2.17

Table 6. Summary of results for unloaded thermal investigation tests

4. Conclusion

This paper aimed to study and highlight the influence of testing conditions described in the existing guidelines for evaluating anchors in concrete under fire on the evaluation of pull-out strength of bonded anchors. Thanks to the strong bond between concrete and steel, mechanical anchors are lightly influenced by these test conditions. However, for bonded anchors, pull-out is more likely to occur at high temperatures. This is due to the rapid degradation of the mechanical properties of the bond. Thus, the variation of temperature profiles has a significant influence on the resistance of bonded anchors. In order to assess the mechanical behavior of bonded anchors, pull-out tests under ISO 834 fire were performed in this study. These tests were conducted on concrete beams with two bonded anchors in each: one loaded until pull-out and another unloaded but instrumented with thermocouples along the embedment depth to measure the same temperature profiles as the loaded one (Fig. 6). The unloaded anchor was not insulated and was left directly exposed to fire. Measured temperature profiles were used later to predict pull-out failure with the help of the resistance integration method. The predicted bond resistance vs. fire exposure time curves gave a reasonably precise accurate failure time for high load levels ($> 6\%$ of the load-bearing capacity at ambient temperature) at 28 minutes for the predicted failure and 29 min for the experimental failure (97% precision). However, for low load levels ($\leq 6\%$ of the load-bearing capacity at ambient temperature) the prediction was not accurate and needed further investigation of the influence of each parameter separately on the precision of this prediction.

In order to study the influence of these parameters, thermal investigation fire tests were conducted on different configurations (Fig. 12). The investigated parameters were: anchor diameter, replacement of steel temperature with concrete temperature for the prediction in the resistance integration method, beam thickness, fixture existence and insulation of the loading system. Testing derived the following conclusions:

- The diameter of larger anchors results in higher temperature profiles but not necessarily to faster failure time because of the increase of the bond area around the rod.
- The use of concrete temperature instead of steel temperature, for bonded anchors directly exposed to fire, in the resistance integration method may result in a non-conservative estimation of bond resistance and failure time consequently.
- The thickness of the concrete beam has low influence on the predicted bond resistance and failure time.
- The existence of the fixture has low influence on the predicted bond resistance and failure time.
- The insulation around fixtures significantly influences thermal distribution. Insulation decreases temperature profiles along the embedment depth of the anchor. This delays the decay of the mechanical properties of the bond hence the failure time by 30-60 min for load levels below 6% of the load-bearing capacity at ambient temperature MPa for bond stress.
- When designing bonded anchors directly exposed to fire, boundary conditions must take into account whether the metallic fixture transferring the load from the loading system to the rod is insulated or directly exposed to fire. This is associated to the intended configuration for the anchor inside the building.

The experimental work in this paper focused on two load ratios: 1.7% and 8.7% of the load-bearing capacity at ambient temperature. Since load ratio is one of the parameters most affecting the structural performance of bonded anchors under fire, other load ratios are advised to be undertaken in other studies to assess the influence of the studied parameters on the precision of failure prediction.

The current design method for bonded anchors under fire based on the resistance integration method was adopted in this paper. The predicted bond resistance and failure time for bonded anchors directly exposed to fire are influenced by insulation around the loading system. In order to precisely evaluate pull-out strength under fire of chemically bonded anchors, a second bonded anchor may be installed in the same concrete element as the loaded rod which is being tested. Furthermore, this anchor must be instrumented along the embedment depth of the anchor and must replicate the same testing conditions as the loaded one. Finally, more detailed guidelines are needed for performing pull-out tests on bonded anchors directly exposed to fire.

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