Construction and Building Materials 184 (2018) 45–57

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Mechanical properties and bond strength degradation of GFRP and steel rebars at elevated temperatures

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HIGHLIGHTS

- Mechanical and bonding properties of GFRP and steel rebars subjected to elevated temperature effects were investigated.
- Pull-out tests of rebars considering concrete cover were performed in the temperature range of 23–800 °C.
- 59% of the initial bond strength was maintained at 600 °C for steel bars, while this ratio is 34% for GFRP bars.
- Empirical modeling approach in the study reveals a higher consistency with the average error percentage of 3.00%.

GRAPHICAL ABSTRACT

ARTICLE INFO

Article history:
Received 17 December 2017
Received in revised form 1 April 2018
Accepted 25 June 2018

Keywords:
Fire effect
Elevated temperatures
Bond strength
Glass fiber reinforced polymers
GFRP rebars
Tensile tests
Pull-out tests

ABSTRACT

Fiber reinforced polymer (FRP) rebars have recently been gaining popularity in the construction industry all around the world while steel rebars have been widely used so far. FRP bars, which have higher tensile strength compared to steel rebars with the same nominal diameter under normal conditions, are composed of resin matrix and fibers. In this study, mechanical and bonding properties of glass fiber reinforced polymer (GFRP) and steel rebars subjected to elevated temperature effects were investigated throughout a correlative comparison. Axial tensile tests and pull-out tests of these materials were performed subsequent to exposing them into elevated temperature effects in the range of 23–800 °C. Severe effects on the tensile properties of bare steel bars were observed after 600 °C, while this critical limit is 300 °C for bare GFRP bars. Test results show that bond strength degradation is almost linear for both type of rebars, however, 600 °C is also the critical temperature regarding the serious deterioration on concrete. Additionally, an empirical modeling approach on the bond strength degradation of rebars at elevated temperatures was proposed and it was found that comparison results have quite promising consistency based on the modeling process.

1. Introduction

High temperature levels, when considering RC structural elements in the existing designs, affect initially the concrete and then the reinforcement bars. Appropriate design of each concrete component could enhance the concrete behavior against elevated temperature effects. For instance; when silica based aggregates and cement are used in the concrete mortar, it is observed that at 573 °C, 15% of the silica's volumetric expansion results in the fragmentize of the concrete [64]. A fresh concrete that is not correctly placed and does not reach adequate hydration, contains free water

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https://doi.org/10.1016/j.conbuildmat.2018.06.203
0950-0618/

and this water evaporates at 100 °C, causing fragmentation. In addition, this situation accelerates the evaporation of the bound water at 300 °C in the hydrated elements [12,36]. Thus, rapid degradation of the concrete strength causes the temperature increase in reinforcement bars. On the other hand, calcium hydroxide, which is an important cement component, shrinks by 33% by losing water and transforms into quicklime at 530 °C. During the fire, the water that is squeezed into the structure causes the quicklime changes from calcium hydroxide to calcium hydroxide, resulting in a volume expansion of 44%, and this sudden volume conversion causes cracking of the concrete [44]. Reinforcement steel starts to lose its yield strength after 600 °C at these stages, alongside even physical damages [25,27].

Considering these situations, which will lead to the end of the service life of the building, enhancement of material properties also could improve of the structural performance of buildings. GFRP bars have recently been used in the construction industry for this purpose, especially considering their high tensile strength and durability in harsh environments, such as corrosion effects. In other respects, having a low value of the glass transition temperature of the polymeric matrix that can be even close to 80 °C; GFRP bars exhibit inadequate resistance to elevated temperatures. This level of temperature is higher than the thermal loads due to seasonal changes and solar radiation in bridge decks [15].

In this study, following a review summary of previous research about elevated temperature effects and bonding behavior of concrete-reinforcement bars; mechanical properties and bonding performance of GFRP and steel rebars subjected to elevated temperature effects were investigated and evaluated considering their use in reinforced concrete structures. Therefore, elevated temperature effects within the range of 23–800 °C (23, 100, 150, 200, 250, 300, 400, 500, 600 and 800 °C) were investigated throughout cubic compressive strength tests of concrete, axial tensile tests of steel and GFRP rebars, and pull-out tests of steel and GFRP rebars. Finally, an empirical model for the bond strength of rebars, which are subjected to elevated temperatures, was developed based on the experimental results of this study.

2. Review of the previous research

Gustaferro et al. [33] performed an experimental research that could be regarded as one of the preliminary research on the fire resistance of lightweight and isolating concrete. In this study, fire resistance of concrete was examined as well as the relationship between the moisture content of the samples and the relative humidity. As the most important outcome of the study, it was shown that the increase in unit weight causes the decrease of fire resistance for each concrete type. Zoldners and Wilson [71] exposed concrete mixtures of expanded schist and cinder aggregates to elevated temperature effects. As a result of this study, it was found that full-light concrete shows better strength than semi-light concrete under different temperature effects; and the use of blast furnace slag does not provide an advantage against fire effects. On the contrary, it affects the bending strength of concrete in the negative direction. Rostasy et al. [58] investigated the effect of elevated temperatures on the porous structure of the concrete by means of mercury porosimetry method and found that elevated temperatures causes an increase in the total pore volume.

In order to go through the studies on bond strength behavior without elevated temperature effects, Larrard et al. [45] investigated the effect of bar diameter and surface condition on the bond strength between high-performance concrete and rebars. Experimental results revealed that the use of high-performance concrete significantly increases the bond strength and this increase in bond strength may be due to the increase of the tensile strength of the concrete. Furthermore, an increase at a higher rate was observed with the use of smaller reinforcement regarding the scale effect. Benmokrane et al. [11] compared the load-bearing capacity and bond strength of GFRP anchor bars with steel bars. It was found that GFRP bars have lower bond strength values than steel bars. Within the study of Fu and Chung [29], it was stated that bond strength between concrete and rebar increases with increasing compressive strength according to the previous studies, so bond strength is considered to decrease with increasing water/cement ratio. On the contrary, it has been seen that increasing the water/cement ratio enhances the bond strength, while the increase in relative humidity and the use of moisturized reinforcement increase the bond strength. Tighiouart et al. [60] compared the bond strength of GFRP bars with steel bars and reported that the maximum bond strength value decreases with the increase of the rebar diameter. It was presented that bond strength of GFRP bars are lower than that of steel bars because the adhesion and friction characteristics of the rebar affect the bond strength depending on the experimental results. Chang et al. [16] investigated the effects of different sizes of river sand and sand/epoxy percentage by weight in their study, which was designed to enhance bond strength of epoxy-coated reinforcement bars. Lee et al. [47] conducted a pull-out testing process by using accelerated electrical corrosion method to investigate the effect of corrosion on bonding properties of concrete and rebar. De Lorenzis et al. [21] studied to determine the mechanism of bonding between FRP bars and concrete and to analyze the most effective parameters on bond strength. Variables such as the type of FRP bar, the properties of the material filling the ribs, anchorage length and rib size, were investigated. It was reported that fracture of concrete pull-out samples, in which FRP bars were embed via epoxy, occurs at the epoxy-concrete interface, and average value of bond strength at the epoxy-concrete interface decreases with increasing anchorage length and rib size. Gallego et al. [31] demonstrated a comparison of bonding behavior between concrete and steel bars for two different types, black steel and galvanized steel, using pull-out tests. Cheng et al. [18] investigated the corrosion resistance of zinc-coated rebars and the effect of coating on bond strength between concrete and steel rebars. Banholzer et al. [10] presented a numerical solution method to determine bonding characteristics over bond-slip relationship and confirmed the results with the data obtained from the pull-out tests. Jendele and Cervenka [39] also suggested a numerical model for determining the bonding performance level between concrete and rebars. Yavuz [66] performed a detailed research on the use of fiber-reinforced polymers as rebars in RC beams. Detailed evaluations were made on the bonding condition of FRP bars in concrete. In the study carried out by Cullazog ˘lu [20], numerical analyzes of concrete beams with FRP rebars, subjected to bending and shear effects, were performed. Within this study, which provides important information on the behavior of bending and shear with regard to the use of steel and FRP bars, it was emphasized that combined use of two types of bars in hybrid beams has the capacity of increases in both ductility and rigidity performance. Fava et al. [28] reported the results of an extensive investigation on the bonding behavior between GFRP bars and concrete. Pull-out tests were performed on helically wrapped and sand-coated GFRP rebars with a wide range of diameters, as well as nonlinear finite element simulations.

It is important to know the effects of elevated temperatures on the bond strength between concrete and rebar so that fire resistance and residual structural performance of the RC buildings can be fully understood. As one of the pioneer studies considering elevated temperature effects on construction materials, Morley and Royles [54] studied the strength of concrete and steel, under and after high temperature levels. Then the methods used to determine bond strength at ambient temperature were listed, researches on