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Mohamed Amine Lahouar, Nicolas Pinoteau, Jean-François Caron, Gilles Forêt. FIRE BEHAVIOUR OF POST-INSTALLED STEEL REBARS: FULL-SCALE EXPERIMENTATION ON A CANTILEVER CONCRETE SLAB. IFireSS 2017, Jun 2017, Naples, Italy. hal-01617408

HAL Id: hal-01617408

<https://hal.science/hal-01617408v1>

Submitted on 16 Oct 2017

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FIRE BEHAVIOUR OF POST-INSTALLED STEEL REBARS: FULL-SCALE EXPERIMENTATION ON A CANTILEVER CONCRETE SLAB



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ABSTRACT

Post-installed rebars offer today new solutions to build more efficiently and sustainably thanks to their high mechanical properties at ambient temperature. However, the absence of a fire design method and the lack of regulations make their usage insecure in case of fire. A fire design model based on thermal calculations and on the knowledge of the variation of the bond resistance depending on temperature is presented and validated in this paper. Full-scale validation fire test carried out on a cantilever concrete slab revealed the presence of physical and thermal phenomena affecting the fire resistance of post-installed rebars and responsible for the decay in their bearing capacity.

1 INTRODUCTION

Thanks to the improvement in mechanical and adhesion properties of polymer resins, post-installed rebars succeeded progressively in replacing cast-in place rebars in some applications by offering equivalent or even higher mechanical properties at ambient temperature [1]. However, the mechanical behaviour of post-installed rebars is essentially governed by the mechanical behaviour of polymer resins, which is highly sensitive to temperature [2]. Consequently, fire safety is a serious problem when using post-installed rebars in constructions. In addition, very few regulations and technical documents [3] [4] exist today proposing methods to assess and to design the fire resistance of chemical anchors.

This paper presents a full-scale fire test performed on “Vulcain” modular gas furnace of Centre Scientifique et Technique du Bâtiment, carried out on a 2.94 m x 2 m x 0.15 m cantilever concrete slab connected to a wall using 8 post-installed rebars and exposed to ISO fire 834-1 [5] until failure (*Fig. 1*). The main goal is to **validate a design model suggested to determine the fire resistance of chemical anchors using pull-out test results**. The first part of this paper describes the test configuration and explains the design method. The second part presents the experimental results obtained during the fire test and compares between the predicted and the measured time of collapse.

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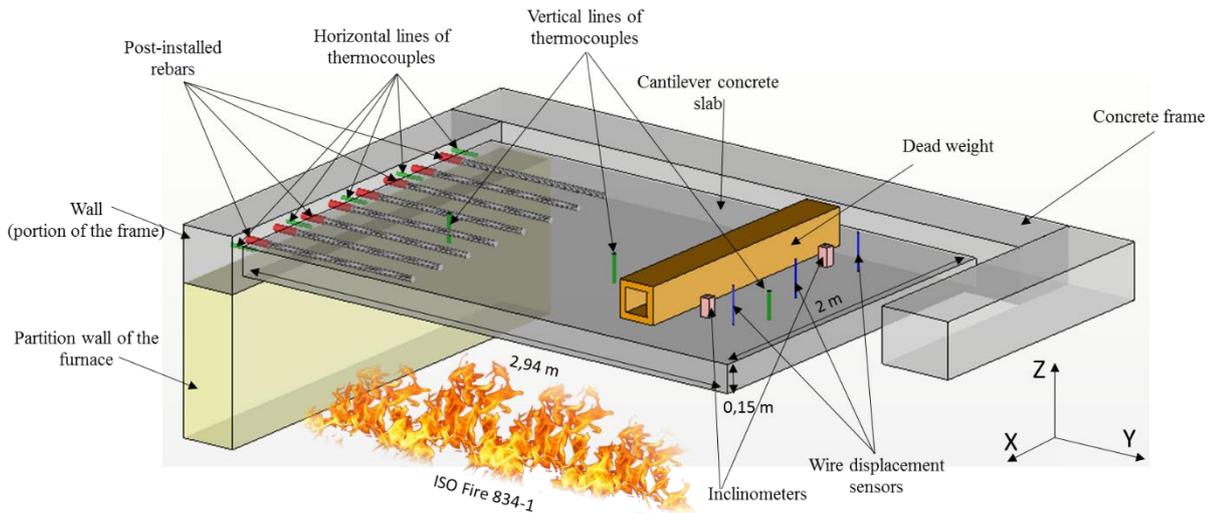


Fig. 1. Vulcain fire test configuration: Instrumentation and set up on the furnace

2 TEST SPECIMEN CONCEPTION AND FIRE RESISTANCE CALCULATION

2.1 Test specimen conception

A full-scale ISO fire 834-1 [5] test was carried out at CSTB Champs-sur-Marne on the “Vulcain” modular gas furnace. This furnace offers three possible exposure areas to perform fire tests on a horizontal configuration: 3m x 3m, 4m x 3m and 7m x 3m. The chosen configuration was 4m x 3m. The set-up of the test specimen on the furnace required the presence of a concrete frame allowing to close the furnace and to ensure its fire integrity during test. The concrete frame was made from a C35/45 fibre reinforced concrete and represents the wall in which post-installed rebars were anchored. The test specimen was composed of a 2.94 m x 2 m x 0.15 m cantilever slab made from C20/25 fibre reinforced concrete, connected to the wall through 8 post-installed rebars bonded into concrete using epoxy resin (Fig. 1). Characterization tests were carried out on cubic concrete samples (150 mm x 150 mm x 150 mm) after 28 days of curing under ambient temperature and moisture conditions. The concrete used for the frame had a compressive strength of 58.7 MPa and a density equal to 2263 kg/m³, while the concrete used for the cantilever slab had a compressive strength of 22.4 MPa and a density equal to 1987 kg/m³. The number of post-installed rebars was determined according to the EC2 design rules [6] which allow a maximum spacing between bonded rebars equal to two times the thickness of the slab. The diameter of the steel rebars was 16 mm. The embedment length was set at 135 mm in order to ensure a failure by rebars sliding during fire test. The rebars were positioned at 100 mm height in the cantilever slab, respecting the minimum concrete cover authorized by EC2 [6]. A spacing of 80 mm at the sides and 200 mm at the free end of the cantilever slab was left to take into account the concrete thermal expansion and to prevent the blocking of the cantilever slab against the frame during fire test. The fire test was performed a little more than 3 months after the concrete casting.

2.2 Fire resistance calculation

A fire design model is proposed in this paper allowing to estimate the fire resistance of post-installed rebars. This model relies on the knowledge and the determination of several parameters. The fire resistance calculation of chemical anchors using the suggested model is composed of 5 steps.

2.2.1 Calculation of the tensile load applied on the anchor F_{app}

The determination of the tensile load applied on each anchor can be done either by analytical calculations or by finite element analysis. This step requires the knowledge of certain parameters such

as the geometrical parameters of the slab, the concrete density, the applied mechanical load, the load position and rebars position in the slab...

The determination of the applied tensile load on each rebar is based on the assumption of a uniform load distribution between the anchors. Calculations showed that for the studied configuration, the tensile load applied on each anchor, considering a uniform distribution between the anchors, is around 70 kN.

2.2.2 Calculation of temperature profiles $\theta(x,t)$

This step consists in determining the temperature distribution in the test specimen at different moments of fire exposure using thermal calculations. Thermal calculations can be done either by finite element analysis, or by analytical calculations using finite difference method based on Fourier equation (Eq. (1)). These two calculation methods require the knowledge of the variation of the thermal properties of the materials composing test specimen ($\lambda(\theta)$, $C_p(\theta)$ and $\rho(\theta)$), which can be obtained directly from the Eurocode [6].

$$\rho(\theta(x,t)).C_p(\theta(x,t)).\frac{\partial\theta(x,t)}{\partial t}=\lambda(\theta(x,t)).\frac{\partial^2\theta(x,t)}{\partial x^2}+h.(\theta_{ext}(t)-\theta_{sur}(t))+\sigma.\varepsilon.(\theta_{ext}^4(t)-\theta_{sur}^4(t)) \quad (1)$$

Where ρ is the material density [kg/m^3]

C_p is the material specific heat [$\text{J} \cdot \text{K}^{-1} \cdot \text{Kg}^{-1}$]

λ is the material conductivity [$\text{W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$]

$\theta(x,t)$ is the temperature of an element of the anchor at position x and at time t [K]

h is the heat transfer coefficient [$\text{W} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$]

σ is the Stefan-Boltzmann constant [$\text{W} \cdot \text{m}^{-2} \cdot \text{K}^{-4}$]

ε is the emissivity of the material

θ_{ext} is the exposure temperature [K]

θ_{sur} is the temperature at the surface of the material [K]

At the end of this first step, a temperature map is obtained, indicating the exact temperature values at every point in the test specimen and at different moments of fire exposure.

2.2.3 Bond resistance-Temperature relationship $\tau_{max}(\theta)$

The bond resistance-temperature relationship is obtained by performing pull-out tests at different temperatures on post-installed rebars anchored in concrete cylinders. These tests consists in applying a constant load on the anchor and then heating the test specimen progressively until the extraction of the rebar (Fig. 2). Thus, this test procedure, called “pull-out tests at constant load”, provides a failure temperature for selected amounts of shear stresses applied on the adhesive joint.

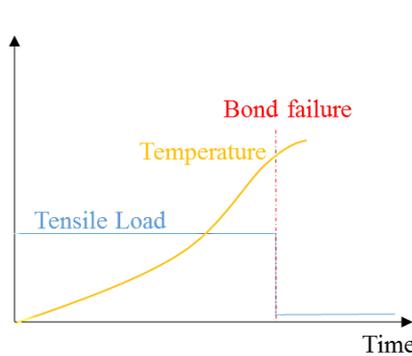


Fig. 2. Test procedure of pull-out test at constant load

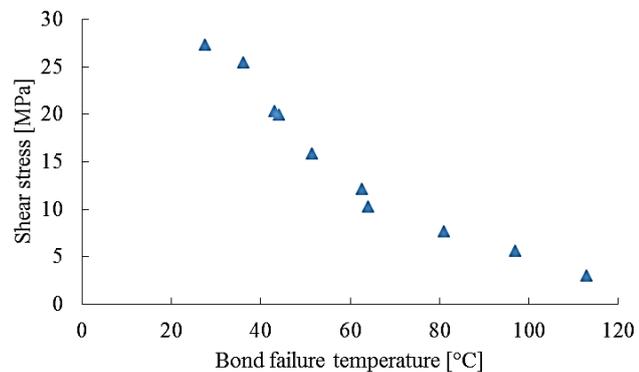


Fig. 3. Results of pull-out tests at constant load

2.2.4 Calculations of the anchor load bearing capacity F_t

The calculation of the evolution of the anchor load bearing capacity during fire exposure is carried out in two stages:

The first stage consists in associating a bond resistance value to each element of the anchor at different moments of fire exposure by knowing the temperature evolution obtained by thermal calculations and by using the relationship bond resistance-anchor temperature. The second step consists in summing the bond resistance values along the anchor for a given moment of the fire exposure as described by Eq. (2):

$$F_t = 2\pi r \int_0^L \tau_{max}(\theta(x,t)) dx \quad (2)$$

Where F_t is the load bearing capacity of the anchor at time t [N]

r is the radius of the steel rebar [mm]

L is the embedment length [mm]

τ_{max} is the bond resistance obtained by pull-out tests [MPa]

$\theta(x,t)$ is the temperature of an element of the anchor at position x and at time t [K].

Table 1 summarizes the evolution of the calculated load bearing capacity of the anchors during fire exposure.

Table 1. Evolution of anchors load bearing capacity during fire test

Fire exposure [min]	Load bearing capacity [kN]		Applied load [kN]
0	178	>	70
30	178	>	70
60	144	>	70
90	101	>	70
120	67	<	70
180	31	<	70

2.2.5 Time of collapse

The fire resistance design model assumes that failure occurs when the shear stress reaches the bond resistance at all the elements of the anchor. Therefore, the time collapse is considered as the time at which the anchor load bearing capacity becomes equal to or lower than the tensile load applied on the anchor. Thus, according to calculations, the failure must occur after about **2 hours** of fire exposure.

3 VALIDATION TEST: FULL-SCALE FIRE TEST ON A CANTILEVER CONCRETE SLAB

3.1 Specimen instrumentation

3.1.1 Temperature measurements

In order to study the temperature increase during fire test, rows of thermocouples have been installed at different positions in the test specimen (Fig. 1):

- 5 rows of thermocouples were introduced horizontally into the wall, at the same height as the anchors and positioned respectively at 111 mm, 555 mm, 1000 mm, 1450 mm and 1889 mm from the lateral side of the slab. Each row was composed of 5 thermocouples positioned respectively at 10 mm, 20 mm, 30 mm, 100 mm and 150 mm depth. These thermocouples measure the temperature increase at the anchors during the fire test.
- 3 rows of thermocouples were introduced vertically at the mid-width into the slab, at 500 mm, 1500 mm and 2440 mm from the wall respectively. Each row was composed of 5 thermocouples

positioned respectively at 10 mm, 20 mm, 30 mm, 70 mm and 100 mm from the fire exposed surface of the slab. These thermocouples measure the temperature increase inside the slab during fire exposure.

Gas temperature inside the oven was controlled by 6 pyrometer plates positioned below the test specimen.

3.1.2 Displacement measurements

The measurement of the vertical displacement of the slab during the test was carried out using three wire displacement sensors attached to the slab at 2600 mm from the wall and at 500 mm, 1000 mm and 1500 mm from the lateral side of the slab (*Fig. 1*). These displacement sensors were attached to a metal piece positioned above the test specimen allowing the measurement of the relative displacement of the slab against the concrete frame (*Fig. 5*).

In addition to displacement sensors, a stereo digital images correlation system positioned above the test specimen was used to measure displacements over the whole test specimen during the fire test. Besides displacement measuring, the digital images correlation system allows to identify the zones of strain concentration and thus allows to identify the zones which present a risk of crack formation and propagation. Therefore, Digital images correlation system allows a better understanding of physical phenomena that occur during the fire test.

3.2 Test description

The test specimen was positioned on the top of the furnace. The wall and the partition wall of the furnace were positioned at the same level in order to reproduce a fire situation in a real cantilever slab connected to a wall using post-installed rebars. This wall position allows to avoid the formation of a shadow inside the furnace which may disturb the radiative heat transfer and hence could modify the temperature increase inside the test specimen. The cantilever concrete slab was mechanically loaded by a 325 kg dead weight, centred and positioned at 2200 mm from the wall (*Fig. 1*) and thermally loaded by ISO fire 834-1 (*Eq. (3)*) until its failure.

$$\theta_{gas}(t) = 20 + 345 \cdot \log_{10}(8 \cdot t + 1) \quad (3)$$

Where θ_{gas} is gas temperature in the furnace [K]
 t is the time of fire exposure [min]

4 RESULTS AND DISCUSSION

4.1 Experimental observations

The mechanical loading of the cantilever slab induced by the dead weight had generated a vertical downward displacement equal to -5.8 mm. This displacement is composed of a mechanical displacement due to the bending of the slab under the loading effect ($\Delta l = -0.8$ mm) and of a geometrical displacement due to the angle created by the slip of the rebars ($\alpha = 0.1^\circ$, $\Delta l = -4.9$ mm).

The slab mechanically loaded has been set as the reference state in the rest of this study. The moment $t=0$ is considered as the moment of the ignition of the furnace burners. Therefore, the vertical displacement of the slab under mechanical load will not be taken into consideration in the following study.

After few minutes of fire exposure, a vertical upward displacement of the slab was observed due to a thermal curvature (Paragraph 4.2). The failure occurred after **1h57min** of fire exposure caused by the anchors bond failure and the fall of the slab inside the furnace.

4.2 Displacements analysis

Displacements recorded by wire displacement sensors (*Fig. 4*) highlighted a thermal curvature manifested by an upward displacement of the slab since the first minutes of fire exposure. This phenomenon appears due to a differential thermal expansion between the fire exposed and non-exposed surfaces of the concrete slab. Indeed, the concrete directly exposed to fire expands under the

heat effect, while the concrete non-exposed to fire expands very little. The difference in thermal expansion leads consequently to the curvature of the slab. As the rotational movements of the slab in the anchored side are blocked by the rebars, the free part of the slab curves and rises upward.

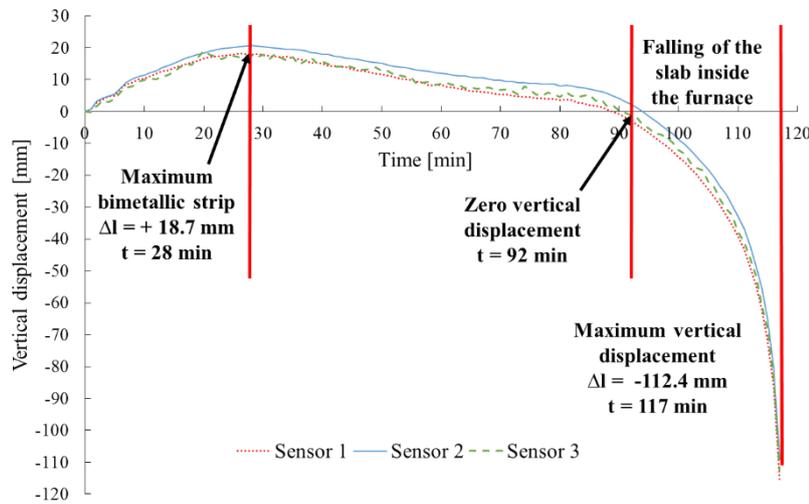


Fig. 4. Vertical displacements evolution during the fire test

The maximum measured value of vertical displacement due to the thermal curvature was 18.7 mm reached after 28 minutes of exposure to ISO Fire 834-1 ($\theta_{gas}(28_{min}) = 832^{\circ}C$).

Beyond 28 min of fire exposure, the slab started falling slowly inside the furnace. The zero value of vertical displacement was reached again after 92 min of fire exposure. The downward displacement of the slab could be explained by the progressive decay in the load bearing capacity of post-installed rebars as a result of temperature increase at the anchors.

Starting from 109 min of fire exposure, the decay in the bearing capacity of the anchors becomes more and more important and the slab falls more quickly inside the furnace until the total bond failure after 117 min of fire exposure.

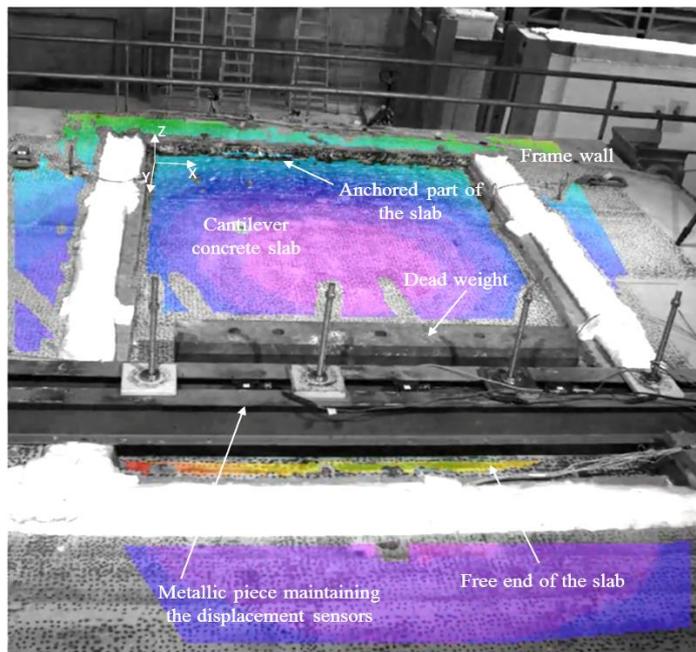


Fig. 6. Fields of vertical displacement recorded by DIC during the fire test

Displacements recorded by wire displacement sensors during fire test show that displacements measured by the sensor positioned at the mid-width of the slab (sensor 2) are slightly greater than the displacements measured by the two lateral sensors which indicate sensitively identical values. These displacement values signify that the concrete slab has curved under the thermal effect in a symmetrical manner to an axis passing through its mid-width plan. This interpretation was confirmed by analysing the results obtained from the stereo digital images correlation system (DIC) which has shown that under the thermal effect, the vertical displacement fields were concentric, which means that the slab had bent symmetrically in its centre (*Fig. 5*).

4.3 Thermal analysis

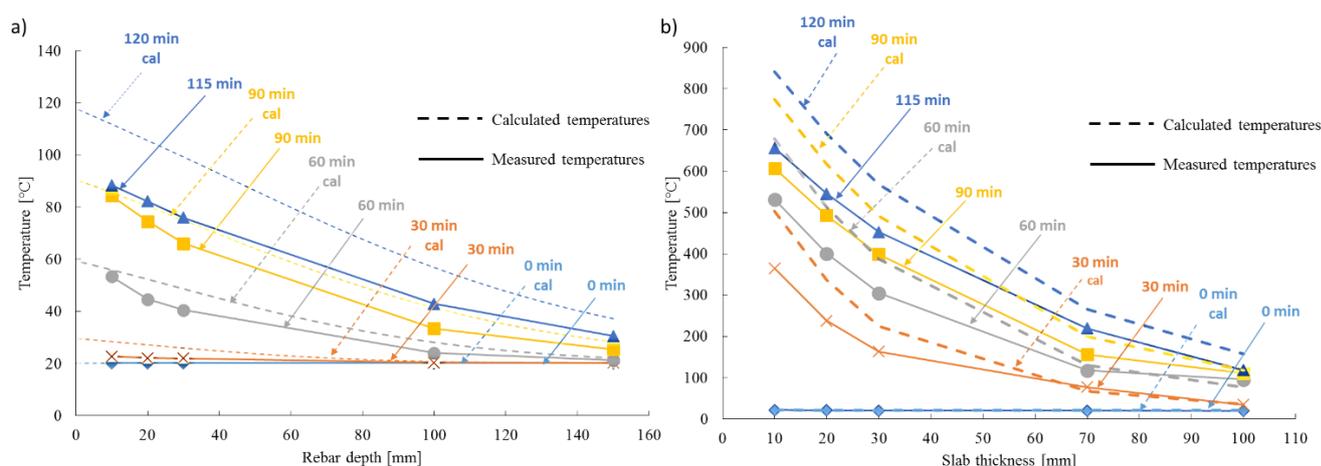


Fig. 7. Experimental and numerical temperature profiles. a) At the anchors. b) In the slab

Thermal profiles recorded by the thermocouples inserted inside the wall (*Fig. 7.a*) show a non-uniform distribution of temperature along the anchors. Indeed, the heating of the slab generated a thermal gradient at the anchors. The top of the anchors presented the highest temperatures while the bottom has the lowest temperatures. The maximum temperature recorded at the top of the anchor was 89°C reached at the moment of the slab collapse.

The comparison between measured and calculated thermal profiles shows that calculated temperatures are higher than measured temperatures. This difference between thermal profiles can be explained on one hand by the use of materials thermal properties provided by EC2 [6] for temperature calculations, which leads to an overestimation of temperatures due to the safety aspect of EC2. On the other hand, this difference may be attributed to the non-consideration of the thermal bridge generated by the steel rebars prolonged inside the slab (*Fig. 1*) when measuring temperatures with thermocouples. In fact, thermocouples measured only the temperature of the concrete wall, and therefore do not consider the contribution of the steel rebars in the heat transfer. Consequently, the anchors temperatures measured by thermocouples can be underestimated.

Similarly, the calculated temperatures in the slab (*Fig. 7.b*) were higher than temperatures measured using vertical lines of thermocouples due to the use of EC2 parameters in thermal calculations which leads to overestimate the temperature profiles.

4.4 Failure mode analysis

The fractography analysis showed the presence of a mixed failure mode along the anchor as shown in *Fig. 8*. A resin/ concrete interface failure mode was observed at the top of the anchor, up to the two thirds of the embedment length, while the last third of the embedded part of the anchor presented a steel/resin interface failure mode. This mixed failure mode is the result of a significant thermal gradient present at the anchor at the moment of failure and indicates that the ruin had mainly occurred due to the resin glass transition which led to a significant decay in the anchors load bearing capacity.

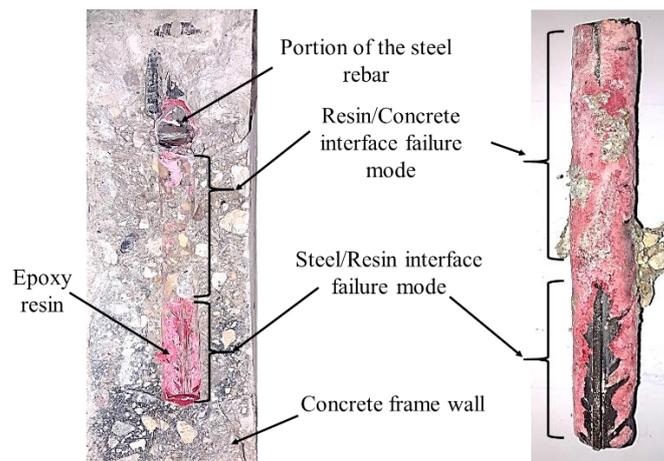


Fig. 8. Failure profile observation after the fire test

5 CONCLUSION

This paper presented a full-scale fire test which was carried out on the CSTB modular gas furnace “Vulcain” in order to validate a computation design method for fire resistance of post-installed rebars. From this study it can be concluded that:

- It is possible to predict the fire resistance of post-installed rebars using thermal calculations and knowing the evolution of the bond resistance under thermal effect.
- The slab failure occurred after 1h 57 minutes of ISO Fire 834-1 exposure, i.e. only 3 minutes before the fire resistance duration predicted by the model. This result confirm the robustness of the calculation method in predicting the fire resistance duration of post-installed rebars and shows that the established assumptions are in good agreement with the reality.
- The fire test highlighted the presence of a thermal curvature of the slab and a bond slip failure.
- The fractography showed the presence of mixed failure mode along the anchors indicating that the resin glass transition was responsible for the slab collapse.

REFERENCES

- [1] Bouazaoui L., Li A. (2008). *Analysis of steel/concrete interfacial shear stress by means of pull out test. International Journal of Adhesion and Adhesives*. International Journal of Adhesion and Adhesives 28 (2008), 101-108 pp.
- [2] Nigro E., Bilotta A., Cefarelli G., Manfredi G., Cosenza E. (2012). *Performance under fire situations of concrete members reinforced with FRP rods: Bond models and design nomograms*. Journal of composites for construction, 16 (2012), August 2012, 395-406 pp.
- [3] EOTA. (2015). *EAD 330087-00-0601, Systems for post-installed rebar connections with mortar*. EOTA 14-33-0087-03.01, July 2015.
- [4] Construction Fixings association. (1198). *CFA Guidance Note: Fixings and Fire*. August 1998.
- [5] CEN. (2002). *EN 1991-1-2. Eurocode 1, Part 1-2: Actions on structures: general actions – actions on the structures exposed to fire*. Brussels, Belgium 2002.
- [6] CEN. (2005). *EN 1992-1-2 Eurocode 2. Part 1-2: Design of concrete structures - General Rules - Structural fire design*. Brussels, Belgium 2005.
- [7] Muciaccia G., Consiglio A., Rosati G. (2016). *Behavior and Design of Post-Installed Rebar Connections under Temperature*. Key Engineering Materials 711 (2016). 783-790 pp.