Adhesion of Stainless-Steel Bars in Concrete Following Elevated Temperatures from a Fire Event

Vicente Albero[1*], David Hernández-Figueirido[1], Marta Roig-Flores[1], Toni Melchor-Eixea[1], Ana Piquer[1]
[1] Universitat Jaume I, Castellón, Spain
valbero@uji.es

Before to the 1980s, the durability of reinforced concrete did not receive special attention. Most standards specify a minimum concrete cover for steel reinforcement as a precautionary measure. For example, the 1978 CEB-FIP model specification, the precursor to the first draft of Eurocode 2 (EN 1992-1-1), did not explicitly address durability issues. However, various corrosion problems in bridge steel bars due to the use of deicing salts in the United States, and severe deterioration of aluminum cement concrete structures in the United Kingdom, have significantly changed this trend. Therefore, all current reinforced concrete regulations contain comprehensive models and recommendations regarding durability and consider it as another limit state to be examined in different project situations.

Concrete coatings protect reinforced concrete structures from corrosion. Concrete coatings act as a physical barrier, protecting steel bars from external erosion. Passivation also protects steel embedded in concrete from corrosion. This passivation is achieved due to the high alkalinity of the concrete mass (pH value between 12.6 and 14). Current reinforced concrete regulations require minimum coatings based on the corrosive nature of the external environment. In many cases, this measure, combined with correct mix design, correct placement, and correct concrete compaction and curing, is sufficient to protect the steel from corrosion and ensure its durability throughout the life of the structure. However, the durability of reinforced concrete elements may be lost if aggressive substances penetrate into the pore network of the concrete and the passivation layer becomes unstable.

In recent decades, various strategies have been developed to achieve better corrosion protection of steel bars, which can be broadly divided into two categories: strategies acting on concrete and strategies acting on steel bars. Currently the most widely used strategy is to act on steel bars. The use of stainless-steel reinforcements with a chromium content of >12% has self-passivating properties and therefore provides excellent performance in long-term corrosion protection. The increased use of stainless steel in the pro-duction of stainless-steel bars is reflected in the publication of specific European standards, such as prEN 10370:2023 for stainless steel bars

The protective measures used to protect reinforced concrete structures from corrosion can have a signifi-cant impact on the bond behavior between steel and concrete. This bonding behavior is a key factor in stress transfer between the two materials. The International Federation of Beton (FIB) Model Specifica-tions for Concrete Structural Structures 2010 and FIB Bulletin No. 10 describe liability issues associated with certain methods of corrosion protection, such as reinforcements with epoxy coatings or the use of fiber-reinforced polymers (FRP) reinforcements. Most international standards (ACI, BS) specify a 20% to 50% extension of the anchorage length for epoxy-coated corrosion-resistant steel bars. On the other hand, the current discussion in the scientific literature on the bond strength of galvanized reinforcements is controversial [1-3].

Fig. 1 1 Stainless Steel Reinforcement REBARINOX©

Certain tests show reduced adhesion strengths, and research suggests lower initial adhesion in the early stages but comparable adhesion in the later stages of concrete [4]. In the case of galvanized steels, the decline in adhesion is commonly linked to hydrogen evolution at the contact interface, arising from the chemical reaction between the zinc coating and the fresh cement matrix of concrete. Conversely, the adhesion of stainless-steel reinforcements, though less explored so far, is approached from a safety standpoint in current design codes [5,6].

Extensive research has been conducted on the adhesion of protected reinforcements in reinforced concrete structures under typical project conditions. Yet, considerable uncertainty arises in accidental scenarios like fires, where elevated temperatures can substantially compromise the mechanical properties of structural materials. The Model Code 2010 stands as the singular standard explicitly stating that, in the case of a fire impacting unprotected reinforced concrete structures, a reduction in adhesion can be expected proportionally to the decrease in the tensile strength of concrete at high temperatures

Regarding the accidental occurrence of fires, it is essential to recognize it as a crucial design scenario for various structural systems. Indeed, all national and international standards related to structural calculations incorporate diverse specifications in this context. Additionally, emphasizing the substantial economic impact associated with this hazard is crucial. As per recent reports from the Spanish Insurance Association (UNESPA) [7], from July 2020 to June 2021, 5.16% of the 73,000 registered fires took place in the industrial sector. These incidents accounted for the most significant economic impact, averaging approximately €50,000 per event. It's noteworthy that these statistics point to an average of about 10 industrial fires daily in Spain, resulting in a daily economic loss of €500,000. This considerable loss is attributed to the typical intensity of industrial fires, associated with significant economic consequences and related to the high combustible load usually present in such establishments. Any efforts directed at enhancing structural fire resistance can yield positive outcomes in alleviating these substantial economic impacts.

Returning to the subject of adhesion, the late 1970s and early 1980s marked the initiation of experiments on adhesion at elevated temperatures. These experiments employed pull-out tests adapted for high temperatures or conducted pull-out tests post-exposure to temperatures reaching up to 800°C. These tests [8–10] covered smooth, corrugated, and drawn steel reinforcements, revealing a more pronounced loss of adhesion for smooth bars and a loss of adhesion of a similar magnitude to the reduction in compressive or tensile strength of concrete for corrugated bars.

However, to date, no known study has explored the adhesion of stainless-steel reinforcements affected by high temperatures. Hence, the CECOM research group at Universitat Jaume I in Castellón, through the GVA research project (CIGE/2021/116) led by Professor V. Albero [11], presents the initial prospective study on this aspect. Additionally, it could prove valuable for expert assessments and decisions regarding repairs or demolitions following a fire incident in reinforced concrete structures with stainless steel reinforcements.

Fig. 2 Adhesion test specimens after exposure to high temperatures. Self-manufactured.

Fig. 3 Execution of specimens for adhesion tests at the UJI facilities.

Tabla I List of parameters.

Material	Diameter [d] (mm)	Concrete	Temperature (ºC)
B500S	12 - 16	C25/30	20
			200
ACX 915			400
			600

The experimental campaign entailed the execution of pull-out tests following the requirements outlined in standard EN 10080 Annex D, using unprotected B500S carbon steel bars as a reference and duplex stainless steel bars ACX915 (EN 1.4362). Evaluations were conducted for both 12 mm and 16 mm diameters in both cases. The repeatability achieved in the tests was 2 specimens per temperature and diameter, resulting in the creation of 16 specimens for B500S steel and an additional 16 for ACX915 stainless steel.

The concrete mixes were designed with a water-to-cement ratio of 0.44 and targeted a strength of C25/30. This quality was assessed for each test and sample, yielding an average compressive strength value of 35.4 MPa for specimens with B500S steel reinforcement and 35.6 MPa for ACX915 stainless steel specimens.

Adhering to the specifications of standard EN 10080 Annex D, all fabricated specimens are of cubic form, measuring 200 mm on each side. In this configuration, a 600 mm steel bar is inserted and securely bonded to the concrete at a distance of 5d (60 mm for 12 mm diameter bars and 80 mm for 16 mm diameter bars). To prevent adhesion in the remaining contact zone, a metallic separation sleeve is incor-porated. After 28 days of concrete curing, the specimens undergo heating in an oven at a rate of 10^{0}C/min to the designated temperature (200, 400, 600 ^{0}C), maintained for 3 hours. Subsequently, natural air cooling is initiated until reaching ambient temperature. Several days post-cooling, the specimens are subjected to pull-out testing, employing a controlled force increase of 80 N/s for 12 mm diameter reinforcements and 143 N/s for 16 mm diameter ones. Throughout the test, both the applied load and the penetration of the bar at its free end or slippage are meticulously recorded. (slip = $\Delta_0 - \Delta_1$).

If the tension-slip curves recorded for various test series are examined (see Fig. 5), a clear decrease in the maximum adhesion stress can be identified with the increase in the exposure temperature. This decrease is more pronounced from 400^{0}C onwards. It should be noted that the maximum adhesion stress values are closely aligned with the models stipulated in Model Code 2010 and EN 1992, which estimate this maximum stress according to the following equation:

controlada de 80 N/s para las armaduras de 12 mm de diámetro y 143 N/s

$$\tau_{b,max}=2,5\sqrt{f_{cm}}$$

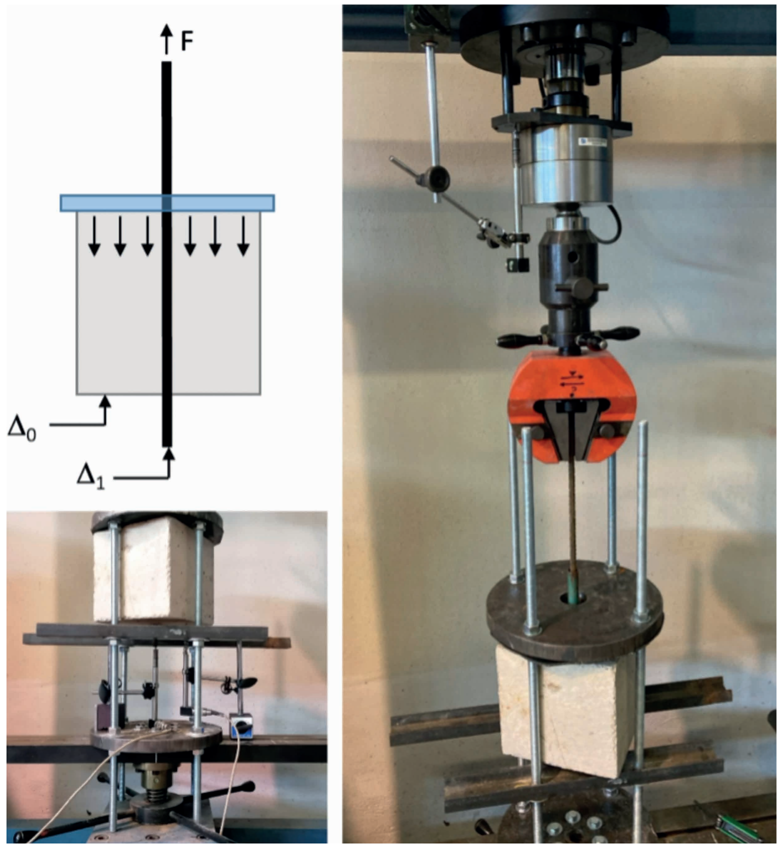

Fig. 4 Pull-out. Test set up

For an average compressive strength of concrete (fcm) of 35.5 MPa, this maximum adhesion stress would result in 14.9 MPa, which, as can be observed, aligns conservatively with the values obtained for 20^{0}C and 200^{0}C.

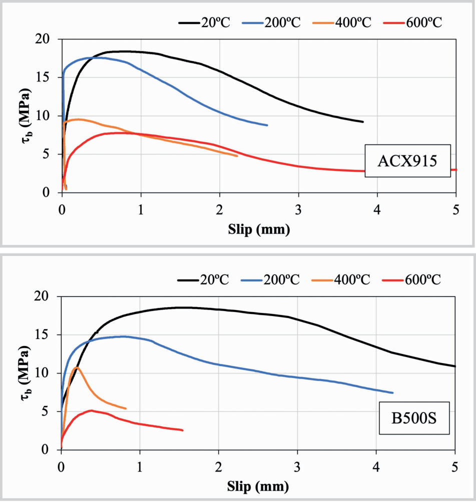

Fig. 5 Adhesion stress-slip curves.

Fig. 6 displays the average values for all tested series, presenting maximum adhesion stress values rela-tive to the compressive strength of concrete (τb/fc). Error bars denote the standard deviation across the obtained results. Notably, at room temperature (20^{0}C) for ACX915 stainless steel reinforcements, slightly lower average values of maximum adhesion stress are evident compared to those for B500S carbon steel reinforcement. This discrepancy is likely attributed to the distinct corrugation configuration of ACX915 steel. However, following exposure to elevated temperatures, ACX915 reinforcements consistently demonstrate superior adhesive behaviour compared to B500S carbon steel reinforcements.

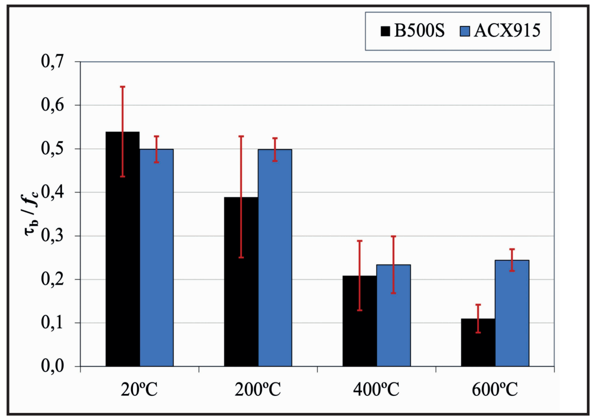

Fig. 6 Maximum adhesion stress.

Conclusions

- To date, there is no known study on the adhesion of stainless-steel reinforcements affected by high temperatures. These temperatures may occur during a potential fire situation, causing irre-versible damage to the structure and compromising the subsequent serviceability of the reinfor-ced concrete structure.
- Following the initial preliminary studies, duplex stainless-steel reinforcements ACX915 have shown better adhesive behaviour after exposure to high temperatures than conventional carbon steel reinforcements.

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