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Influence of low elevated temperature on the mechanical behavior of steel rebars and prestressing wires in nuclear containment structures

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HIGHLIGHTS

- Between 20–140 °C, tensile behavior for rebars and wires is little affected.
- Between 20–140 °C, bond between concrete and rebars may decrease strongly.
- At low elevated temperature levels, relaxation rates increase drastically.
- The initial load ratio has also a strong influence on relaxation.

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ABSTRACT

This paper investigates the influence of a low elevated temperature on the mechanical behavior of steel B500B rebars and T15.2 prestressing wires in nuclear containment structures. Tensile tests were carried out to evaluate the evolution of mechanical properties during heating. The bond between concrete and rebars was also studied and relaxation tests on prestressing wires have been done. Between 20 °C and 140 °C, the mechanical behavior of rebars and tendons exhibited no major deteriorations. However, a high decrease of the ultimate bond was observed for pull-out tests. Concerning relaxation tests, the temperature tends to significantly increase the relaxation rate.

1. Introduction

The main role of prestressed concrete nuclear containment structures is to prevent possible leakage of radioactive elements. From different accident scenarios, nuclear containment structures may be subjected to a temperature increase that influences the prestressed concrete structure behavior. The maximum temperature that could be reached by steel rebars and tendons in the containment structure has been evaluated to be 140 °C. Our study is a contribution to the National French project MACENA (Control of Nuclear Vessel in Accident Condition) led by EDF (Electricity of France). This project is linked to an experimental mock-up which consists of a reactor containment building at one third scale named VERCORS (Realistic Verification of Reactor COntainments). It aimed at demonstrating the robustness of the structures in severe accident situation and improving the heuristics phenomena of aging and leakage. All the presented experimental tests have been carried out on steel rebars, concrete and prestressing steel wires coming from this experimental mock-up.

Several studies show that between 20 °C and 140 °C the mechanical tensile properties of steel rebars and prestressing tendons are not affected by temperature although there is limited test data at low elevated temperature. Rostasy et al. [1] conducted tensile tests on prestressing steel wires, 1470/1670 MPa, under steady-state and transient elevated temperature (20–175 °C). Only the yield stress $R_{p0.1}$ exhibits a marked decrease at about 70 °C. Elghazouli et al. [2] performed tests at ambient temperature as well as under steady-state and transient elevated temperature conditions on five bar configurations (hot-rolled and cold-worked rebars). It was shown that mechanical properties are unaffected at low elevated temperature. In [3], Hou et al. show that prestressing bar exhibits slower loss of strength and stiffness throughout

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20–800 °C temperature range, than prestressing tendon and wire. Eurocode 2 [4] also includes some data regarding the dependency of the mechanical tensile behavior of steel rebars and prestressing tendons with temperature. It provides more particularly decrease factors for mechanical tensile properties with temperature up to 1200 °C. Regarding temperatures under 140 °C and according to [4], temperature seems to have slight impact on the tensile behavior of steel rebars and prestressing tendons.

Most of the investigations concerning the bond between concrete and rebars have been reported in [5]. Concerning the influence of the temperature on this bond, most of the studies reported in [5] got interested in the behavior of the interface between concrete and rebars after a temperature cycle. The obtained interfacial models (or bond-slip laws) from [5] will be presented in Section 2.3.2 and compared with other models. It was indicated that the bond stress-slip relationship depends on the temperature [6,7] and the steel bar diameter [8] and other influencing factors as the length embedded into the concrete, the concrete strength or the rebar geometry. The bond strength decreases with temperature and with diameter of rebars. Very few studies focused in the prediction of the influence of temperature on this bond and though, for the temperature range we are interested in, some influence has already been determined [9,6], it is not taken into account in classical modeling approaches [5].

The relaxation mechanism has been less investigated than the tensile and the bond behavior, especially regarding the influence of the temperature taking into account the initial prestress ratio. Indeed, standards currently only include the influence of the initial prestress ratio [4] though it has been established that temperature has a high impact on the relaxation losses. J.M. Atienza [10] demonstrated that the relaxation loss of steel wire at 70% of the ultimate tensile strength (UTS) at 20 °C was 2.5 times greater than the relaxation at 10% of UTS at 100 °C. For the same applied stress, the relaxation loss at 100 °C was 3 times the relaxation loss at 20 °C. J.P. Guilbaud [11] has tested 7-wires prestressing strands T15.2 at 20 °C and 60 °C at 70% of UTS. After 200 h of test, the relaxation loss was found to increase from 1.09% to 2.36% as the temperature increased from 20 °C to 60 °C. A. Raharinaivo [12] conducted tests on "very low relaxation" wires with a tensile strength of 1780 MPa. They were heated up to 65 °C and tensioned up to 90% during 120 h and 1000 h. After 120 h at 70% of UTS, the relaxation loss has been increased from 0.55% to 3.47% as the temperature increased from 20 °C to 65 °C.

Temperature actually tends to increase the relaxation phenomenon and more knowledge is consequently needed on this issue to be able to predict stress losses due to this phenomenon. This implies the realization of experimental investigations and the development and appraisal of adapted modeling tools [1,13].

In order to be able to conclude on the influence of the low-level increase temperature on steel reinforcements, it was thus decided to carry out four different experimental investigations in the studied temperature range 20 °C–140 °C. Regarding the steel rebars, it was decided to perform tensile tests and pull-out tests to study the adhesion with concrete. Regarding the prestressing steel wires, tensile tests and relaxation tests were done.

2. Experimental investigations on steel rebars

2.1. Specimens

The B500B rebars (ultimate strength of 500 MPa) with diameters of 12 mm and 16 mm and length of 1200 mm, have been subjected to tensile and pull-out tests. The microstructure of these specimens is ferrito-pearlitic, Fig. 1.

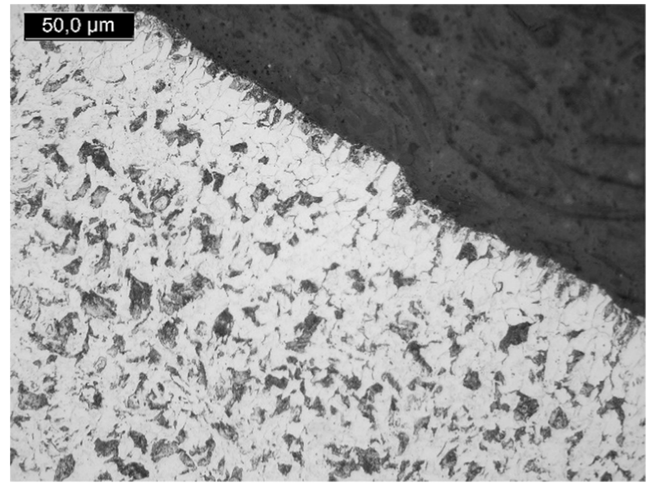

Fig. 1. Microstructure of a B500B rebar.

2.2. Evolution of mechanical properties via tensile tests

2.2.1. Test settings

During tensile tests, a video extensometer prevents the measure from being affected by temperature. The tests were carried out at an ultimate temperature of 20, 40, 100 and 140 °C and three samples have been tested for each temperature state. The used heating device is a silicon tissue regulated using an internal temperature sensor. An insulating material is added on top of the heating device to minimize the heat exchanges with the air as described in Fig. 2a. The rebars are heated before the application of the load and it is checked that temperature variations are smaller than 1 °C during 15 min to ensure being in a stabilized temperature state. The obtained temperature profiles are not constant along the studied length and are measured using additional thermocouples, as illustrated on Fig. 2b. The average temperature has thus been precisely determined for each initial target temperature 40, 100 and 140 °C, Table 1.

2.2.2. Evolution of the tensile behavior of rebars

The results for each studied case and for ultimate tensile strength R_m, characteristic yield stress $R_{p0.2}$ and the elastic tensile modulus E are given in Fig. 3. It can be observed that for R_m and $Rp_{0.2}$, the influence of temperature remains low with a maximum decrease of 3%. Regarding the elastic modulus E, an important deviation is observed for this parameter. This is in contradiction with Eurocode 2 that predicts no temperature's influence on E. In contrast, formulas established by Li and co-workers [14] for predicting yield strength, tensile strength, modulus of elasticity of different steels at elevated temperature are in good agreement with our results.

2.3. Behavior of the bond between concrete and rebars

2.3.1. Test settings

The behavior of concrete/rebar interface was investigated using the pull-out test [15]. The test configuration proposed in [15] was adopted in order to dispose of a higher bonded length (6d instead of 5d) as described in Fig. 4a. A cylindrical oven was used with an adapted regulating system and some insulating material to limit over-heating and allow a quick stabilization. A thermocouple was placed closed to the interface in order to be able to measure the inner temperature and check it was stabilized before testing (Fig. 4b). Pull-out test started when a variation smaller than 1 degree during 15 min was observed. The tests were carried out