BOND BETWEEN STEEL AND STEEL FIBER REINFORCED CONCRETE AFTER EXPOSURE TO ELEVATED TEMPERATURES

VERHALTEN VOM VERBUND ZWISCHEN STAHL UND STAHLFASERVERSTÄRKTEM BETON NACH EINER THERMISCHEN EINWIRKUNG

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SUMMARY

Bond between steel and concrete is essential for the performance of reinforced concrete structures. Investigations of the bond behaviour after exposure to elevated temperatures have so far been mainly considered only one failure mode (pull-out failure) and the data has been mainly obtained for normal strength concrete, only very limited data exists on the bond degradation of high strength concrete and fiber reinforced concrete. In the present work, the degradation of bond after exposure to elevated temperatures was considered for both failure modes (pull-out failure and concrete splitting) for high strength concrete without and with addition of steel fibers. Tests were performed using pull-out specimens in temperature range from 20°C to 700°C. It is found that the effect of temperature on bond in high strength concrete is similar to that in normal strength concrete.

ZUSAMMENFASSUNG

Der Verbund zwischen Stahl und Beton spielt eine zentrale Rolle für das Verhalten der Stahlbetonbauteile. Die Versuche zur Bewertung des Verbundverhaltens nach einer thermischen Beanspruchung wurden bisher hauptsächlich unter Berücksichtigung nur eines Versagensmodus (Verbundversagen) durchgeführt, dabei wurden hauptsächlich normalfeste Betone betrachtet. Es gibt nur wenig Daten für hochfeste und faserverstärkte Betone. In dieser Arbeit wurde das Verhalten für beide Versagensarten (Verbundversagen und Betonspalten) für hochfesten Beton ohne und mit Stahlfasern betrachtet. Die Versuche wurden mit Ausziehprüfkörpern im Temperaturbereich von 20°C bis 700°C durchgeführt. Es wurde gezeigt, dass der Einfluss der Temperatur auf das Verbundverhalten im hochfesten Beton ähnlich ist wie im normalfesten Beton.

1. INTRODUCTION

Development of sufficient bond between reinforcement and concrete is necessary for the efficient transfer of forces between concrete to steel. Although bond strictly refers to the relative interfacial slip between the reinforcing bar and concrete, concrete splitting sometimes precedes the pull-out failure and the full bond strength cannot be achieved. This aspect is considered in the codes [1] by restricting the allowable bond stress to a low value such that the splitting of concrete is avoided. The fib Model Code 2010 [2] recommends an analytical bond stress-slip relationship where the bond stress-slip relationship can be derived for both pull-out failure and splitting failure under ambient conditions (room temperature) for a given concrete cover, concrete strength, rebar diameter etc.

The function of bond could be strongly compromised during fire and needs to be assessed after the fire accident. The tests to evaluate the bond degradation due to exposure to elevated temperatures have so far been mainly performed considering only one failure mode (pure pull-out failure). Furthermore, the data has been mainly obtained for normal strength concrete, only very limited data exists on the bond degradation of high strength or fiber reinforced concrete.

In the present work, two aspects of the bond behavior after exposure to elevated temperatures are considered: i) the degradation of bond is considered for both failure modes (pure pull-out failure and concrete splitting) and ii) the influence of steel fibers in concrete on residual bond is investigated. Tests were performed using standard pull-out specimens exposed to slow-rate heating (2°C/min), whereby the target temperatures ranged from 20°C to 700°C. In order to investigate both failure modes, the test rebar was placed: i) in the center of the specimen (pull-out failure), ii) at the edge of the specimen (concrete splitting failure) and iii) at the corner of the specimen (concrete splitting failure). Additionally, the degradation of concrete compressive strength was measured on standard cubic specimens.

The tests were performed for high strength concrete without and with addition of steel fibers. Earlier, similar tests were performed by the authors in normal strength concrete without steel fibers [3]. The obtained results demonstrated a significant influence of the failure mode as well as the concrete type on the residual bond behavior.

2. EXPERIMENTAL INVESTIGATIONS

2.1 SPECIMEN

In this work, static pull-out tests with confined test setup were performed on reinforcement in concrete in the residual state after exposure to elevated temperature. Square prismatic concrete specimens of dimensions 160 mm x 160 mm x 300 mm are used to carry out the tests, see Fig. 1. Standard test rebar (European grade BSt 500) of diameter d_s = 16 mm is used. The test rebar is provided with a debonded length of 135 mm in the front, followed by a bonded length of 80 mm and further followed by a debonded length of 85 mm. For practical reasons of gripping the test rebar and measuring the rear end slip, the test rebar protruded out of the test specimen by 150 mm in the front and 50 mm in the rear.

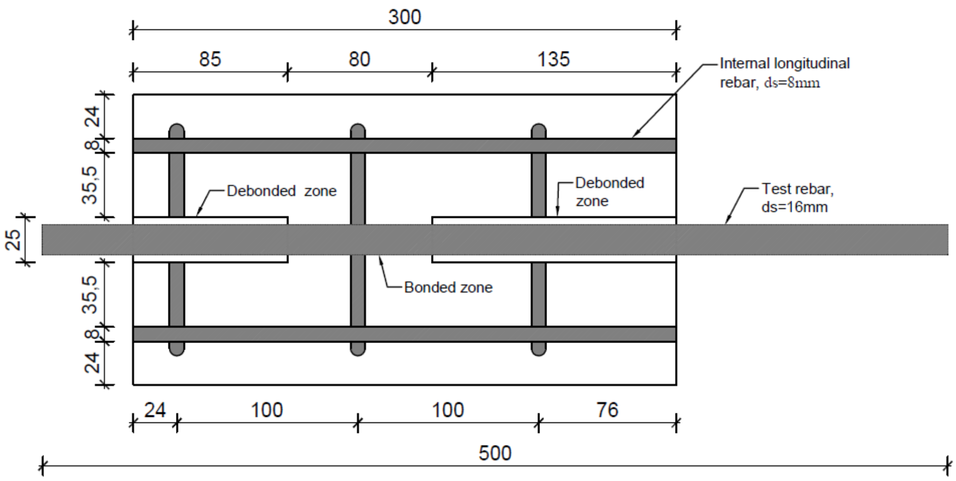


Fig. 1: Typical reinforcement detailing of the test specimen

The test specimen was provided with three rectangular stirrups of diameter 8 mm, one of which was located at the center of the bonded length while the other two stirrups were placed at a distance of 100 mm on either side of this stirrup (see Fig. 1). To keep the stirrups in position, 8 mm diameter rebar were placed at the corners of the specimen to form a reinforcement cage. Three different positions of the rebar were investigated: in the middle of the specimen, at the edge and at the corner, see Fig. 2. For testing at the edge and corner, the minimum clear concrete cover was kept as c_{min} = 24 mm (= 1.5 d_s).

The debonded zones were made by using glass tubes covering the test rebar for the specified length. The glass tubes were selected instead of plastic tubes as they could melt at high temperatures. Fig. 3 shows a typical rebar sample prepared for casting.

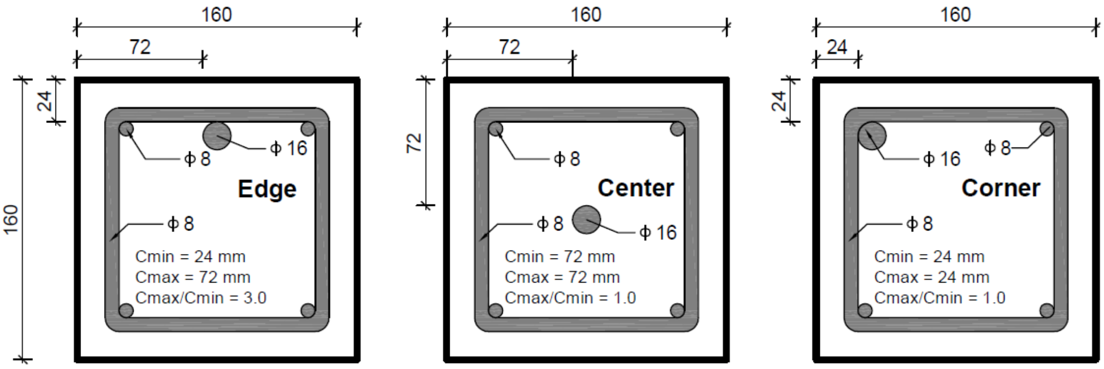


Fig. 2: Positions of test rebar investigated in the test program

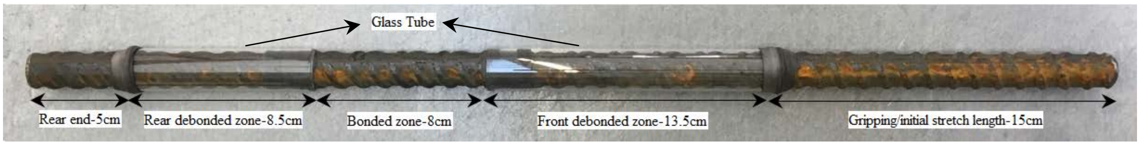


Fig. 3: Test rebar with glass tubes

2.2 CONCRETE MIX

Two different concrete mixes were used in this test program, namely, high strength concrete (HSC) and steel fiber reinforced concrete (SFRC). The basic composition (other than steel fibers) for both types of concrete was same. In order to prevent explosive spalling of concrete at elevated temperatures, 0.5 kg/m^3 of polypropylene (PP) fibers were added to the mix. The recipe of the concrete mixes is summarized in Table 1.

Table 1: Details of the concrete mixes (in kg/m^3)

Mix.	Cement	Sand	Aggregates		w/c	Superplasti-cizer	Fibers	
			2-4 mm	4-8 mm			Steel	PP
HSC	363	683	629	485	0.48	0.2	0	0.5
SFRC	363	633	583	449	0.48	0.3	50	0.5

The average strength of concrete measured at an age of 28 days using the standard 150 mm cubes at ambient temperature was obtained as 72.2 MPa for HSC and 73.6 MPa for SFRC. The heating of the specimens to the target temperatures was performed at concrete age between 60 and 140 days.

2.3 TEST PROGRAM

The test program consisted of testing the above-mentioned three configurations, namely rebar positioned in the middle of the specimen, rebar at the edge and rebar at the corner. Each case was tested at room temperature (20°C) and after exposure to elevated temperature of 300°C, 500°C and 700°C. For each case two specimens were tested to verify repeatability. The test program is summarized in Table 2.

Table 2: Test program

Rebar position → / Target temperature	Center	Edge	Corner
20°C (Ref)	2	2	2
300°C	2	2	2
500°C	2	2	2
700°C	2	2	2

3. TEST PROCEDURE AND SETUP

3.1 HEAT TREATMENT

For heating, the test specimens were placed inside an electric oven with programmable controls for the heating rate as well as retention time for the temperature. The target temperature in each case was reached at a relatively slow heating rate of 2°C/min. After reaching the desired temperature, the temperature was maintained for 3 hours to ensure uniform heating of the test specimen. The temperature was allowed to gradually come down after the completion of retention time by opening the small ventilation holes in the oven, while keeping the oven door closed. When the oven temperature reached approx. 150°C, the door of the oven was opened to allow relatively fast cooling.

3.2 PULL-OUT TESTS

On the heat treated specimens, pull-out tests with confined test setup were performed. The typical test setup for the pull-out tests is shown in Fig. 4. The specimen was placed with the rebar passing through the slot in the reaction bracket. A loading frame was used to connect the hydraulic cylinder to the test rebar, which was gripped using a wedge fixture. One LVDT was used to measure the rear end displacement (slip) of the test rebar and three LVDT were used to measure the crack width of the splitting crack, if any. A calibrated load cell was used to measure the applied load. The specimen was loaded with oil pressure control quasi-statically while continuously recording the applied load, the rear end displacement and the splitting crack width.

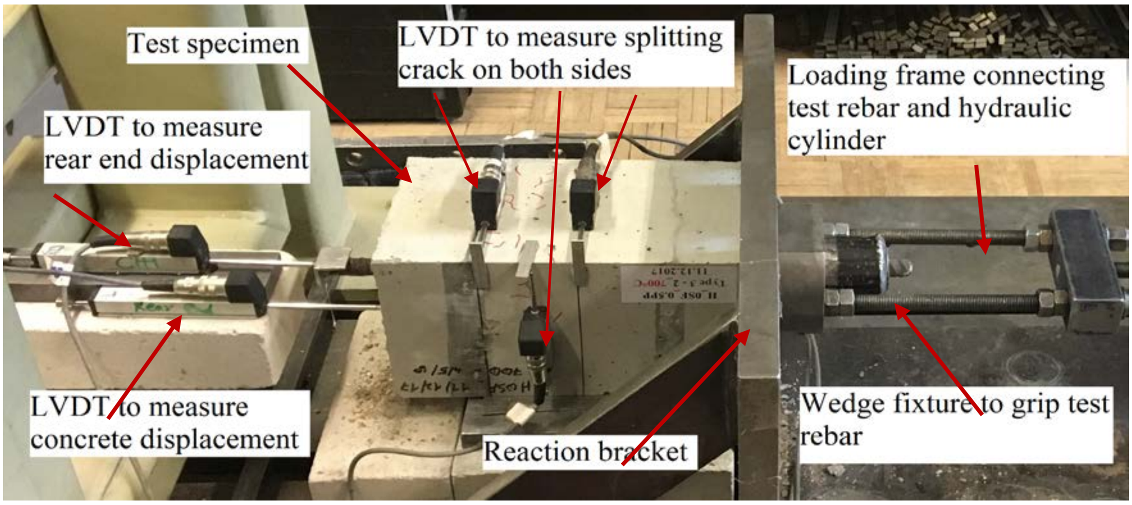


Fig. 4: Test setup employed for performing pull-out tests

4. RESULTS AND DISCUSSION

4.1 COMPRESSIVE STRENGTH

The compressive strength of concrete was tested using standard 150 mm cubes which were exposed to the same heating and cooling regime and tested on the same day as the pull-out specimens. The average values (six cubes per case) of the compressive strength of concrete thus obtained are summarized in Table 3. It is observed that both concrete types exhibit similar compressive strength, both under ambient conditions as well as after the exposure to elevated temperatures.

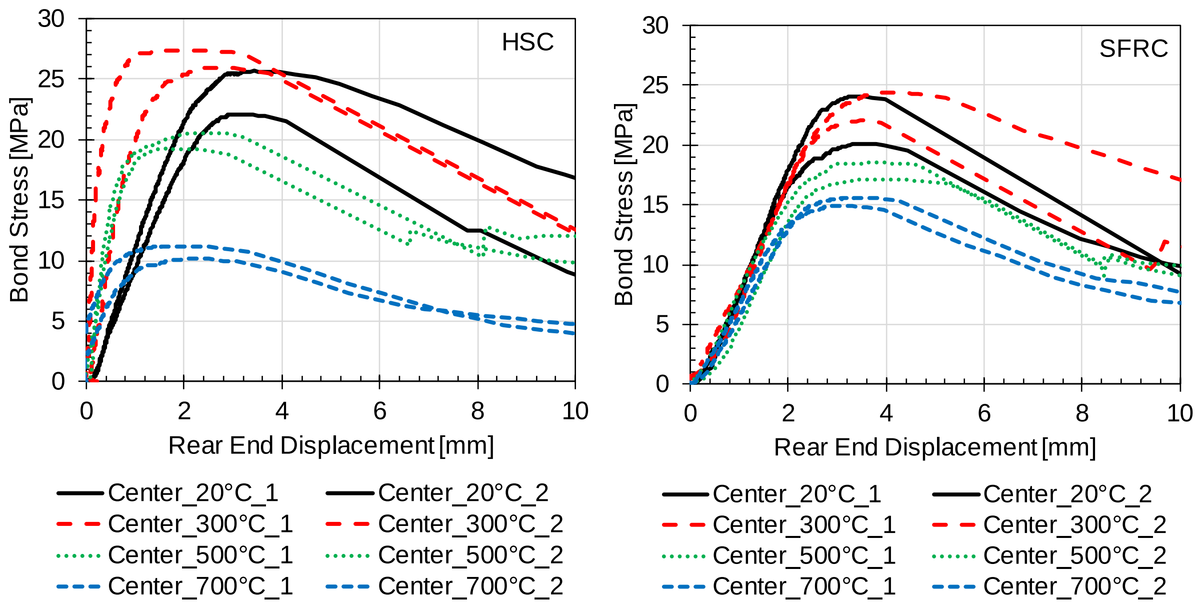
Table 3: Average compressive strength of concrete at different temperatures

Temperature [°C]	HSC (no steel fibers) [MPa]	SFRC [MPa]
20	72.2	73.5
300	66.5	64.4
500	47.8	44.8
700	28.7	29.4

4.2. BOND STRENGTH

4.2.1 Specimen with rebar in the center

The results of the pull-out tests performed on the specimens with test rebar located in the center are plotted in Fig. 5a for concrete without steel fibers and in Fig. 5b for concrete with steel fibers. The curves display a typical bond stress-slip behavior in case of pull-out failure. Initially, a linear ascending branch is seen followed by a nonlinear ascending branch showing relatively large increase in slip with small increase in the stress due to the crushing of concrete in front of the lugs of the test rebar. This is followed by a plateau at the peak stress until the concrete key between the lugs of the rebar is partially sheared off. Further slippage of the rebar requires a lower force and the bond stress gradually drops down until only frictional resistance is available.



(a) Concrete without steel fibers (HSC) *(b) Concrete with steel fibers (SFRC)*

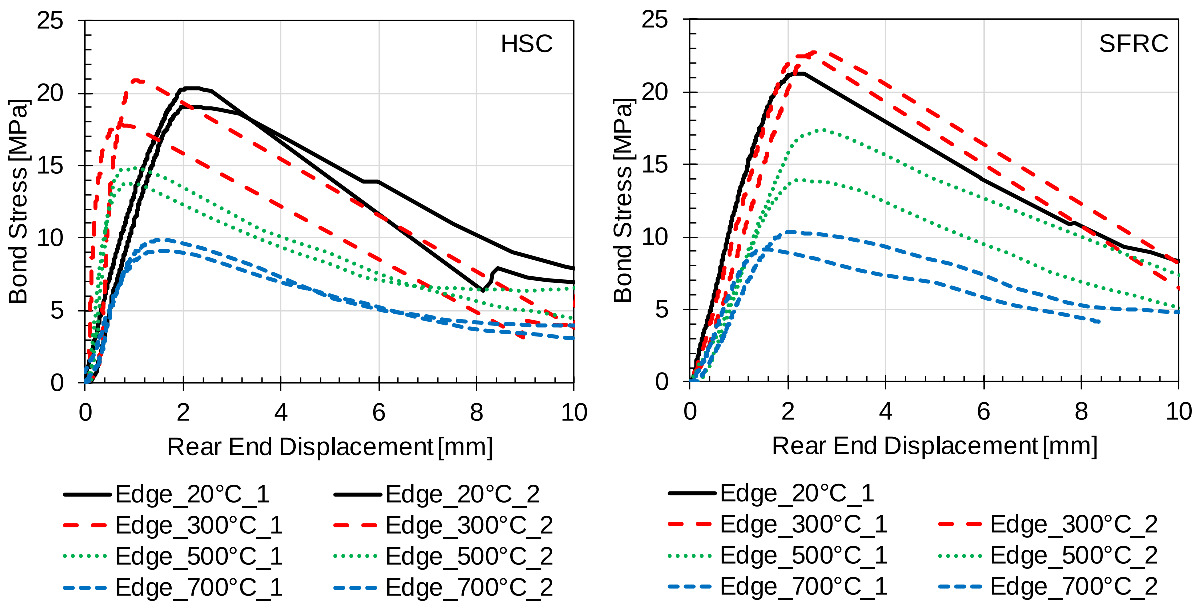
Fig. 5: Bond stress-slip curves obtained - pull-out tests on specimens with rebar in the center

It is interesting to note that the peak bond stress values obtained for the tests performed after an exposure to a temperature of 300°C display no degradation, rather in some cases higher bond strength compared to the pullout tests carried out at room temperature for both HSC and SFRC. This is attributed to the scatter of test results and the fact that up to 300°C the strength of concrete is not significantly affected by the temperature. The peak bond stress obtained for 20°C, 300°C and

500°C was similar or slightly lower for SFRC compared to HSC but for the exposure temperature of 700°C, the peak bond stress for SFRC was significantly higher than that of HSC.

4.2.2 Specimen with rebar at the edge

The results of the pull-out tests performed on the specimens with test rebar located at the edge are plotted in Fig. 6a for concrete without steel fibers and in Fig. 6b for concrete with steel fibers. In this case, the bond stress-slip curves for a given temperature reach a lower peak stresses in comparison to those attained by the rebar in the center for the corresponding temperature. This suggests the occurrence of premature splitting of the concrete cover prior to reaching the pull-out bond strength, under the influence of tensile stresses radiating out of the test rebar into the surrounding concrete with small cover. It is marked by the absence of plateau in the bond stress-slip curves close to the peak bond stress. All curves display a relatively pointed peak followed by a steeper descending branch compared to the curves shown in Fig. 5. In principle, the behavior of HSC and SFRC concrete is very similar.

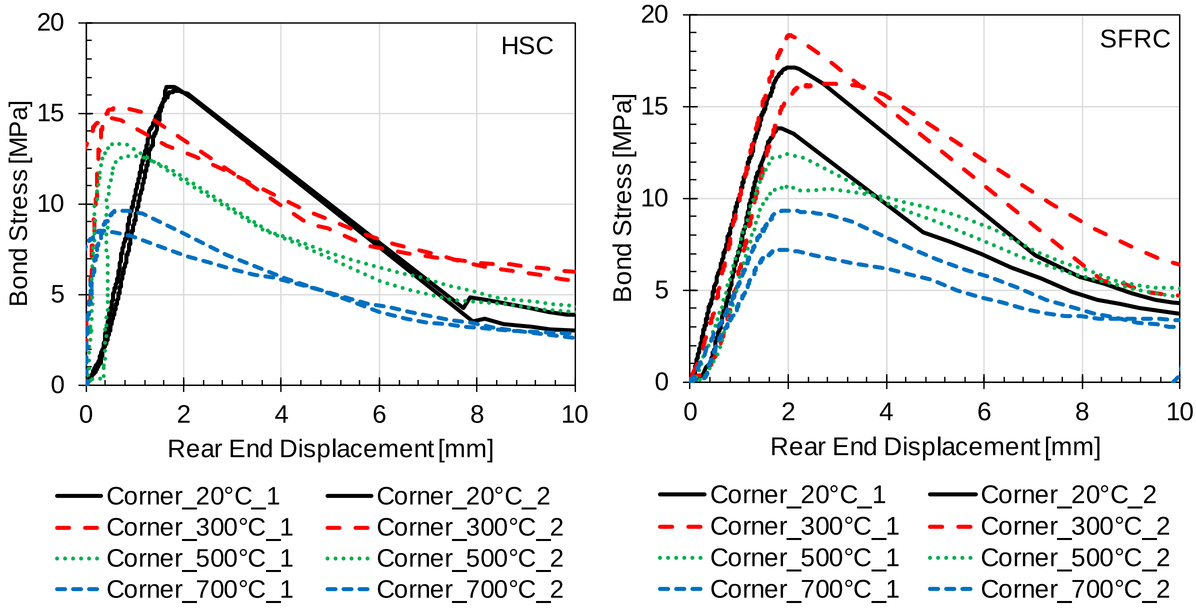


(a) Concrete without steel fibers (HSC) *(b) Concrete with steel fibers (SFRC)*

Fig. 6: Bond stress-slip curves obtained - pull-out tests on specimens with rebar at the edge

4.2.3 Specimen with rebar in the corner

The results of the pull-out tests performed on the specimens with test rebar located in the corner are plotted in Fig. 7a for concrete without steel fibers and in Fig. 7b for concrete with steel fibers. Again, the bond stress-slip curves are marked with sharp peak and steep descending branch associated with concrete splitting failure. The rebar positioned at the corner is surrounded by small cover on two sides, which leads to even lower peak bond stresses compared to the rebar positioned at the edge. It can be observed that the two concrete types exhibit very similar behavior.



(a) Concrete without steel fibers (HSC) *(b) Concrete with steel fibers (SFRC)*

Fig. 7: Bond stress-slip curves - pull-out tests on specimens with rebar in the corner

4.3 FAILURE PATTERNS

The specimens were inspected for any cracks after exposure to elevated temperature, which were marked in red color (the cracks were marked only in the bonded zone). The cracks obtained as a result of the pull-out test on the rebar were marked by blue color.

4.3.1 Specimen with rebar in the center

The specimens with the rebar located in the center failed by bond pull-out without the formation of any splitting cracks (Fig. 8). Even at high temperatures, where the surface cracks were visible on the concrete after exposure to temperature, the failure in the pull-out tests was due to bond failure. This is attributed to relatively large concrete cover on all sides of the test rebar.

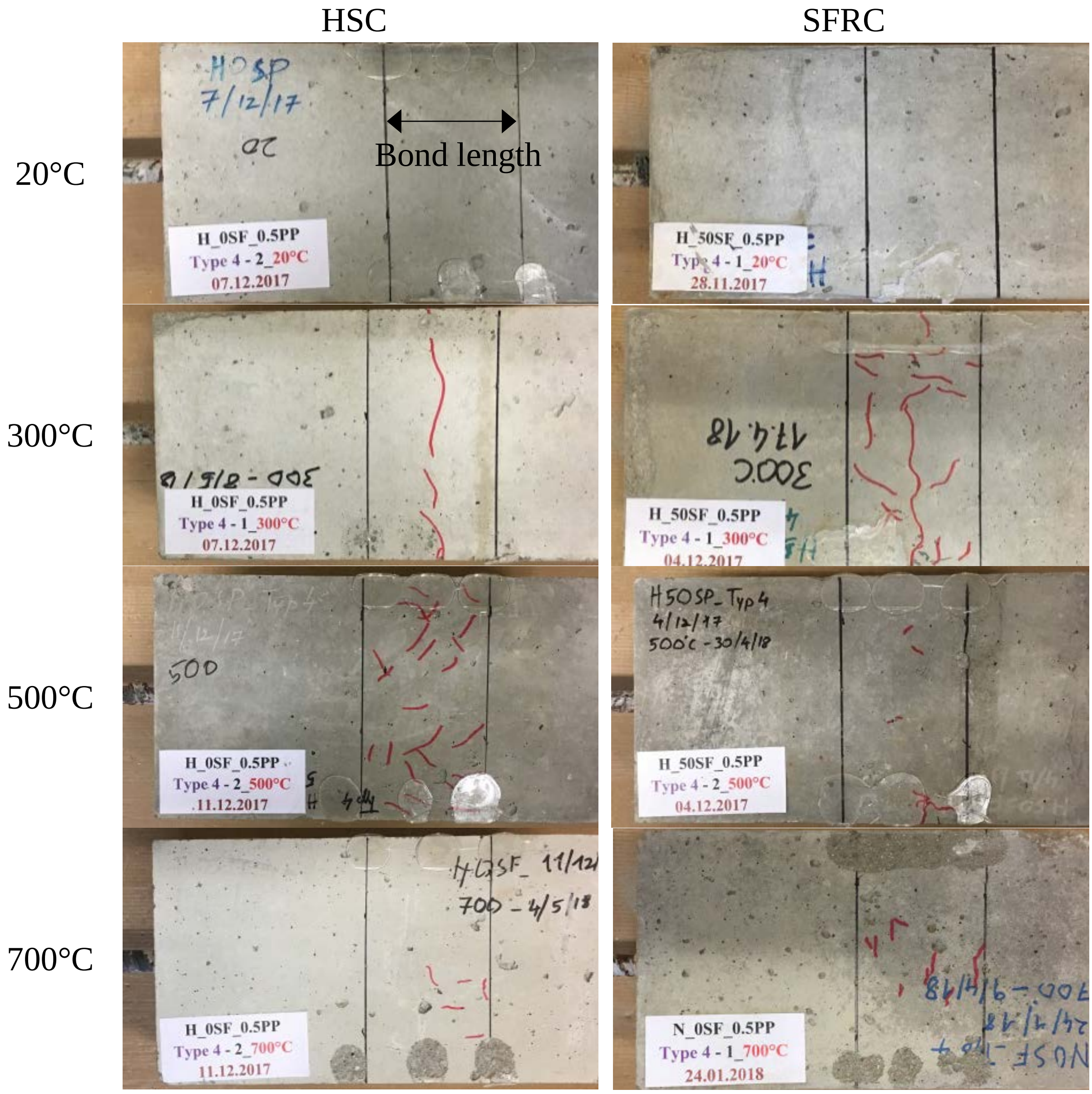


Fig. 8: Typical failure patterns - pull-out tests for specimens with rebar in the center

4.3.2 Specimen with rebar at the edge

The specimens with the rebar located at the edge of the specimen displayed one major splitting crack parallel to the axis of the test rebar (Fig. 9), which is formed due to the radial tensile stresses generated by pulling out the rebar. Although the failure mode was similar for both types of concrete, the splitting cracks observed in the tests with SFRC were finer than those observed in the tests with HSC.

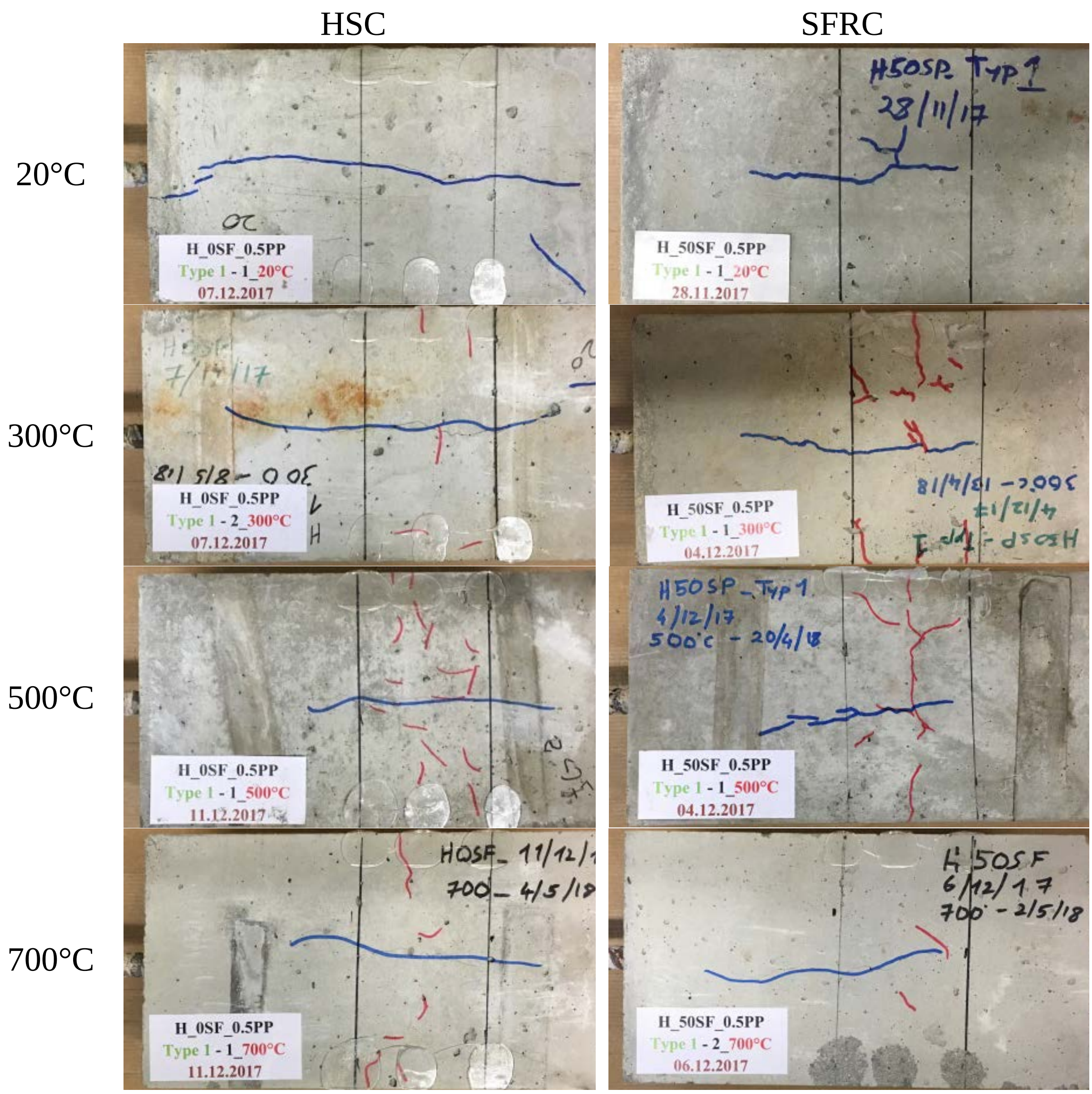


Fig. 9: Typical failure patterns - pull-out tests for specimens with rebar at the edge

4.3.3 Specimen with rebar in the corner

The tests on the specimens with the rebar in the corner displayed severe splitting along the length of the test rebar, sometimes on both faces of the specimen close to the rebar (Fig. 10). Exposure to elevated temperature did not result in any change of failure mode i.e. concrete splitting was observed in all investigated cases.

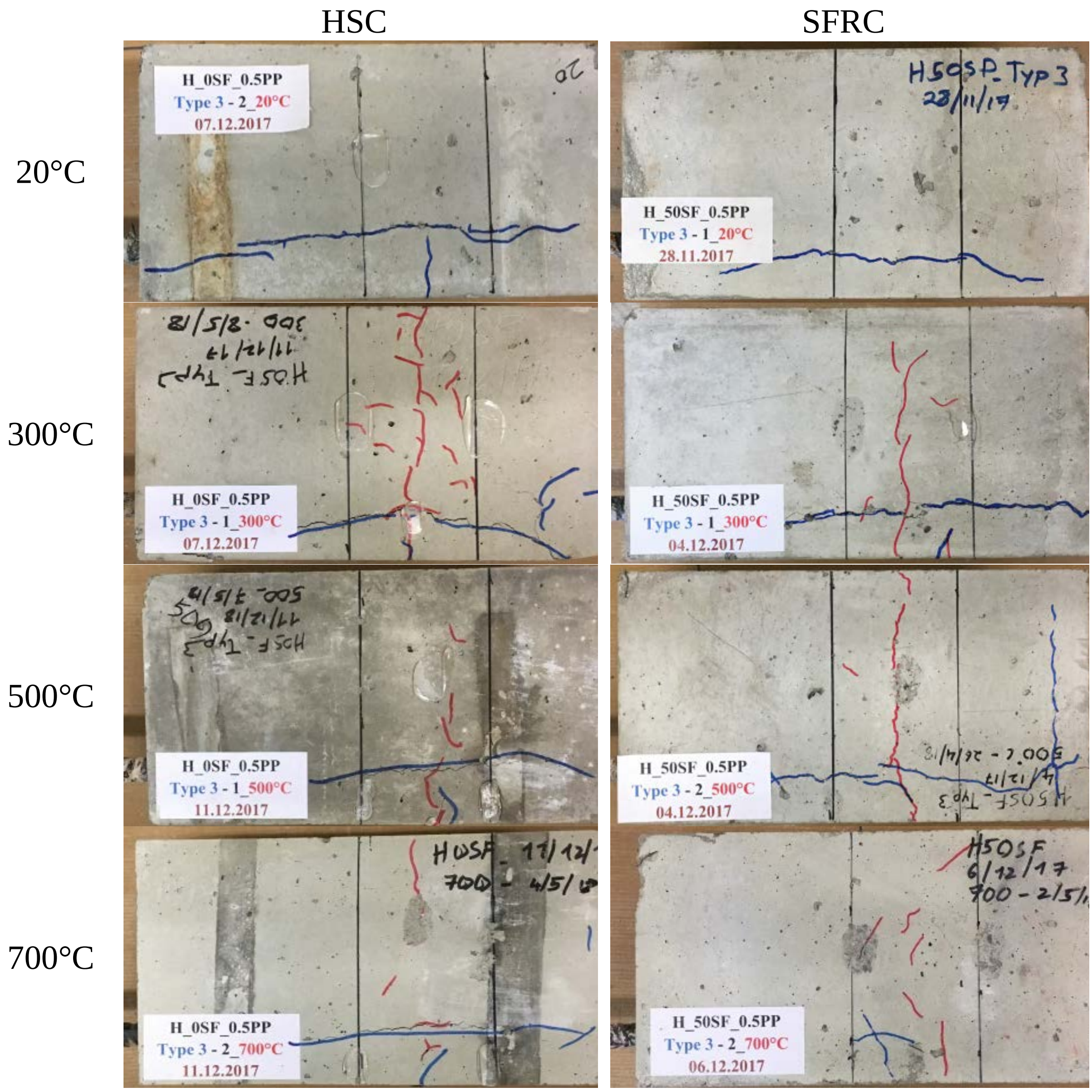
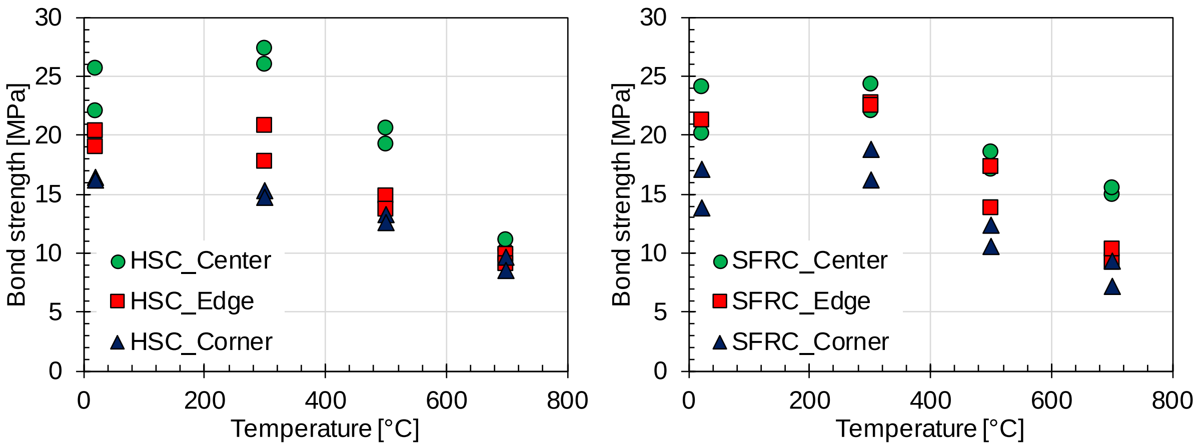


Fig. 10: Typical failure patterns from pull-out tests for specimens with rebar in the corner

4.4 BOND STRENGTH VS. TEMPERATURE

The degradation of peak bond stress as a function of temperature is depicted in Fig. 11a for concrete without steel fibers and in Fig. 11b for concrete with steel fibers. In case of concrete without steel fibers, at low temperatures, the bond strength for rebar in the center was higher than the bond strength for rebar at the edge, which in turn was higher than the bond strength for rebar in the corner. After exposure to 700°C, the bond strength was found to be similar for all the cases irrespective of the position of the rebar. In case of concrete with steel fibers, the bond strength for rebar in the center was always higher than the bond strength for rebar at the edge, which in turn was higher than the bond strength for rebar in the corner, for all the temperatures.

In general, the degradation of bond capacity in case of high strength concrete is very similar to that observed in normal strength concrete [3].



(a) Concrete without steel fibers (HSC) *(b) Concrete with steel fibers (SFRC)*

Fig. 11: Bond strength as a function of temperature for different specimens

5. CONCLUSIONS

In this work, pull-out tests with confined test setup have been performed on reinforcement in concrete without and with steel fibers after exposure to elevated temperature (20°C to 700°C). In order to study the effect of the failure mode on the residual bond capacity, three different configurations of the rebar were investigated (rebar in the center, at edge and in the corner of the concrete specimen). The first configuration yielded pure bond failure (pull-out) for the complete temperature range, whereas a splitting failure was observed for the latter two configurations. As expected, the splitting failure occurred at significantly lower level of usable bond stress than the bond failure.

For concrete without steel fibers, in the case of bond failure, the thermal degradation is gradual and approximately corresponds to thermal degradation of compressive strength. This result correlates well to the results found in the literature [3-6]. In case of the splitting failure, however, there is a somewhat more pronounced degradation with temperature. Similar results were obtained for the behavior in normal strength concrete [3].

For concrete with steel fibers, the degradation of bond is more gradual for both pull-out and splitting failure modes compared to that in concrete without fibers. The results indicate that the inclusion of steel fibers have a potential to slightly improve the bond performance even at relatively high temperatures.

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