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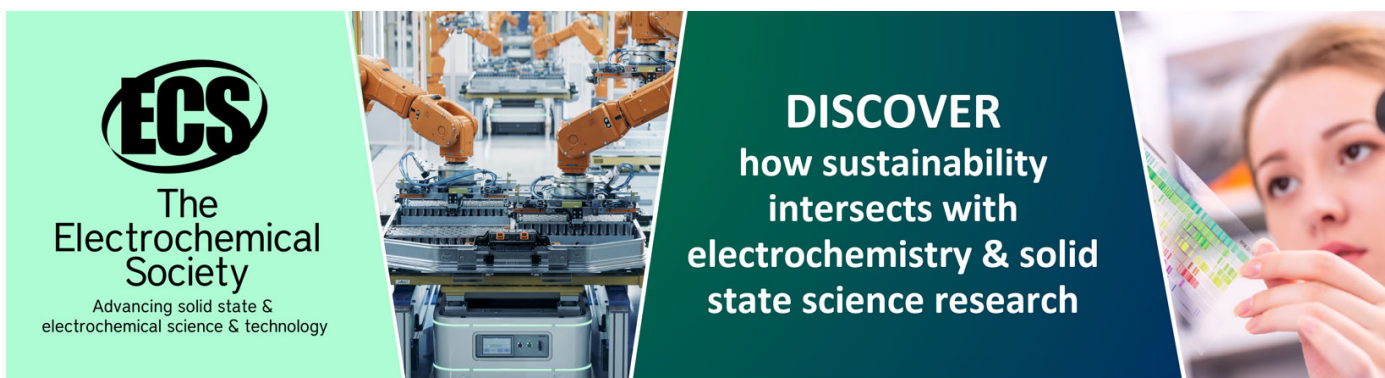
Parametric study of factors influencing the thermal distribution and load-bearing capacity of bonded anchors directly exposed to fire

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Parametric study of factors influencing the thermal distribution and load-bearing capacity of bonded anchors directly exposed to fire

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Abstract. Pull-out has been proved to occur more often for bonded anchors under tensile loads at high temperatures than at ambient temperature. The existing evaluation method of bonded anchors under fire only covers steel failure mode. Due to the absence of guidelines for evaluating the pull-out of bonded anchors directly exposed to fire, only the evaluation method for mechanical anchors (without resin) is applicable. This paper presents an experimental study on the influence of different parameters linked to the existing evaluation method by means of pull-out fire tests. Additional unloaded fire investigation tests were conducted to compare different configurations of pull-out fire tests. This paper highlights the level of accuracy of load prediction using the resistance integration method based on temperature profiles of bonded anchors directly exposed to a standard ISO 834 fire. Results showed that parameters such as the existence of metallic fixtures on the rod barely influence the predicted load-bearing capacity and failure time. However, parameters such as adopting concrete element temperature along the thickness instead of steel temperature along the embedment depth, and the existence of insulation around the fixture have a greater influence and may result in a false estimation of the load-bearing capacity and failure time.

1. Introduction

Bonded anchors are a construction technique consisting of anchoring a threaded rod in a drilled hole in a hardened concrete element using an adhesive resin. This technique allows a fast installation and presents similar or greater bond strength compared to mechanical anchors at service temperature [1]. However, the high sensitivity of the adhesive resin to the increase of temperature leads to the degradation of its mechanical properties. This results in a decrease of bond strength and leads to the incapacity of this type of anchors to support applied loads in fire situations.

The mechanical properties of the resin vary strongly from one product to another and depend on their quantity in the bearing element, as well as the employed anchor type [2]. Adhesive resins used for bonding anchor elements in concrete can consist of polyester, vinylester and epoxy resins [3]. Many researchers consider the glass transition of polymers at high temperatures as an indicator of their durability [4]. The mechanical properties of adhesive resins were investigated by Pinoteau [5].



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The assessment and design of the load-bearing capacity of bonded anchors under fire are defined in the technical report EOTA TR 020 [6]. The fire-resistance duration for a certain applied load can be given by establishing the bond resistance vs. fire exposure time relationship. This relationship can be obtained by performing fire tests on anchors following the guidelines in the Technical report EOTA TR 020 [6]. A bonded anchor can reach failure under tensile loads by many failure mechanisms: a) concrete failure (concrete cone or concrete splitting), b) steel failure, c) combined failure (concrete cone + bond failure + possibly tensile failure at the lower part of the adhesive) and d) bond failure by pull-out of the anchor [7]. Only steel failure mode is covered for bonded anchors under fire in this guide.

Research studies have shown that pull-out failure mode for bonded anchors may occur more frequently than other failure modes under fire. Thus, for safety reasons, it is the most decisive failure mode for bonded anchors under fire. Reichert and Thiele [8] conducted a study on a combination of different types of fire tests and numerical simulations on bonded anchors. This work demonstrated that the existing guidelines in the technical report EOTA TR 020 [6] are not clear till today.

Similar testing conditions in the technical report EOTA TR 020 [6] were studied by Lakhani and Hofmann [9] by means of finite element numerical modeling. The thermal distribution of the configuration where the anchor was directly exposed to fire (anchor acts as heat transfer path) was much higher than the configuration where the anchor was insulated (along with a fixture). This large difference may lead to a pull-out failure for non-insulated anchors which occurs faster than the failure of insulated anchors.

In this paper, tested bonded anchors were threaded rods fastened using an epoxy resin. In order to obtain a good prediction of the resistance of tested bonded anchors under fire, the resistance integration method was adopted. The resistance integration method requires a good knowledge of temperature profiles along the embedment depth of the anchor. The obtained temperature profiles are used then to establish a bond strength vs. temperature relationship by dividing the anchor into little segments. Each segment is attributed a certain bond resistance as a function of its average temperature using the test procedure described in EAD 330087-00-0601 [10]. The resistance integration method presented promising results for different types of bonded anchors, such as the prediction of pull-out failure of post-installed rebars at high temperatures [11-13], and the determination of pull-out strength of bonded anchors directly exposed to fire [9].

It is difficult to precisely estimate the bond strength vs. fire exposure time relationship. In order to get a better understanding of the behavior of bonded anchor systems directly exposed to fire, this experimental study explored the influence of the following parameters on the precision of failure prediction using the resistance integration method:

- Adopting concrete temperature along the concrete element thickness instead of steel temperature at the steel/resin interface.
- Existence of a metallic fixture on the anchor.
- Existence of insulation around the fixture.

2. Experimental study

Fire tests were conducted at the fire resistance laboratory, CSTB, using a gas furnace with the following dimensions: 1.4 m of length, 1 m of width and 1.05 of height. The temperature inside the furnace was controlled to follow the ISO 834 [14] fire curve. Furnace temperature (T) is measured using plate thermometers. It should be measured and controlled by following equation (1):

$$T=20+345\log_{10}(8t+1) \quad (1)$$

Figure 1 shows the used loading system and furnace. The furnace satisfies the requirements of fire resistance studies in the international standard ISO 834 [14]. Therefore, thermal exposure is uniform on all samples. According to the technical report EOTA TR 020 [6] a steel fixture must be attached to the anchor to transfer the tensile loads from a tension member. Only fixture dimensions are detailed in the

technical report. The insulation ensures that the steel of the fixture does not reach failure before the pull-out of the anchor. However, many anchor systems use non-insulated fixtures.

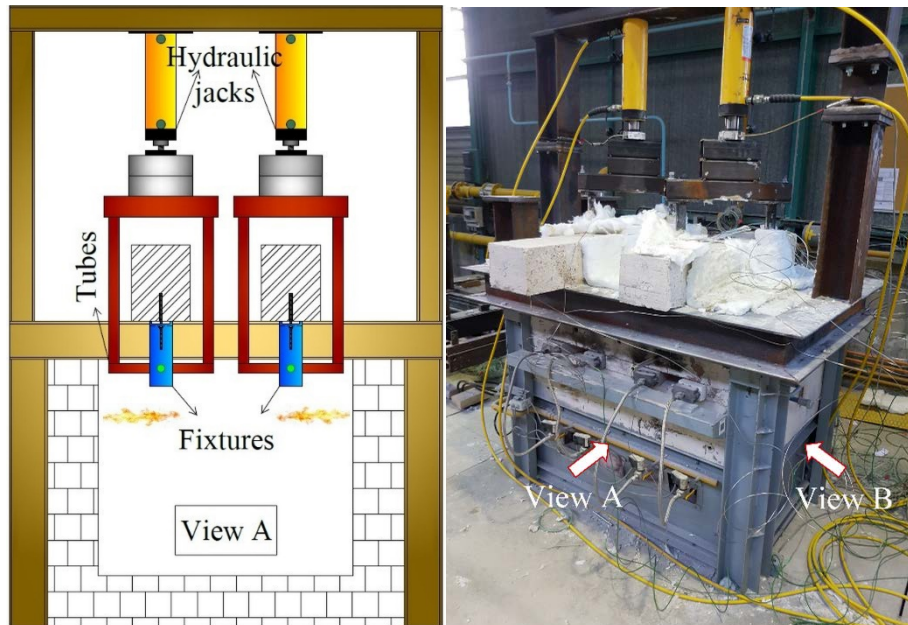


Figure 1. View A (left) and photo (right) showing the gas furnace and the loading system.

Bonded anchors were installed on the exposed surface. A loading system was put on top of the furnace for three loaded pull-out fire tests. In order to ensure a one-dimensional heat-transfer inside the beams and along the bond, the lateral faces of the beams were insulated. Bonded anchors were fastened using a polymer-based resin with a 2 mm thickness around the rod diameter. In order not to avoid influencing the bond surface between adhesive resin and steel of the rod, no thermocouples were positioned on the mechanically loaded anchors. Another unloaded anchor rod was instrumented with at least 4 thermocouples and installed in the same beam as the loaded one. The instrumented anchor is not loaded (does not interact with the loaded anchor). Thus, a distance of 150 mm distance was chosen between the loaded anchor (centered above the furnace) and the unloaded one.

As recommended in the details of the technical report EOTA TR 020 [6] and in order to reuse the metallic parts transferring the load to the fixture and the metallic tubes, insulation using a glass wool based material was put around these elements with a thickness of 50 mm. The adhesive resin presents a bond stress up to 25 MPa at ambient temperature for threaded rods with a diameter below 16 mm.

Temperature profiles along the embedment depth of unloaded anchors were measured during the fire tests. The resistance integration method used these temperature profiles as entry data to calculate the bond-stress vs. temperature and bond stress vs. fire exposure time relationships. This is done with the help of the characterization of the mechanical properties of the adhesive resin according to [10]. In this paper, the application of loads was only to validate the predicted failure times obtained from the resistance integration method.

2.1. Loaded pull-out tests

The conducted pull-out fire tests are summarized in table 1.

It is concluded that predicted failure time for high load levels is more accurate than for low load levels ($< 6\%$ of the reference bond stress at ambient temperature = 1.5 MPa). The hypothesis that unloaded anchors emulate the same temperature profiles as loaded anchors leads to uncertain results for failure time prediction. This requires further investigation tests to determine the influence of the loading system on thermal diffusion and the precision of the prediction method.

Table 1. Details of loaded pull-out fire tests.

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

2.2. Unloaded thermal investigation tests

Studies on other types of anchors in concrete at high temperatures have shown that thermal boundary conditions of test setup have a significant influence on the prediction of the anchor's resistance [15]. During the unloaded thermal investigation tests; beams were only subjected to their weight and thermal loading due to fire exposure. Two beams were tested at a time with two bonded anchors installed in each beam with the same test configuration. The configuration of these anchors varies from one test to another according to the studied parameter. During thermal investigation tests, no load was applied on tested bonded anchors. Measured temperature profiles served to determine bond resistance vs. fire exposure time relationship using the resistance integration method.

2.3. Experimental results

2.3.1. Adopting concrete temperature along the concrete element thickness instead of steel temperature at the steel/resin interface. In the work of Pinoteau [5] and Lahouar [16] on bonded anchors in concrete, the effect of steel was not taken into account for calculating temperature profiles along the bond. Concrete temperature in the same position of the anchor was adopted in the resistance integration method. This hypothesis may be valid for post-installed rebars in concrete where the thermal diffusion occurs via the concrete. In the case of anchors directly exposed to fire, the rod behaves like a heat transfer path and thermal diffusion occurs via the steel of the anchor and concrete simultaneously. In order to determine the influence of this parameter, anchors were directly exposed to fire without any fixtures or insulation.

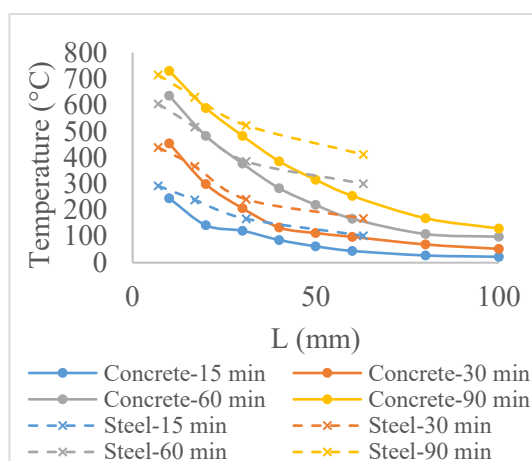


Figure 2. Comparison between the thermal gradient of the beam and the temperature profile of the anchor.

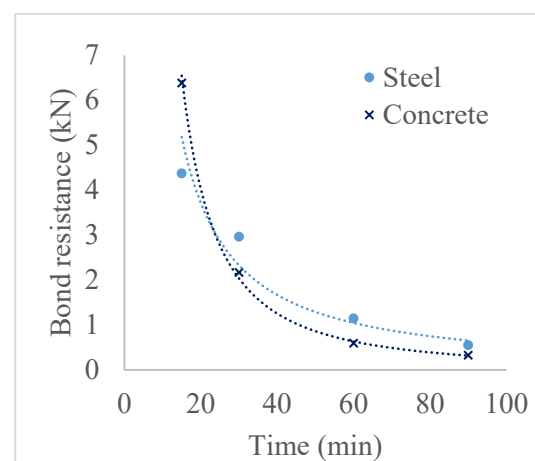


Figure 3. Comparison between resistance integration results based on concrete and steel temperature.

Figure 2 presents temperature profiles measured at the steel/resin interface and concrete temperature at the same distance from the fire exposed surface. Results show that steel homogenizes its temperature faster than concrete due to its higher conductivity. The resistance integration method was applied to the first 60 mm of concrete and steel using temperature plotted in figure 2 for a bond stress of 0.43 MPa (corresponding to 1.7% of the reference bond stress at ambient temperature). Figure 3 presents the results of the resistance integration method based on concrete and steel temperature. A difference up to 27% in the calculation of failure time prediction can occur. This difference is not negligible. The adoption of concrete temperature instead of steel temperature leads to a false estimation of failure for low and high load levels.

2.3.2 Influence of the existence of a metallic fixture on anchors. Concrete beams exposed to fire are subjected to one-dimensional heat-transfer. A different thickness leads to a different boundary condition and may influence temperature profiles along the embedment depth of anchors. Three different beam thicknesses were tested: 150 mm, 180 mm and 300 mm. Figure 4 shows the temperature of the unexposed surface with fire exposure time. Two unloaded bonded anchors with a diameter of 8 mm and an embedment depth of 70 mm were installed in two different beams (thicknesses 180 mm and 300 mm) and were directly exposed to fire. Figure 5 presents temperature profiles for both anchors.

The resistance integration method was applied on both cases for a stress of 0.43 MPa (corresponding to 1.7% of the reference bond stress at ambient temperature). The predicted failure times were: 75 min for the anchor installed in the 180 mm thickness beam, and 71 min for the anchor installed in the 300 mm thickness beam. The influence of concrete element thickness is most likely negligible for high and low load levels.

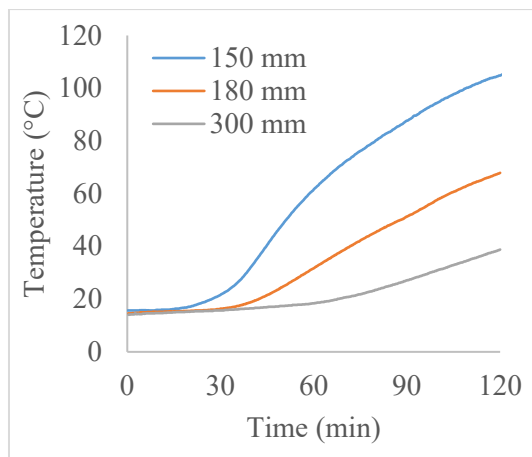


Figure 4. Comparison between the temperatures of the unexposed surface vs. Time for different beam thicknesses.

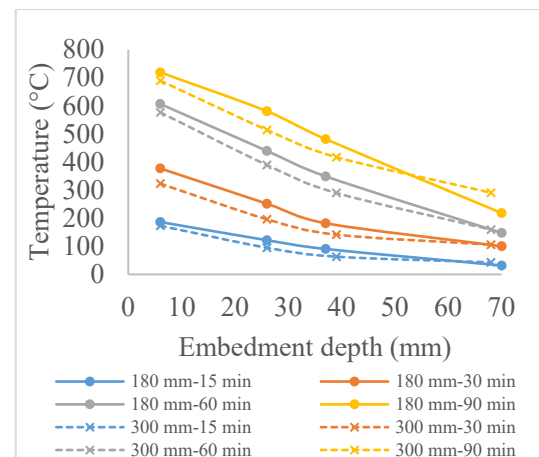


Figure 5. Comparison between temperature profiles vs. Embedment depth for two anchors in different beam thicknesses.

2.3.3 Influence of the existence of a metallic fixture on the anchor. Unloaded bonded anchors with a diameter of 12 mm and an embedment depth of 110 mm installed in a 300 mm thickness beams were tested under fire with and without fixtures. Figure 6 presents the measured temperature profiles for both cases. A slight difference is noticed near the fire exposed surface up to 90 min of fire exposure. After 90 min, fixture temperature seems to homogenize with furnace temperature. Without the existence of the fixture, heat transfer mostly occurs by radiation.

The resistance integration method was applied to quantify the influence of the existence of a fixture on the anchor, for a bond stress of 0.43 MPa (corresponding to 1.7% of the reference bond stress at ambient temperature). The predicted failure times were: 74 min for the rod without fixture, and 80 min for the rod with fixture. However, for a bond stress of 2.17 MPa (corresponding to 8.7% of the reference

bond stress at ambient temperature), the predicted failure times were: 27 min for the rod without fixture, and 28 min for the rod with fixture. Figure 7 shows that the existence of a fixture barely influences failure time prediction for both high and low load levels at high temperatures.

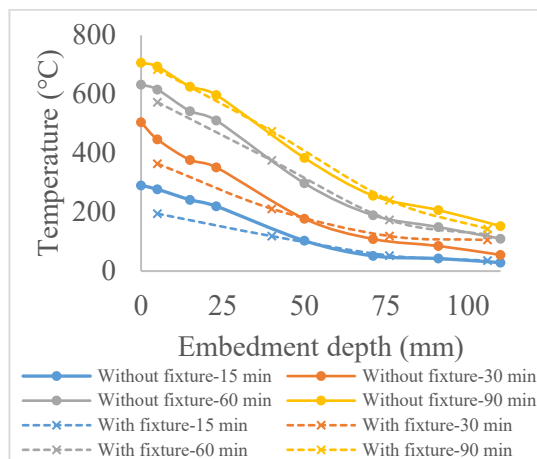


Figure 6. Comparison between temperature profiles for bonded anchors with/without a fixture.

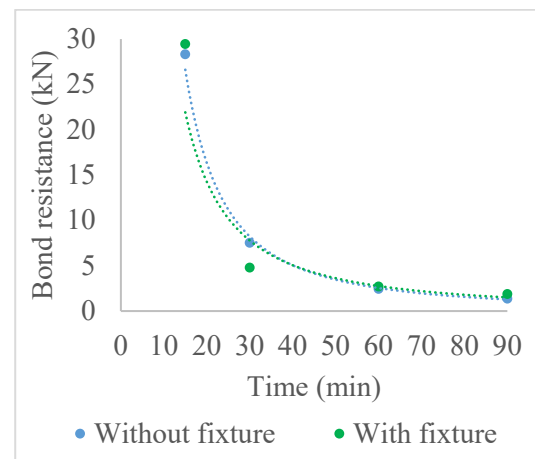


Figure 7. Bond stress vs. Fire exposure time for anchors with/without fixtures.

2.3.4 Influence of insulation. In order to assess the influence of insulation around the fixture, unloaded bonded anchors with a diameter of 12 mm and an embedment depth of 110 mm installed in a 300 mm thickness beams were tested with fixtures, and with/without insulation around fixtures. Insulation used a glass wool-based material with a thickness of 50 mm. Results presented in figure 8 show a significant reduction in temperature profiles for bonded anchors with insulated fixtures.

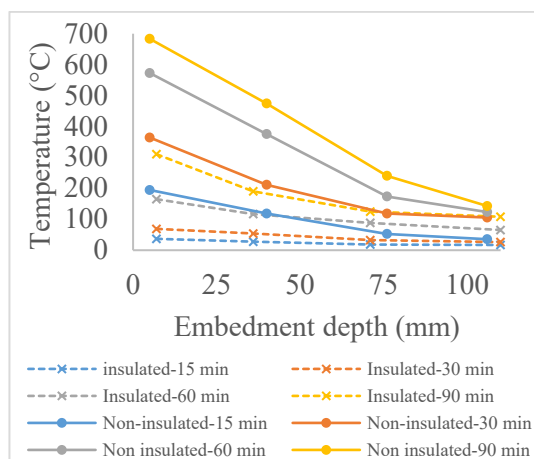


Figure 8. Comparison between thermal profiles for anchors with insulated and non-insulated fixtures.

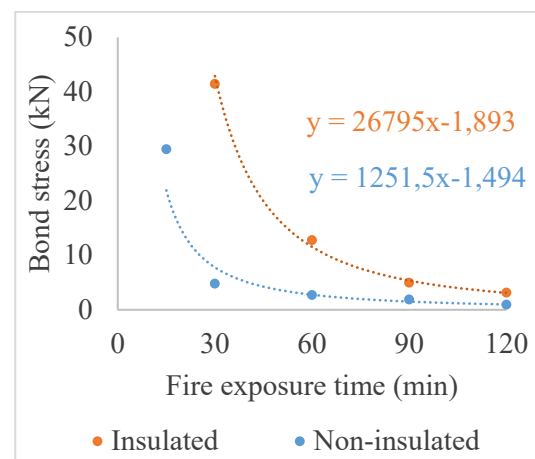


Figure 9. Bond stress vs. fire exposure time for bonded anchors with insulated and non-insulated fixtures.

The resistance integration method was applied (figure 9). For a bond stress corresponding to 1.7% of the reference bond stress, predicted failure times were: 80 min for the rod with non-insulated fixture, and 160 min for the rod with insulated fixture. For a stress corresponding to 8.7% of the reference bond stress at ambient temperature, predicted failure times were: 28 min for the rod with non-insulated fixture, and 69 min for the rod with insulated fixture. Fixture insulation influences significantly the precision of failure time prediction for both high and low level loads at high temperatures.

3. Conclusion

The influence of the following parameters on the precision of failure prediction using the resistance integration method was studied: Adopting concrete element temperature instead of steel temperature at the steel/resin interface, concrete element thickness, existence of a metallic fixture on the anchor and fixture insulation. Testing derived the following conclusions:

- Using concrete element temperature instead of steel temperature at the steel/resin interface in the resistance integration method time may result in a non-conservative estimation of the load-bearing capacity and the resulting failure time.
- Fixture existence on the anchor has low influence of the prediction of the load-bearing capacity and failure time.
- Insulation around fixtures significantly decreases temperature profiles by reducing heat transfer to conduction via concrete only. This delays the degradation of the mechanical properties of the bond and hence failure time by 30-60 min.

The current guidelines for evaluating the pull-out strength of bonded anchors directly exposed to fire require more details for test setup.

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