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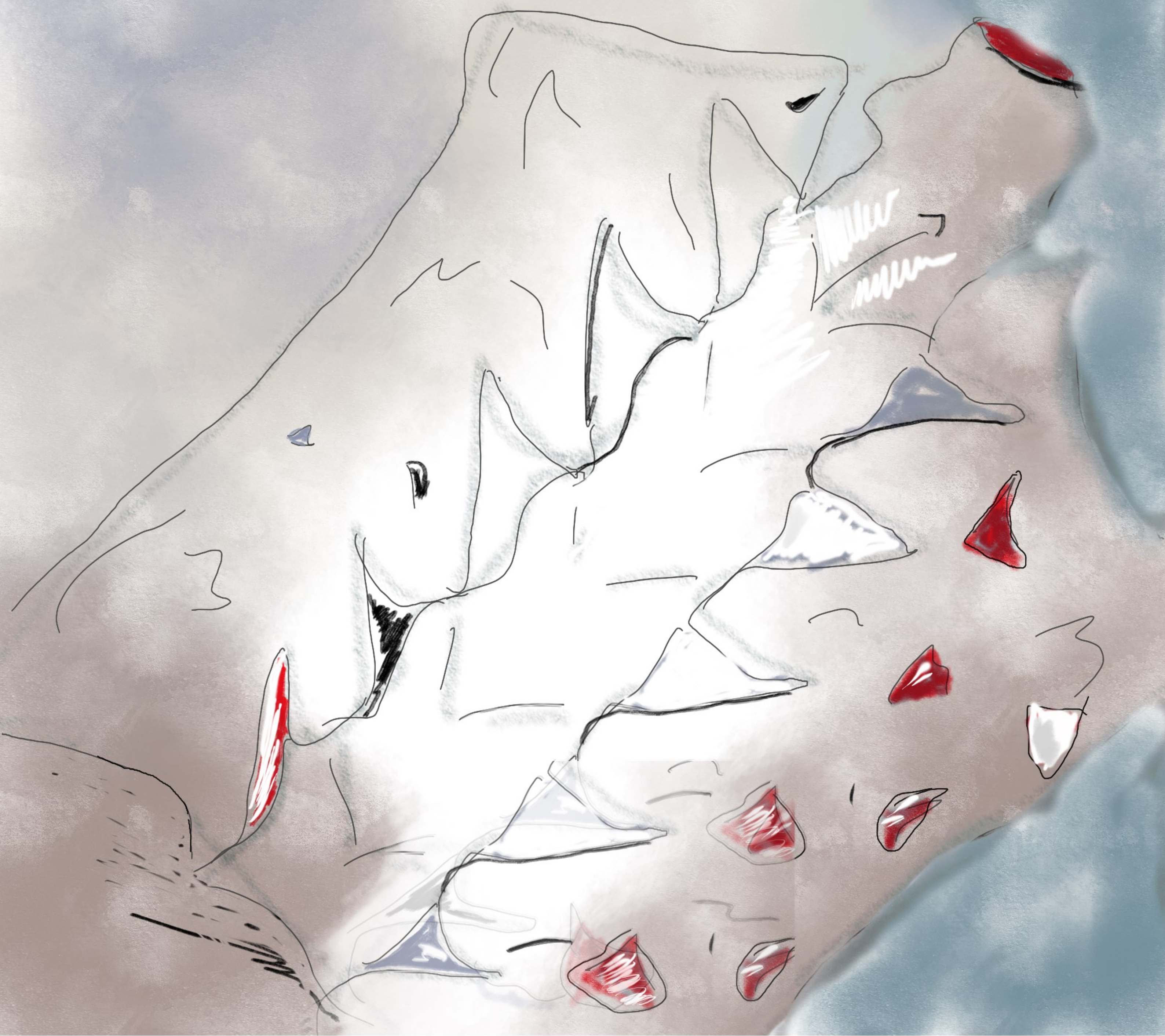


Bond in RC structures at high temperature and in fire: lessons from the past and hot issues still open to investigation

Pietro G. Gambarova[1], Giovanni Muciaccia[1]*
[1]*Politecnico di Milano - DICA, Milan, Italy*

*Corresponding Author Email: giovanni.muciaccia@polimi.it

ABSTRACT

High temperatures and fire are definitely among the various exceptional load situations RC structures are required to resist, as demonstrated by the extensive research activity performed so far, from the behavior of cementitious materials to that of single members and entire structures. Reinforcement-concrete bond, however, has become a hot issue at a relatively late stage, with an acceleration in the new millennium. The objective of this paper is to recall some of the major issues treated in the literature since the last conference "Bond in Concrete" (Brescia, Italy, 2012) and still open to investigation, such as: (1) bond micromechanics in fire; (2) bond stress-slip law as a function of the temperature; (3) the role of polypropylene, steel and hybrid fibers; (4) tension stiffening in fire; and (5) bonded fasteners in fire. This re-examination takes advantage of the tests performed in Milan in the last decade on bond-stress distribution along anchored bars in fire, pull-out vs. splitting failures, in-fire capacity of post-installed fasteners and tension stiffening at high temperature. Only by improving the knowledge – and the modelling - of the basic resisting mechanisms, bond included, today's refined FE codes will provide rational structural responses based on clearly-recognizable contributions.

1 INTRODUCTION

Bond is by all accounts one of the three pillars of any R/C structure subjected to bending and shear, together with concrete strength in compression and reinforcement strength in tension. However, contrary to the other two pillars – that are deeply rooted in the natures of the materials - bond depends on a variety of parameters related to the chemo-physical and mechanical behavior of the materials, to the shape and arrangement of the reinforcement, and to the protection offered by the concrete to the reinforcement. Bond effectiveness cannot, therefore, be given for granted, even if the plurality of bond-related resisting mechanisms generally makes bond little sensitive to each single cause of distress, as extensively demonstrated in many studies, bulletins and proceedings (*fib* Bulletin No.10 "Bond Models", 2000; 3rd and 4th Bond-in-Concrete Conferences, 2002 and 2012, to limit one's attention to a few well-known documents published in the actual millennium).

Among the causes of bond distress, high temperatures and fire play a sizeable role (RILEM, 1985; Bažant and Kaplan, 1996; ACI, 1998), as documented also in several studies spanning the last twenty-thirty years, with an acceleration in the past decade. In fact, these phenomena

(a) affect the properties of both the materials (concrete, steel and other organic or inorganic structural materials) and the interface between the concrete and the reinforcement, and (b) limit the ability of bond to take upon itself the following well-known tasks (Gambarova, 2012):

- to guarantee the cooperation between the concrete and the reinforcement in tension, providing concrete members the tensile strength, that concrete as such is deprived of;
- to guarantee the same cooperation in compression, limiting creep in concrete;
- to allow the reinforcement to control – and limit – cracking;
- to stiffen R/C members in bending or tension after cracking, via tension stiffening;
- to provide R/C members the ductility and strength, that come from the composite action of concrete and reinforcement, even in extreme load conditions (impact, blast, fire, ...);
- to provide concrete the anchoring ability, that is required to guarantee the effectiveness of any embedded reinforcement, inclusive of pre-tensioned strands and bonded fasteners; and
- to allow the fibers – metallic, organic and inorganic – to adhere and stick to concrete in order to increase concrete toughness and even provide a strain-hardening behavior.

Looking at the events devoted to structures in fire in the last decade (4 SiF Conferences from 2010 to 2016; SiF 2018 and Sif 2020) and at the two most recent symposia on fire safety (IFireSS 2017/19), among more than 220 papers on (a) concrete and concrete structures in fire, and (b) fire safety of concrete structures, 10% of the papers is focused on bond, while less than 5% can be found in specialty symposia focused on bond as such (BiC 2002 and BiC 2012). No wonder, as in Structural Fire Engineering the primary issue is the impact of fire on the structural performance, where the loss of bond due to cover damage - and even cover expulsion, called thermal spalling – plays a major role. As for bond as such, fire is just one of the many hot issues, and impact, fatigue, corrosion, cyclic and dynamic loading have the upper hand.

Bond degradation in fire is still a topical issue for both ordinary concrete and innovative cementitious composites. In the former case, see - for instance – Choi et al. (BiC 2002); Chiang and Tsai (2003); Haddad and Shannis (2004); Bingöl and Gül (2009); Lublóy and Balázs (2012); Aslani and Samali (2013); Gambarova (2012); Agrawal and Kodur (2016); Bošniak et al. (2017); Lublóy and Hlavička (2017); Agnoletti et al. (2019); Khalaf and Huang (2019); Sharma et al. (2019); Banoth and Agrawal (SiF 2020); Muciaccia and Consiglio (2021); Haddad et al. (2008); and Varona et al. (2018) for fiber-reinforced concrete. As for innovative cementitious composites, Zhang and Yan (SiF 2014, for geopolymeric concrete) may be cited. Bars bonded to concretes with nontraditional aggregate have been investigated as well (Recycled Concrete Aggregate in Abu Yusuf et al., 2020; Zou et al., 2020). Not only bonded bars (even epoxy-bonded, like in Pinoteau et al., SiF 2014) but also lapped splices (Tonidis et al., 2021) have been studied, coupling experimentation and modelling (Huang, 2010; Khalaf et al., SiF 2014). Special issues, as tension stiffening in cracked concrete and thermal spalling (Bamonte et al., BiC 2012; Lo Monte and Gambarova, 2014) have been treated as well.

Bond in nonmetallic reinforcement, either pre-installed (CFRP bars in Lublóy et al., BIC 2002; Maluk et al., 2010; Thiago and Rodrigues, SiF 2018; FRP bars in Nigro et al., 2012; GFRP bars in Mousavi et al., IFireSS 2019) or post-installed near member surfaces (FRP in Yu et al., SiF 2014; CFRP in Proia and Matthys, IFireSS 2017) has been – and still is - a top issue, with reference also to externally-glued strengthening laminates (Blontrock et al., BiC 2002) and to FRP incorporated into textile-reinforced mortars cast against existing concrete (Raoof and Bournas, IFireSS 2017). Needless to say, post-installed rebars can be metallic as well (Pinoteau et al., BiC 2012; Lahouar et al., IFireSS 2017, 2019; Muciaccia and Consiglio, 2021).

Bond of pre-tensioned strands (Fellinger and den Uijl, BiC 2002; Maluk et al., 2010; Khalaf and Huang, SiF 2016) and of post-tensioned tendons (Wu et al., SiF 2020) is also raising further interest, with specific reference to some technological details like - in the latter case - the effect of the possible eccentricities inside the grouted ducts.

Worlds apart in the domain of bond are: (a) bonded fasteners, whose behavior in fire has become quite recently a *hot topic* because of the structural relevance of heavy-duty connectors installed in fire-sensitive structures, like tunnels and high-rise buildings (Lakhani and Hofmann, SiF 2018; Al-Mansouri et al., IFireSS 2019, 2019; Hlavička and Lublóy, IFireSS 2019); (b) post-installed rebars used in structural retrofitting and restoration (Pinoteau et al., 2017; Qamar and Muciaccia, 2019); and (c) steel pipes filled with concrete to make composite columns (where pipe-to-concrete bond – not treated here – plays a sizeable role).

Starting from the complex behavior of bond along a bar (Fig.1a,b) and at the local level (Fig.1c), in this paper a number of issues thoroughly investigated in the past ten years is recalled and commented, making reference to some relevant papers on each subject, as well as to the tests performed in Milan by the authors: (1) bond micromechanics at high temperature; (2) bond stress-bar slip law as a function of the temperature; (3) bond and fibers; (4) tension stiffening in fire conditions; and (5) bonded fasteners in fire.

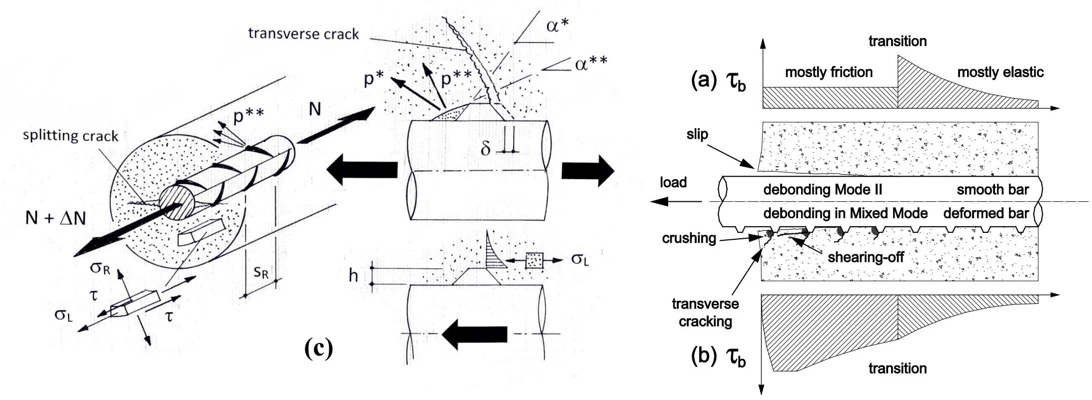


Figure 1: Bond mechanics along the bar (a,b) and at the local level (c), from BiC 2012.

2 BOND MICROMECHANICS IN FIRE

As well known, the properties of the concrete in contact with any reinforcement are very different from those of the bulk material (undisturbed concrete), and the concept of interface transition zone - *ITZ* clearly indicates the layer in contact with an obstacle, be it a bar or a large aggregate particle (Fig.2). In this zone, fines prevail and the water-binder ratio tends to be locally higher than in the bulk material, because of internal water bleeding. Hence, the ITZ is rich in portlandite (calcium hydroxide = $Ca\ (OH)_2$), consisting in rather weak layered crystals.

After a slight improvement in bond mechanical properties at temperatures up to 100°C (thanks to the enhanced hydration processes in the cement paste), bond starts degrading because of free water vaporization and expulsion, pore pressure, bound water dissociation, breakdown of siliceous aggregate and concrete microcracking in the ITZ due to restrained shrinkage. These phenomena mostly occur at temperatures below 400°C. Between 400 and 500°C portlandite dissociates into calcium oxide and water (largest contribution to bond degradation, Fig.3a), and between 500 and 600°C the quartz in the siliceous fines undergoes a change in the crystalline system, with a 0.85% volume increase, to the detriment of concrete integrity. Above 700°C, calcination starts (onset of concrete breakdown as structural material).

In fire, bond mechanical degradation is even worse because of the high thermal gradients in the concrete during both the heating and cooling phase (Aslani and Samali, 2013), with (a) enhanced cracking and spalling in the cover, and (b) bond breakdown due to cover splitting rather than bar pull-out in ribbed bars.

In ribbed bars, bond degradation at high temperature is initially close enough to that of concrete in compression, but becomes closer to that of concrete in tension (greater decay than in compression) above 500°C (Lublóy and Hlavička, 2017, Fig.4a; Sharma et al., 2019).

In the end, concrete degradation makes bond predominantly controlled by interface interlock.

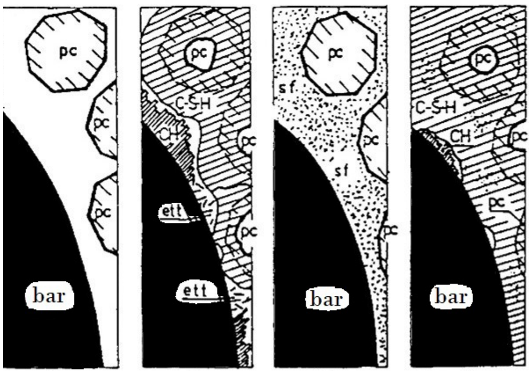


Figure 2: Interface Transition Zone – ITZ around a bar; from left to right: fresh/hardened state without sf, and fresh/hardened state with sf ; pc = Portland cement particle ; sf = silica fume ; CH = calcium hydroxide ; C-S-H = calcium silica hydrated gel ; ett = ettringite ; and bar = reinforcing bar . The more homogeneous the ITZ (from left – no sf - to right – with sf), the better the bond properties.

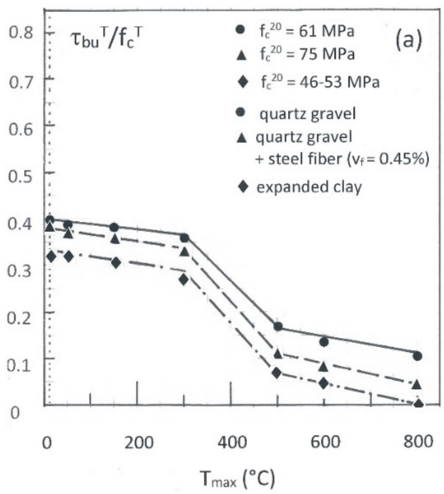
3 BOND STRESS-BAR SLIP LAW AT HIGH TEMPERATURE

Bond stress/bar slip law is the fundamental relationship of bond and may be considered as a sort of constitutive law (bond law or bond-slip law), as long as bond failure is accompanied by bar pull-out or push-off, since in this case bond mainly depends on local concrete properties, on the roughness of the bonded surface (macro or micro roughness) and on the stress state around the bar (due - for instance - to active confinement). However, should bond failure be caused by cover splitting, passive confinement and transverse reinforcement would come into play (Muttoni and Ruiz, BiC 2012), both at ambient and high temperature (RILEM, 1985).

Also the type of test - from the very common pull-out test, to push-off and push-pull tests - affects the local bond law (Muttoni and Ruiz, and Auer and Stempniewski, both in BIC 2012). A short bonded length (≤ 5 bar diameters) is required in the tests, to make bond stress uniformly distributed. With reference to bond failure by splitting, more specific tests have been proposed as well, to take care of the clear cover of the bar with/without confining stirrups (Sharma et al., 2019). Also tests under sustained loads (which is a typical situation in real fires) have been proposed and carried out, as concrete creep during the heating process increases the damage in the embedment (Muciaccia and Consiglio, 2021), though stirrup-induced confinement is very effective in preventing bond failure by cover splitting. In the end, bond decay under sustained loads is more severe than in residual conditions. Furthermore, at any temperature the material of the bar - either steel or reinforced polymers - affects bond behavior, because of the different bar stiffness and surface characteristics. Here reference is made to ribbed steel reinforcement.

In the tests at high temperature under increasing load, the low-rate heating (necessary in all tests) should be followed by a rest period at the maximum temperature (whose duration has sizeable though little-studied effects, see Zou et al., 2020) and by a lower-rate cooling (in residual tests), to make the thermal damage in the concrete and at bar interface as uniform as possible. As for hot vs. residual bond capacities, some tests indicate a very limited difference (Morley and Royles, 1983, cited by Sharma et al., 2019).

The formulation of the bond law has evolved from the single four-branch curve proposed in CEB-FIP Model Code 1990 (ascending parabola + plateau + linear softening + residual plateau) to that of fib Model Code 2010, which differentiates between pull-out and splitting failures. In the case of pull-out failures, bond modelling is the same as in MC 1990. In the case of splitting failures, two different three-branch curves are introduced, to take care of the presence or absence of confining reinforcement (in both cases, there is no plateau after the ascending branch). Since the bond stress-bar slip curves at high temperature exhibit a decreasing strength (Fig.3a), but are similar to that at ambient temperature (Fig.3b), the same approach introduced in MC 1990 has been adopted also by fib Task Group 2.5 "Bond and Material Models" in drafting the section "Local bond-slip under elevated temperature" for Model Code 2020. Starting from the curve at 20°C, and based on many recent test results and proposals for the bond law (Lublóy and Hlavička, 2017; Varona et al., 2018), all the fixed points of the bond law are expressed as a function of the temperature, max. bond stress included.



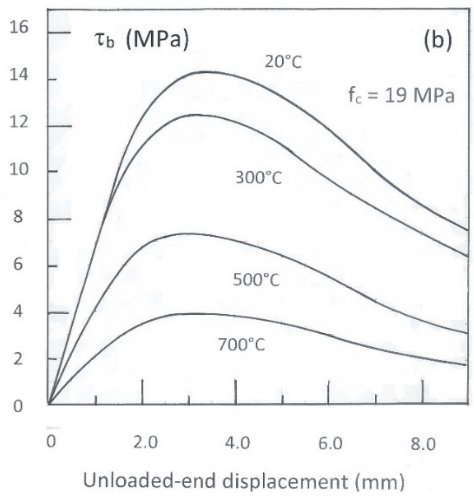


Figure 3: Pull-out of ribbed bars: (a) max. bond stress vs. temperature (adapted from Lublóy and Hlavička, 2017); and (b) bond stress-bar slip curves (adapted from Sharma et al., 2019).

4 BOND VS. FIBERS AT HIGH TEMPERATURE AND IN FIRE

Fibers are well known as a tool to improve certain characteristics of concrete, in both ambient and high-temperature conditions. Among the many types of fibers available on the market, hooked steel fibers (with different aspect ratios) and polypropylene fibers are the most commonly used and tested in laboratories. Adding pp fibers to the mix – even in small amounts by volume – improves concrete fire resistance, because fiber swelling and melting above 150°C produce microcracks that make porosity more connected. Consequently, vapor-pressure release is facilitated and cover spalling is either prevented or delayed (see. refs. in Varona et al., 2018).

Adding steel fibers to the mix is beneficial to concrete behavior in normal ambient conditions in the members subjected to bending and shear (as cracking is more effectively controlled and concrete behavior in tension is improved), while at high temperature the benefits are less clear (slightly-higher thermal conductivity, some extra microcracking due to fiber-concrete thermal incompatibility, passive confinement on the bars, ability to keep concrete shards together after local popping and spalling, to the advantage of bar protection, see refs. in Varona et al., 2018). It is also true – and well known at room temperature - that adding any type of fibers to the mix tends to increase concrete porosity and to decrease its strength in compression (by a few percents), something that may have some effects at high temperature.

Adding hybrid fibers is another possibility, since the advantages of using different types of fibers in the same mix - like steel and pp fibers – are combined and offset the disadvantages typical of each fiber type. The results shown in Fig. 4a indicate that in ordinary concretes – NSCs (f_c = 24 MPa, average value), adding fibers and increasing their aspect ratio improve the bond strength with respect to. the compressive strength, at any temperature. On the contrary, in high-strength concretes - HSCs (f_c = 90 MPa, average value, Fig. 4b), a non-negligible advantage is provided only by the steel fibers characterized by the largest aspect ratio.

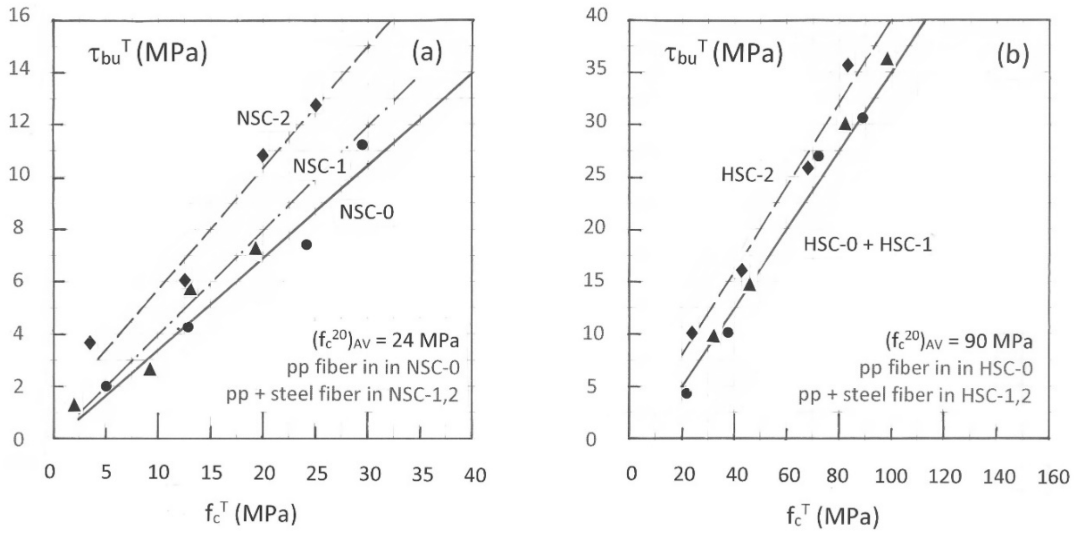


Figure 4: Bond strength vs. compressive strength at high temperature: (a) normal-strength, and (b) high-strength concrete (adapted from Varona et al., 2018); pp/st = polymeric/steel fibers; v_{pp} = 0.15% in all NSC mixes and 0.25% in all HSC mixes; v_{st} = 0.25% in all mixes; steel-fiber aspect ratio: 47 in NSC-1 and HSC-1, and 86 in NSC-2 and HSC-2; % by volume.

5 TENSION STIFFENING IN FIRE CONDITIONS

In any tension bar embedded in regularly-cracked concrete, the segment of the bar comprised between two cracks is relieved by the concrete and has a stiffer behavior compared to a similar naked bar. This is tension stiffening, that (a) plays a considerable role in crack control and in enhancing structural stiffness in cracked RC members, and (b) is the other side of the coin of bond, where the first side is the anchoring ability.

In ordinary environmental conditions tension stiffening has been extensively studied within the framework of bond (Yankelewsky and Jabareen, BiC 2002; Bischoff, 2003; Bentz, 2005; Lee et al., 2011 and others, see refs. in Lo Monte and Gambarova, 2014), and various design codes contain appropriate provisions (see for instance EC 2; see also *fib* Bulletin 10, Chapter 1, 2000).

In spite of its relevance to serviceability after a fire, tension stiffening has been given so far very limited attention with reference to high temperature. For instance, bond shear modulus (or bond stiffness) $k^T = [F/L^3]$ appears in a couple of papers (BiC, 2012) and in Sharma et al. (2019). Hence, assessing the relevance of tension stiffening at high temperature (T > 400°C) and evaluating the bond shear modulus k^T (Eqs.1 and 2) is still a largely open issue:

$$\tau_B(s) = k^T(s)\, s \ ; \ \ d^2s(x)/dx^2 - k^T(s)\,[\pi d_B/(E_S{}^T A_S)]\,(1 + n^T p)\, s(x) = 0 \qquad (1,2)$$

where Eq.1 = constitutive relationship of bond; Eq.2 = controlling equation of bond in the linearly- elastic domain; $\tau_B(s)$ = local bond stress; $k^T(s)$ = bond shear modulus; $s(x)$ = local bar slip; d_B, $E_S{}^T$, A_S = bar diameter, elastic modulus (of the steel) and section; $n^T = E_S{}^T / E_c{}^T$ with E_c = concrete elastic modulus; p = effective steel ratio. (As a reference, the secant value of k^{20} varies between 50 and 150-200 MPa/mm in ordinary environmental conditions, according to the equation given in MC10 and reproposed in MC20 ($k^{20} = 6\ \tau_{bmax} = 6 \times 2.5\ f_c{}^{1/2}$).

In a research project whose preliminary results were presented at BiC 2012 and the full results were published in Lo Monte and Gambarova (2014), 11 prismatic tension members (length 240 mm; side of the square section 80 mm, Fig.5a,b,c) reinforced with a single ribbed bar (d_B = 16 mm) were put in a furnace at 750°C, in order to reach in 2 hours a rather homogeneous temperature close to 640°C; then, the specimens were cooled down to 20°C.

During the heating process, only two contiguous sides were exposed to high temperature, while the other two sides were kept in quasi-adiabatic conditions, to simulate the typical conditions found in RC columns (Fig.5d) and beams (Fig.5e). In the first 20 minutes, the temperature-time curve was comprised between hydrocarbon and ISO 834 fires. The specimens were instrumented and tested according to a displacement-controlled procedure (Figs.5a-c).

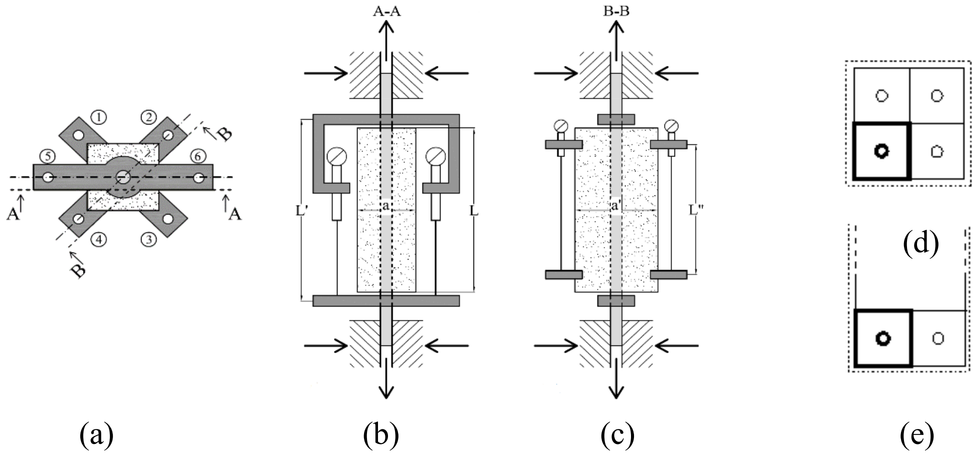


Figure 5: Geometry and instrumentation of the specimens (a,b,c); and typical structural cases (d,e), where the dotted lines indicate the sides exposed to the fire, and the internal thin/thick lines represent adiabatic or quasi-adiabatic sides (Lo Monte and Gambarova, 2014).

Three mixes were prepared, all containing a calcareous filler but each differing for the cement type and/or amount, to produce 3 different self-consolidating concretes: NSC/HPC/HSC (cement type II/A-LL 42.5 / I 52.5 / I 52.5; c = 350/480/520 kg/m^3; w/c = 0.50/0.35/0.33; target strength f_c = 50/80/90 MPa; no. of successfully-tested specimens per each concrete 3). The aggregate was mixed. The carbon-steel bars were spring-tempered (f_y = 400 MPa; f_{yk} = 373 MPa; E_s = 205 GPa). After cooling, the thermal cycle brought about a 10% reduction in E_s, while the reduction in E_c was much higher ($E_s{}^T/E_c{}^T$ close to 30 after a thermal cycle at 640°C).

In Fig. 6a-d the four better stress-strain curves (RC specimens and naked bars, after the removal of the concrete) are plotted. In each specimen group (NSC, HPC and HSC), one specimen was moist (Symbol W, moisture content = 3.5-4.5% by mass) and the other specimen was dry (Symbol D, moisture content = 1-2.5%), see Lo Monte and Gambarova (2014).

In Fig. 6e, the values (either residual or hot) of the bond shear modulus k^T are plotted vs. the actual compressive strength f_c^T, according to five experimental campaigns. In the tests by Lo Monte and Gambarova (2014), the values of k^T were obtained by fitting the average bar-concrete slip (derived from the elongations of the concrete and of the rebar) with the predictions yielded by the model represented by Eqs.1 and 2, valid in the linearly-elastic domain.

The plots in Fig.6a-d show that (a) tension stiffening (represented by the area comprised between the curve of each specimen and that of the naked bar) is rather limited but not negligible; (b) the bond shear modulus – or stiffness (Fig.6e) – can be described by means of different interpolating functions, though the test results are rather dispersed. Note that the dash lines in Fig. 6a-d refer to the average residual value of steel young's modulus (E_s^{640} = 184 GPa). The curves (^) and (^^) envelope more than 80% of the test results considered in this paper, while the dash-dotted curve (^^^) is a reasonable average curve.

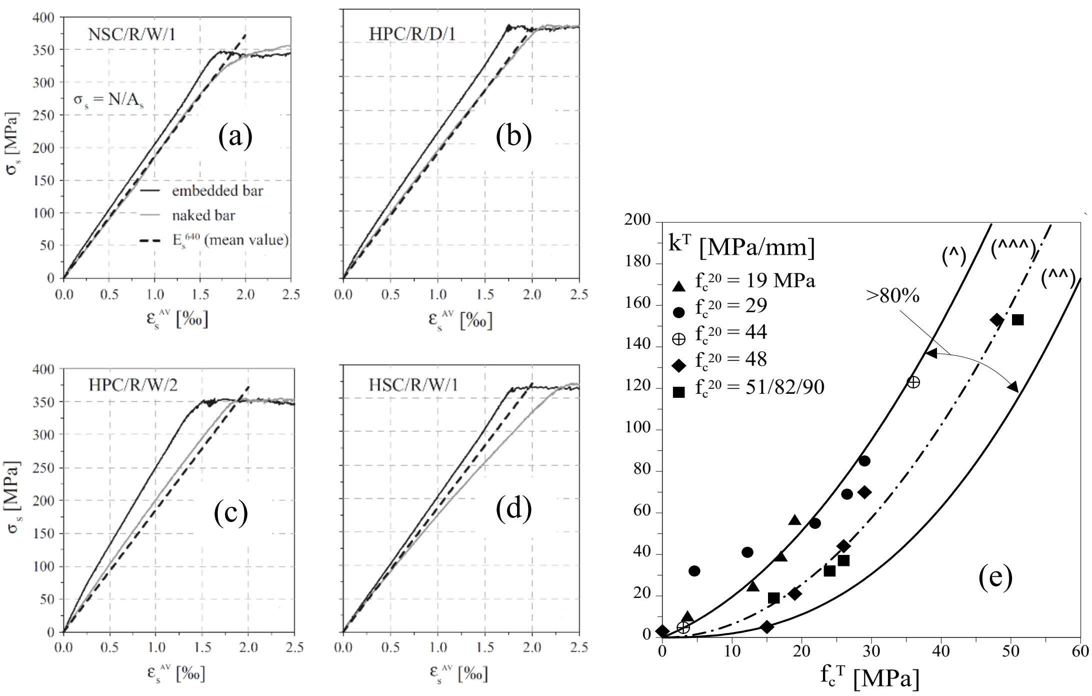


Figure 6: (a-d) Stress-strain curves by Lo Monte and Gambarova (■ SCC*, 2014, T = 640°C, black and gray curves refer to bonded and naked bars, respectively); and (e) bond stiffness as a function of the strength in compression; tests by ● Morley and Royles (Mag. Concrete Res., V.35, No.123,1983), ▲ Sharma et al. (2019), ♦ Diederichs and Schneider (Mag. Concrete Res., V.33, No.115,1981), ⊕ Lublóy, Balázs, Hlavička (2012, 2017). Interpolating curves: (^) $k^T = 135 f_c^* (1 + 4.5 f_c^*)$; (^^) $k^T = 620 f_c^{*2.5}$; and (^^^) $k^T = 640 f_c^{*2}$, with $f_c^* = f_c^T/100$.*

6 POST-INSTALLED REBARS AND BONDED FASTENERS IN FIRE

Post-installed bars and bonded fasteners are becoming increasingly popular as a means to repair or strengthen existing structures, and to connect different structural members in new construction. Because of the very nature of these devices, applied research, industrial technology and design provisions go hand-in-hand, and only a close coordination yields fruit.

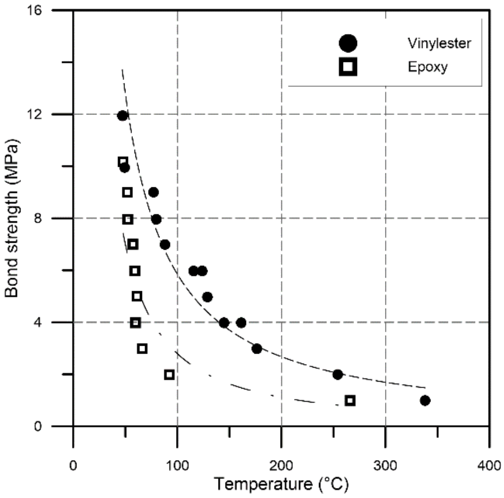
Concerning the design of post-installed polymer-bonded rebars in ambient conditions, the basic assumption is that no differences exist with respect to pre-installed rebars if the former devices exhibit a larger (pull-out) bond strength and a comparable bond stiffness compared to the latter devices (EOTA, 2020). Such equivalence has been confirmed by well-confined pull-out tests, that make reference to threshold values for both the bond strength and the slip measured at the loaded end of the specimens. Of course, to perform these tests a well-defined geometry for the specimens and specific procedures have been introduced.

In fire conditions, the extensive research activity performed so far, with a peak in the past decade, has yielded the following results:

- In medium-diameter anchored bars (d_b = 12 mm; L/d_b = 10), the bond-strength decay associated to a given temperature can be experimentally evaluated provided that the bar is uniformly heated (Pinoteau et al., 2017) after the application of the load (Muciaccia and Consiglio, 2021). The tests show that the mechanical behavior of the specimens is strongly product dependent, with a well-definite decrease of the load transfer capacity for any temperature approaching the glass-transition temperature of the bonding agent. For instance, epoxy-based bonding agents typically show a more rapid and sizeable bond-strength decay compared to vinylester resins (Figure 7a).

- For any given bar position and fire duration, the load-bearing capacity of a single post-installed bar can be evaluated based on the temperature distribution along the bar itself, by lengthwise integrating the values of the bond strength (variable with the temperature on the lateral surface of the bar, see Pinoteau, 2017; Muciaccia et al., 2017). Such approach has been validated by Lahouar et al. (2019) by performing full-scale tests on a concrete cantilever slab connected to a wall via eight post-installed bars, bearing a dead weight applied at the tip of the cantilever and exposed from below to the standard fire (ISO 834-1 time-temperature curve). However, since the bars had to resist a negative moment and were placed close to the extrados, their temperature never exceeded 100 °C.

- When post-installed bars are used in lapped splices close to the intrados of a given structural member (positive moment), the local temperatures in fire may become so high that the load-transfer capability of the bonding agent is almost null. Consequently, load-transfer mechanisms other than bond (alternative mechanisms) should be identified between the existing RC member and the reinforcing system.



(a) (b)

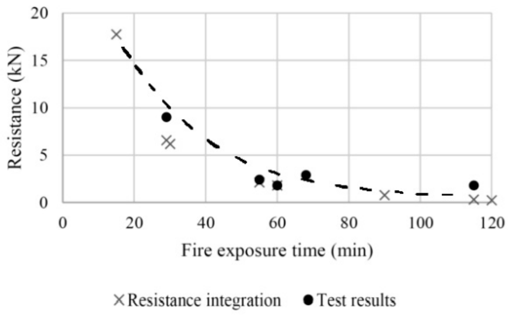


Figure 7: Temperature-dependent (a) and exposure time-dependent (b) decay of: (a) post-installed bar connections with different bonding agents (adapted from Muciaccia at al., 2017; fitting curves based on a power law) ; and (b) post-installed fasteners (adapted from Al-Mansoury et al., IFireSS 2019).

- In post-installed bonded fasteners, the load-bearing capacity in fire has been mostly investigated by performing real-scale tests with pre-loaded fasteners exposed to the standard fire (ISO 834-1, Fig. 7b). The results of the tests are generally available in the technical reports of the manufacturers. To the authors' knowledge, however, the tests have been limited so far to uncracked concrete, as performing hot tests (i.e., at high temperature) in controlled crack conditions (concerning crack formation and opening) is very difficult. Needless to say, this is a challenging issue for researchers and experts!

- The Resistance Integration Method (initially introduced for post-installed bars) has been recently extended to bonded fasteners (Al-Mansoury et al., 2020) for the usual values of the embedment depth (from 4 to 20 times the fastener diameter). This extension has been validated based on the tests performed by the same research group (Fig.7b, Al-Mansoury et al, IFireSS, 2019).

As previously mentioned, the behavior of bonded fasteners post-installed in cracked concrete is still an open – and knotty – issue. Despite the substantial unavailability of test results in such conditions, it is clear that fastener behavior cannot be independent of the stress state and related cracking in fire-exposed RC members, where kinematic restraints control cracking as well. Consequently, real-scale testing under realistic fire scenarios remains the only way to gather badly-needed information (see the PhD Thesis by Reichart on the fire resistance of injected anchors for different embedment depths, 2020, T.U. Kaiserslautern, Germany).

Last but not least, neglecting the kinematic compatibility between post-installed bars or bonded fasteners and the embedment leads to a conservative evaluation of the bearing capacity in fire conditions. The main reason of such over-evaluation is that both the strength and the stiffness of the concrete and of the bonding agent decrease, to the advantage of bond-stress redistribution (Muciaccia et al., 2017, 2021).

7 CONCLUSIONS

This fairly concise and certainly non-exhaustive review of the work performed since BiC 2012 on bond-related problems at high temperature and in fire clearly shows that many issues are still open to investigation, from bond as a local mechanism to bond as a structural player, from bond of embedded reinforcement to bond of post-installed reinforcement, from bond testing to bond modelling, just to cite three broad domains.

At the local level, steel yielding, concrete strength, aggregate type, fiber type and amount, thermal cracking, cover spalling, non-traditional aggregate (like recycled concrete aggregate), concrete creep, and the effect of pre-loading (before and during a fire) are as many topics to be further investigated, not to mention short vs. long bonded lengths, hot vs. residual tests and the passage from pullout-controlled to splitting-controlled failures.

At the structural level, the effect on bond of heat-triggered membrane action and of the cooler regions at member extremities, the interaction with the transverse reinforcement, tension stiffening, and transient vs. static heating may be cited as largely open issues.

As for post-installed bars and fasteners, force redistribution is still an issue to be tackled whenever these devices are part of an unevenly-loaded group, all the more if the thermal field is nonhomogeneous. In such cases, further tests should be carried out, as their results would be instrumental in refining and/or completing the design provisions.

Finally, high-level detailed modelling – already feasible thanks to a number of available numerical 3D codes specifically designed for reinforced concrete – definitely appears to be an effective means to extend the experimental results, especially at high temperature and in transient conditions, where testing is rather difficult, inevitably limited and very costly, in terms of human efforts, instrumentation and technological tools.

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