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Fire design of post-installed bonded rebars: Full-scale validation test on a 2.94 × 2 × 0.15 m^3 concrete slab subjected to ISO 834-1 fire

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ABSTRACT

Thanks to the improvement in mechanical and adhesion properties of polymer resins, Post-Installed Rebars (PIRs) succeeded progressively in replacing cast-in place rebars in some applications by offering equivalent or even higher mechanical properties at ambient temperature. However, the mechanical behavior of PIRs is essentially governed by the mechanical behavior of polymer resins, which is highly sensitive to temperature. Consequently, fire safety presents a potential hazard that should be taken into account when designing. This paper presents an experimental full-scale fire test carried out on the Vulcain furnace of CSTB Champs-sur-Marne on its 7 m × 3 m horizontal configuration, in order to test a new fire design method proposed for PIRs. The 2.94 × 2 × 0.15 m^3 tested slab was mechanically loaded by 325 kg and heated following the ISO 834-1 time-temperature curve until its collapse. The experimental time of collapse is compared to that predicted by the new design method.

1. Introduction

Anchoring systems are used in reinforced concrete structures in order to ensure the stress transfer between two neighboring structural elements [1]. Their installation can be carried out using two different methods. The first method, called "Cast-in-place rebars", consists in placing a steel rebar in a desired position in the formwork and then casting the concrete around. While, the second method, called "Post-installed rebars", consists in embedding the steel rebar inside a hole drilled into the hardened concrete [2]. Post-installed rebars (PIRs) offer advantageous solutions for concrete construction by proposing a viable and economical method for adding new concrete sections or attaching steel members to existing structures [3,4]. Indeed, PIRs were initially used for correcting fabrication errors in precast concrete, and then in retrofitting, extending and repairing existing structures [5,6]. Today, PIRs are also used in new constructions to meet the high architectural requirements by providing more flexibility in the planning and design of concrete structures [7].

Post-installed bonded rebars can be divided into two groups according to the bonding agents used for the rebar setup [8]. "Chemical post-installed rebars", where rebars are bonded using chemical bonding agents such as polyester, vinylester and epoxy resins, and "Grouted rebars", where rebars are bonded using nonchemical bonding agents such as mortars and cement grout [3]. Mortars and cement grout can be easily pumped into deep embedded holes, which allows making PIRs with high load bearing capacity [9]. However grouted rebars require a long curing time and generally a large hole diameter. Nevertheless, chemical post-installed rebars provide a high load bearing capacity using small hole diameter and embedment length. Therefore, the use of chemical PIRs in concrete constructions is today more suitable than grouted rebars. Indeed, the preference for chemical PIRs is the result of the minimization of the curing time of chemical bonding agents by the introduction of fast-curing adhesives, and is also the result of the high stiffness provided by the fillers added to structural resins in order to increase their viscosity and mechanical properties [10,11].

Several experimental research studies have been conducted in order to compare the mechanical behavior between the various existing anchoring systems. Spieth et al. [12] had carried-out a series of pull-out tests on cast-in-place rebars, chemical PIRs bonded with epoxy and polyester resins and on hybrid PIRs bonded with a combination of vinylester and cementitious compounds. Results showed that the hybrid system had a mechanical behavior very close to cast-in-place rebars with a slightly better bond resistance. While chemical PIRs bonded with epoxy resin showed a much higher stiffness and a larger bond strength

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than cast-in-place rebars. However, chemical PIRs bonded with polyester resin showed a softer behavior and a significantly lower bond strength than all other systems. These results were subsequently confirmed by Rosca et al. [13] with an experimental study on grouted rebars bonded with a cement mortar. Results showed that the mechanical behavior of grouted rebars was very close to cast-in-place rebars. Thus, the comparison between the different anchoring systems showed that in general, PIRs bonded with epoxy resins provide higher mechanical properties than all other anchoring systems. Note that these results are only valid for pull-out performance of anchoring systems and did not cover the eventual concrete splitting.

The mechanical behavior of chemical PIRs is governed by several parameters such as materials and geometric parameters [1,14,15,11], the installation process [16–19] and by the environmental factors to which they are subjected. Several studies had confirmed the sensitivity of polymer resins to environmental factors such as moisture and temperature [20–22]. Indeed, temperature seems to be the factor that affects the most the mechanical behavior of chemical PIRs. In a previous paper [23], we showed that the temperature increase up to values blow the resin glass transition temperature leads to increase the mechanical properties of chemical PIRs due to the resin post-cure phenomenon. However, when temperature exceeds the resin glass transition temperature, a change in viscosity and physical state occur [24], leading therefore to a new bond stress distribution along the bond joint [25,26]. The influence of the heating increase rate was studies by Pinoteau et al. [5], who showed that high heating rates can generate a thermal gradient along the steel rebar and consequently can lead to a new bond stress distribution. To conclude, the mechanical behavior of chemical PIRs at high temperature seems to be very complex due to several mechanical and physicochemical changes happening at the adhesive joint, affecting its mechanical properties [23,27]. Therefore, fire is a potential hazard which should be taken into account when designing structures containing chemical PIRs [28].

Finally, several evaluation methods and design rules exist today in order to design and to secure the use of chemical PIRs at normal operating temperatures [29–33]. Nevertheless, few researchers have focused on the variation of the mechanical behavior of PIRs at high temperature and have suggested design methods in case of fire. Zhang el al. [22] has carried out several pull-out tests at different temperatures and proposed an empirical method allowing deducing the bond stress value for different temperature ranges. Pinoteau et al. [26] proposed a “bond resistance integration method” allowing predicting the time of collapse of post-installed rebars using thermal calculations and bond resistance variation at different temperatures. This method was validated in [26] by performing a full-scale ISO fire test on a cantilever-wall connection using chemical PIRs and figures today on the European Assessment Document (EAD) 330087-00-06.01 [34].

This paper presents an experimental full-scale fire test on a cantilever concrete slab (2.94 m × 2 m × 0.15 m) connected to a wall using 8 chemical post-installed rebars. This paper aims to predict the time of collapse of PIRs under mechanical and thermal loading (according to the ISO 834-1 time-temperature curve [35]), in order to compare between experimental and calculated times of collapse. The calculation method used to predict the fire resistance of post-installed rebars was inspired from that presented in the European Assessment Document (EAD) 330087-00-06.01 [34]. The goal was to verify the relevance of the proposed design method on a new configuration, other than that previously tested in [26]. The first part of this paper explains and details the design method used to predict the fire resistance of chemical post-installed rebars in a concrete structure, and then shows how it can be applied in the case of a slab-wall connection. The second part presents the full-scale fire test used to validate the design method. Analyses and discussion are developed in the last part to explain the phenomena that occurred and led to the collapse of the slab, and finally to conclude on the accuracy and the weakness of the design method.

2. Fire design method description

The bond resistance integration method is a design method allowing to calculate the evolution of the bearing capacity of a PIR subjected to a temperature variation and then to predict its time of collapse. To reach this goal, the design method requires the knowledge and the determination of several parameters.

The prediction of the time of collapse of a structure containing PIRs requires five steps.

1- Determination of the applied load (F_{app})

PIRs embedded in concrete structures have the function of transferring the tensile forces applied on the concrete section. The first step in calculating the fire resistance of PIRs consists in determining the applied load, which can be done either by analytical calculations (Eurocode 2 part 1–1 method [29]) or by finite element analysis. In all cases, this step requires the knowledge of some parameters such as the geometric parameters of the structure, the concrete density and the position of the steel rebar in the structure…

2- Temperature mapping ($\theta(x, t)$)

After determining the amount of tensile load applied on the PIRs, the next step consists in determining the temperature distribution at each element of the bond and at different moments of fire exposure, using thermal calculations. Thermal calculations can be done either by finite element analysis, or using finite difference method to solve Fourier's equation (Eqs. (1)–(3)). Regardless of the chosen method, it is necessary to know the thermal properties of the PIR components (*thermal conductivity* $\lambda(\theta)$, *specific heat* $C_p(\theta)$ *and materials density* $\rho(\theta)$) to be able to perform thermal calculations. Materials thermal properties can be determined by carrying out appropriate tests or can be directly found in design guides such as Eurocode 2 part 1–2 for steel and concrete [35].

$$\rho(\theta(x, t))\cdot C_p(\theta(x, t))\cdot\frac{\partial\theta(x, t)}{\partial t} = \lambda(\theta(x, t))\cdot\frac{\partial^2\theta(x, t)}{\partial x^2} \quad (1)$$

$$\dot{q}_{conv} = h(\theta_{ext}(x, t) - \theta_{surf}(x, t)) \quad (2)$$

$$\dot{q}_{rad} = \sigma\cdot\varepsilon\cdot(\theta_{ext}^4(x, t) - \theta_{surf}^4(x, t)) \quad (3)$$

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

C_p is the material specific heat [J K^{-1} kg^{-1}]
λ is the material thermal conductivity [W m^{-1} K^{-1}]
$\theta(x, t)$ is the temperature of an element of the PIR at position x and at time t [K]
$\dot{q}_{conv}$ is the convective heat flux [W m^{-2}]
$\dot{q}_{rad}$ is the radiative heat flux [W m^{-2}]
h is the heat transfer coefficient [W m^{-2} K^{-1}]
σ is the Stefan-Boltzmann constant [W m^{-2} K^{-4}]
ε is the emissivity of the material
θ_{ext} is the gas temperature [K]
θ_{sur} is the temperature at the surface of the material [K]

3- Bond strength – temperature relationship ($\tau_{max}(\theta)$)

The third step in the calculation of the evolution of the PIR bearing capacity is to assign a bond resistance value to every element of the PIR depending on its temperature. This step relies on the bond strength-temperature relationship obtained by pull-out tests at high temperature [5,23] performed on chemical PIRs made from the same resin.

4- Calculation of the load baring capacity (F_t)