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Bond behavior of carbon rebars and concrete

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1 Abstract

The material carbon reinforced concrete finds more and more acceptance in construction. Comprehensive research results are at hand already for the use of carbon reinforcements in the form of mats concerning their tensile and bond behavior. However, many research activities are still urgently required regarding the use of carbon rebars, particularly in view of the bond behavior of the bars in concrete. For this reason, different carbon rebars with varying surface profiles have been tested in a number of experimental tests for their bond behavior. The influence of the concrete strength on the bond behavior was additionally tested at a preferred rebar.

Keywords: carbon rebars, bond behavior, carbon reinforced concrete

2 Introduction

The material carbon reinforced concrete has experienced an astonishing development. Carbon reinforced concrete has become more than an alternative to traditional steel-reinforced concrete. In particular, comprehensive research results and practice projects have been made for the use of carbon mats, e.g. [1]. However, this statement does regrettably not apply to components reinforced by carbon rebars. Although there are a few publications in hand concerning the tensile strength of carbon rebars, e.g. [2], or about carbon-concrete components with mixed reinforcement (carbon rebars and mats), e.g. [3]-[5], but no sufficient knowledge has been obtained regarding the general bond behavior between the rebars and the concrete. For safe and efficient designing, calculation and dimensioning however, the bond behavior and its influencing factors must be known.

For this reason, experimental bond tests have been made for carbon rebars with varying surface profiles in concrete, as described in the following. The influence of the concrete strength on the bond behavior was additionally tested for a selected preferred rebar.

3 Materials used

The materials used in the experimental tests are described below. For more details, please refer to [6]-[9].

3.1 Carbon rebars and steel rebar

Eight different carbon bars (fig. 1) and a conventional steel bar (fig. 2) were used as reinforcing bars. The carbon bars used were made of differed source materials, in particular their impregnation, and had varying surface profiles.

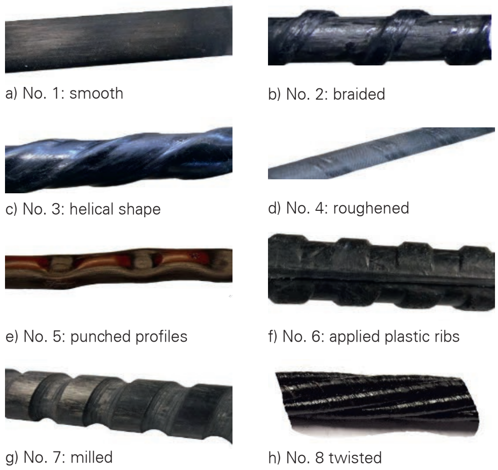

Figure 1: Used carbon rebars | graphic: Alexander Schumann

Figure 2: Used steel rebar (rebar 9) | graphic: Alexander Schumann

3.2 Concretes

In the first test series (touch test series), a high-strength concrete developed in the C³ project, maximum grain size 5 mm and compressive strengths >90 N/mm², was applied. For further details to the concrete used, please refer to [7].

To investigate the influence of the concrete strength on the bond behavior, two normal-strength concretes (NC 1 und NC 2) and an ultra-high strength concrete (UHPC) were applied in addition to the high-strength concrete (HC). The mixture formulations of the regarding concretes are given in [9].

3.3 Test setup

The tests were prepared in the Otto-Mohr-Laboratory of the Technische Universität Dresden. Two different test specimens were used for the touch test series. Fig. 3 b) shows the specimen defined as standard for the touch test series. It was used for almost all tests. Just for the investigation of the bond behavior of rebar configuration 6, the smaller specimen showed in figure 3 c) had to be applied, caused by the length of the carbon rebar, which was limited because of production reasons. Furthermore, when compared to specimen 1, the bond zone had to be positioned in the center of specimen 2, because of technological manufacturing aspects for this geometry.

In the second test series, the specimen shown in figure 3 d) was generally applied.

In all tests, the bond length uniformly corresponded to the five-fold of the rebar diameter (5 d_v). Only in the test series using the steel rebar, the bond length had to be reduced to 2 d_v to avoid any yielding of the steel rebar in the bonding test, as high-strength concrete was used in it. To introduce the test force into the carbon rebar without damaging the bar, steel sleeves were glued to the end of the carbon rebars, see figure 3.

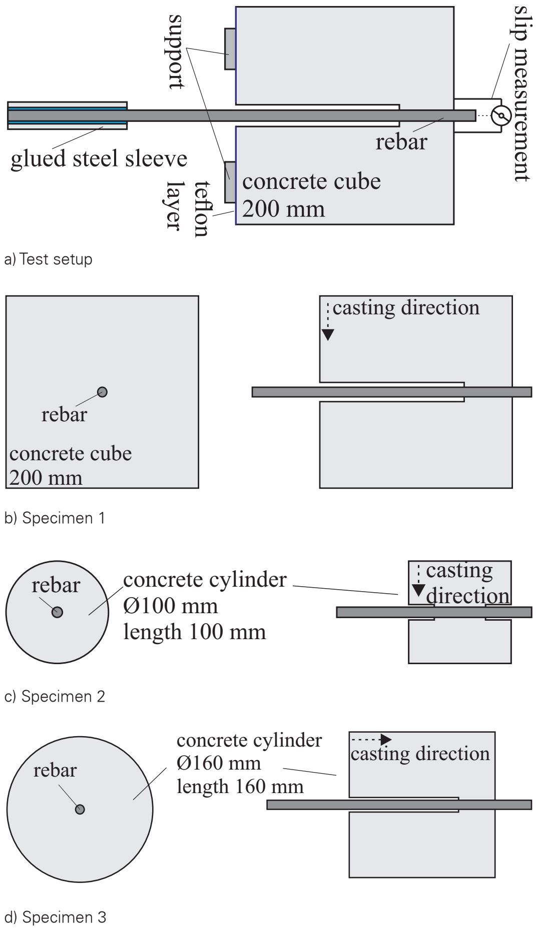

Figure 3: Used test setup and specimens | graphic: Alexander Schumann

In test series 1 (touch tests), the bond test specimens were fabricated in recumbent position, and in test series 2 in upright position. After manufacture, the specimens remained covered in their shuttering for three days. Afterwards the specimens were stripped and stored at room temperature and 65% relative humidity under a plastic membrane until the date of the test. In the touch test series, the tests were made after approx. 14

days, and in the test series 2 after approx. 28 days. During the execution of the tests, the slip of the rebar at the unloaded bar end and also the tool path and the test force were permanently measured. The force was applied deformation-controlled at a test speed of 0.01 mm/sec.

For each test series, three concrete prisms of the dimensions 40 x 40 x 160 mm^3 were additionally fabricated in accordance with DIN EN 196-1 [10], and tested on the bond testing date to determine the bending tensile strength and the compressive strength. Deviating from DIN EN 196-1 [10], the prisms were stored analogously to the bond test specimens.

4 Results of the touch test series

The individual test series for the different rebar variants have been evaluated and compared by means of the bond-stress–slip ratio. For traceability reasons, table 1 shows a list of all relevant parameters.

A rebar configuration to be applied for further bond investigations shall be determined by means of the tests made. To determine a preferred variant, fig. 5 shows a comparison of the mean value curves of the regarding rebar variants.

It can be seen from figure 4 that the transferable bond stresses significantly depend on the surface profile. It is further shown that the steel rebar (rebar configuration 9) reaches the highest bond stresses. Additionally, the steel rebar has the highest bond rigidity, best demonstrated in fig. 4 b). Based on the experimental bond tests, it can be further stated that rebar configuration 7 (profiling by milling) can transfer maximum bond stresses, reaching the ones of the steel rebar. Concerning the comparison of the two variants, it has to be mentioned that the bond tests with the steel rebar had to be carried out with a bond length of 2 d_v to avoid any yielding of the reinforcement; whereas all carbon rebars had a bond length of 5 d_v; indicating that the bond stresses at the steel

Term	Rebar	l_b m	d_v mm	A d	τ_{max} MPa	$s_{o,max}$ mm	f_{cm} MPa	$f_{ctm,fl}$ MPa
V-1-1	1	40	8	10	4.3	0.2	107.3	10.4
V-1-2	1	40	8	10	4.3	0.3	107.3	10.4
V-2-1	2	40	8	14	8.1	0.2	108.2	11.2
V-2-2	2	40	8	14	6.9	0.2	108.2	11.2
V-2-3	2	40	8	14	10.7	0.3	108.2	11.2
V-3-1	3	45	9	11	6.0	10.9	108.7	10.0
V-3-2	3	45	9	11	7.4	10.8	108.7	10.0
V-3-3	3	45	9	11	5.8	5.7	108.7	10.0
V-4-1	4	30	6	12	20.0	5.7	112.4	9.8
V-4-2	4	30	6	12	21.5	4.2	112.4	9.8
V-4-3	4	30	6	12	19.9	10.2	112.4	9.8
V-4-4	4	40	8	12	21.2	6.1	112.4	9.8
V-4-5	4	40	8	12	21.1	5.3	112.4	9.8
V-4-6	4	40	8	12	21.2	6.7	112.4	9.8
V-5-1	5	30	6	11	21.5	6.5	108.7	10.0
V-5-2	5	30	6	11	28.9	2.6	108.7	10.0
V-6-1	6	50	10	12	29.1	1.1	112.4	9.8
V-6-2	6	50	10	12	26.8	1.4	112.4	9.8
V-6-3	6	50	10	12	28.9	0.9	112.4	9.8
V-7-1	7	40	8	13	36.0	0.5	115.0	10.1
V-7-2	7	40	8	13	38.1	0.6	115.0	10.1
V-8-1	8	46	9.3	12	11.7	2.3	111.5	9.9
V-8-2	8	46	9.3	12	11.0	1.7	111.5	9.9
V-8-3	8	46	9.3	12	11.2	1.8	111.5	9.9
V-9-1	9	20	10	11	38.0	0.3	108.7	10.0
V-9-2	9	20	10	11	40.1	0.4	108.7	10.0
V-9-3	9	20	10	11	40.0	0.3	108.7	10.0

l_b ... bond length; A ... specimen age at test day; τ_{max} ... max. bond strength

$s_{o,max}$ ... slip at τ_{max}

f_{cm} ... mean compression strength tested at prism

$f_{ctm,fl}$ ... mean flexural tensing strength tested at prism

Table 1: Results of Serie 1:

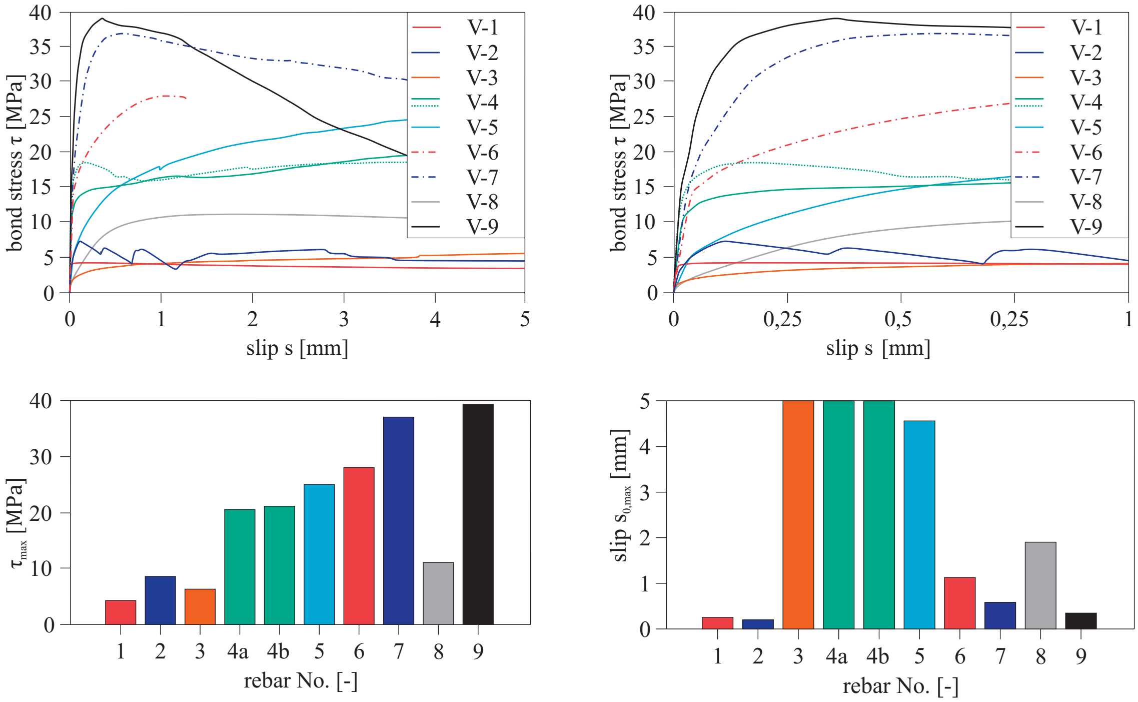

Figure 4: Results of series 1 | graphic: Alexander Schumann

rebar of 2 d_v are overestimated in comparison to 5 d_v. Thus, when applying the formulae of [11], this results in a decrease of approx. 15% for the conversion of the bond values from 2 d_s to 5 d_s, so that the maximum bond stresses of rebar configurations 7 and 6 are already in the range of the steel rebar or even above. As in construction, the bond rigidity and thus also the slip development are of essential importance, fig. 4 d) additionally shows the slip values $s_{0;max}$ related to the maximum bond stress τ_{max} . Because the maximum bond stresses in some rebar configurations occur at slip values of higher than 5 mm only, and these ranges are of minor importance in construction, the x axis of the diagram has been limited to the value of 5 mm for simplified presentation. Based on figure 5 d), it can be concluded that all rebar configurations that have a distinct form closure or no profiling at all (smooth bar, rebar configuration 1) reach maximum bond stresses below the slip value of 1 mm, indicating good bond rigidity. For the other rebar variants, the bond stresses rise continuously with increasing slip value up to the maximum bond stress at a very large slip $s_{0;max}$. For in contrast to the rebars with a high bond rigidity, the rebars with a low bond rigidity do not show a distinct form closure, with the result that the failure of these carbon rebars in the bond test happens successively and finally at high slip values only.

Further evaluations for finding a preferred variant are given in [9]. Here, end anchoring lengths and derived from them mean bond stresses were calculated for each rebar configuration by applying gradual integration on the basis of the experiments. Based on this and on fig. 4, the rebar configuration 7 (fig. 5) was determined as preferred variant for further bond tests.

Figure 5: Selected preferred variant | photo: Alexander Schumann

5 Results of test series 2

The influence of the concrete strength on the bond behavior was studied in the second test series. Four different concretes were used for this purpose, which shall cover a possible application range of the carbon rebars. For this reason, concrete No. 1 (NC 1) should purposefully have low strengths, as it can be considered as the lower limit, and concrete No. 4 (UHPC) should have extremely high strengths to represent a possible upper limit. Below, the two other concretes (NC 2 and HC) should reflect the strength ranges in between. In the following, the obtained bond re-

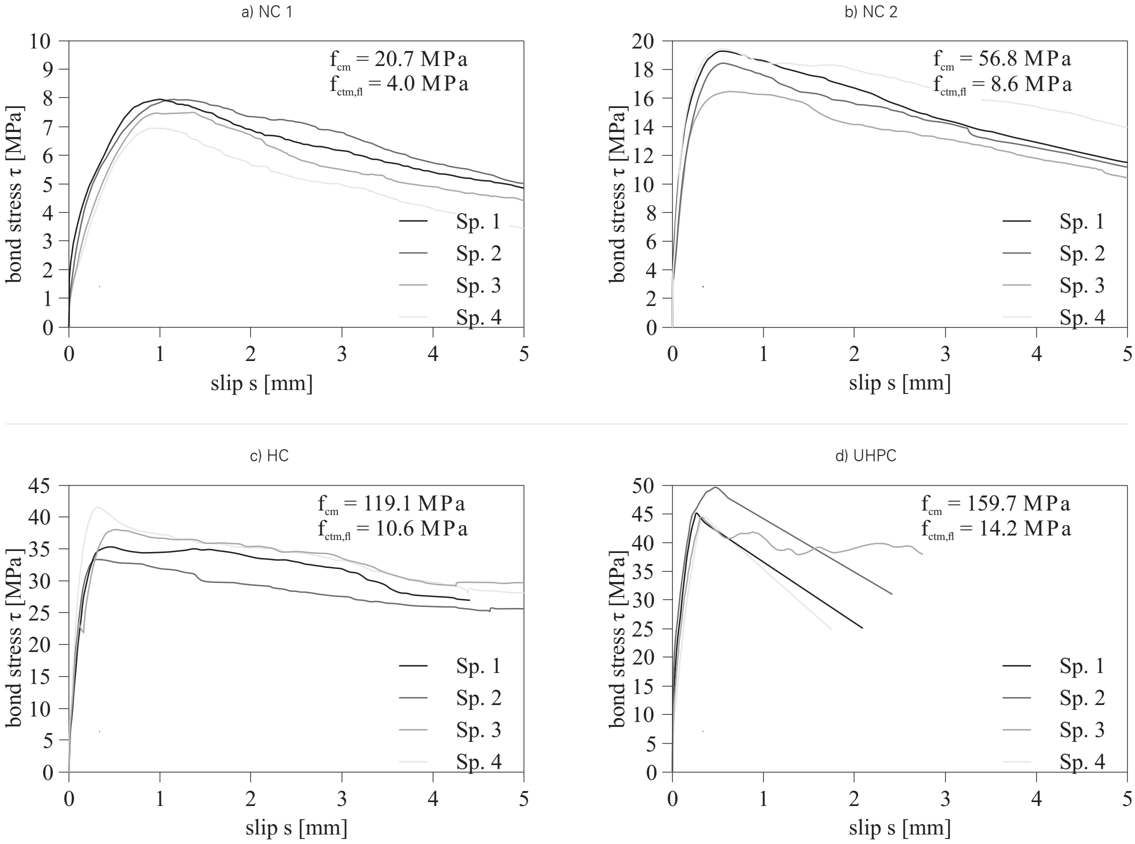

Figure 6: Bond-strain–slip relations for different concrete strengths | graphic: Alexander Schumann

sults in dependence on the concrete strength are shown and compared to each other.

Figure 6 a) - d) shows the bond-strain–slip curves for the different concretes. The diagrams additionally contain the mean values of the bending tensile and compressive strength tests obtained at the mortar prism after approx. 28 days.

As can be seen from the diagrams, the maximum bond stresses rise with increasing concrete strength. For example, the test series with the lowest concrete strength (NC 1, fig. 6 a)) shows the lowest bond stresses, and the test series with the highest concrete strength (UHPC, see fig. 6 d)) the highest maximum bond stresses. In the test series with the normal-strength and high-strength concretes (NC 1, NC 2 and HC), the failure was marked by the extraction of the carbon rebar from the specimen. When UHPC was used, the specimen was split after the maximum bond stress had been exceeded (see fig. 7), as can be seen from the steep drop in the bond-stress–slip curve in fig. 6 d) As the splitting happened after the maximum bond stress was exceeded only, the values can be used for the comparisons given below. After the tests had been made, the specimens of all series were split to measure the real bond length and to determine the failure mechanism. Fig. 8 shows pictures of the failures after the end of the tests.

In this connection, it could be stated that the failure in concrete 1 (NC 1) was caused by a complete shearing of the concrete consoles between the FRP ribs (see fig. 8 b)).

Figure 7: Splitting failure at UHPC | photos: Frank Schladitz

But fig. 8 a) also shows that some slight traces of scratching from the carbon rebar can be seen at the concrete. With rising strength, the failure changes from a pure shearing of the concrete consoles to a combined failure, a shearing of the concrete consoles and a shearing of the FRP profiles. This is shown in fig. 8 c) - d) and 8 e) - f) by the larger carbon residuals at the concrete. In the test series with UHPC, the failure is clearly characterized by a full-surface shearing of the FRP profiles from the carbon rebar (see fig. 8 g) and h)).

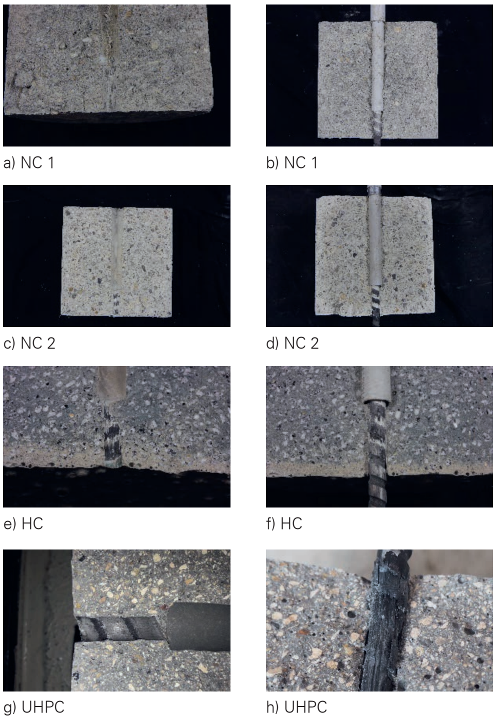

Figure 8: Failure mechanisms in dependence on the concrete strength; 1st line: NF, 2nd line: NF 2; 3rd line: HF; 4th line: UHPC | photos: Alexander Schumann

Caused by the complete shearing of the FRP profiling from the rebar core when applying UHPC, the splitting of the specimen can be traced back to the high bond stresses, on the one hand, and on the famous „wedging effect", which happens only in the case of a complete shearing of the FRP reinforcement.

Figure 9 a) shows the mean value curves of the bond-stress–slip relations obtained in the different series. Analogously to steel-reinforced construction, the carbon rebars develop higher bond values and a more rigid bond behavior with increasing concrete strength. For better comparability of the test results, the curves in fig. 9 b) and c) are related to the mean concrete compressive strength f_{cm} and the bending tensile strength $f_{ctm;fl}$.

The bond curves related to the concrete compressive strength show similar values, with decreasing maximum related bond stresses at increasing concrete compressive strength. In contrast to that, no definite dependence can be seen for the related bond stresses with regard to the bending tensile strength (see fig. 9 c)). These findings can be substantiated by fig. 9 d) and e).

As shown in fig. 9 d), an almost linear connection between the maximum bond stress and the concrete compressive strength can be proven for the reference rebar up to the compressive strength of approx. 160 N/mm² tested in this study. When a quadratic regression function is applied instead of the linear connection, the influence of the concrete compressive strength on the maximum bond stresses can be described more exactly, as the maximum bond values proportionally decrease at high concrete strengths. When the maximum bond stresses are applied in relation to the tensile strength of the concrete (see fig. 9 e)), no clear tendency can be derived from the test results. To characterize the bond rigidity in dependence on the concrete strength, fig. 9 f) includes the slip values $s_{u;max}$ related to the maximum bond stress. It can be seen that the slip values $s_{u;max}$ decrease with increasing concrete strength, caused by the higher bond rigidity at a higher concrete compressive strength. Fig. 9 g) and h) additionally show the bond stresses at a slip of 0.1 mm ($\tau_{0,1}$) and 0.2 mm ($\tau_{0,2}$) in relation to the compressive strength and the bending tensile strength of the concrete. They can be applied to prove the statements made above that the description of the influence between the concrete compressive strength and the bond behavior leads to more conclusive results, as there is an almost linear relation between the concrete strength and the bond values $\tau_{0,1}$ and $\tau_{0,2}$.

6 Discussion, conclusions and acknowledgements

In this study, several carbon rebars with different surface profiles were tested for their bond behavior in concrete. By means of the first test series (touch tests), it could be proven that the surface profiling has a significant influence on the bond behavior and the maximum transferable bond stresses. In conclusion of the test results, the milled carbon rebar was chosen as the preferred variant for further bond investigations. In a second test series with the milled rebar, the influence of the concrete strength on the bond behavior was studied. It was found that, for this carbon rebar, the concrete strength has a significant influence on the maximum bond stresses and the bond rigidity. It was further stated that the concrete strength at the carbon rebar also has an influence on the form of the failure. With low-strength concretes, the concrete consoles between the

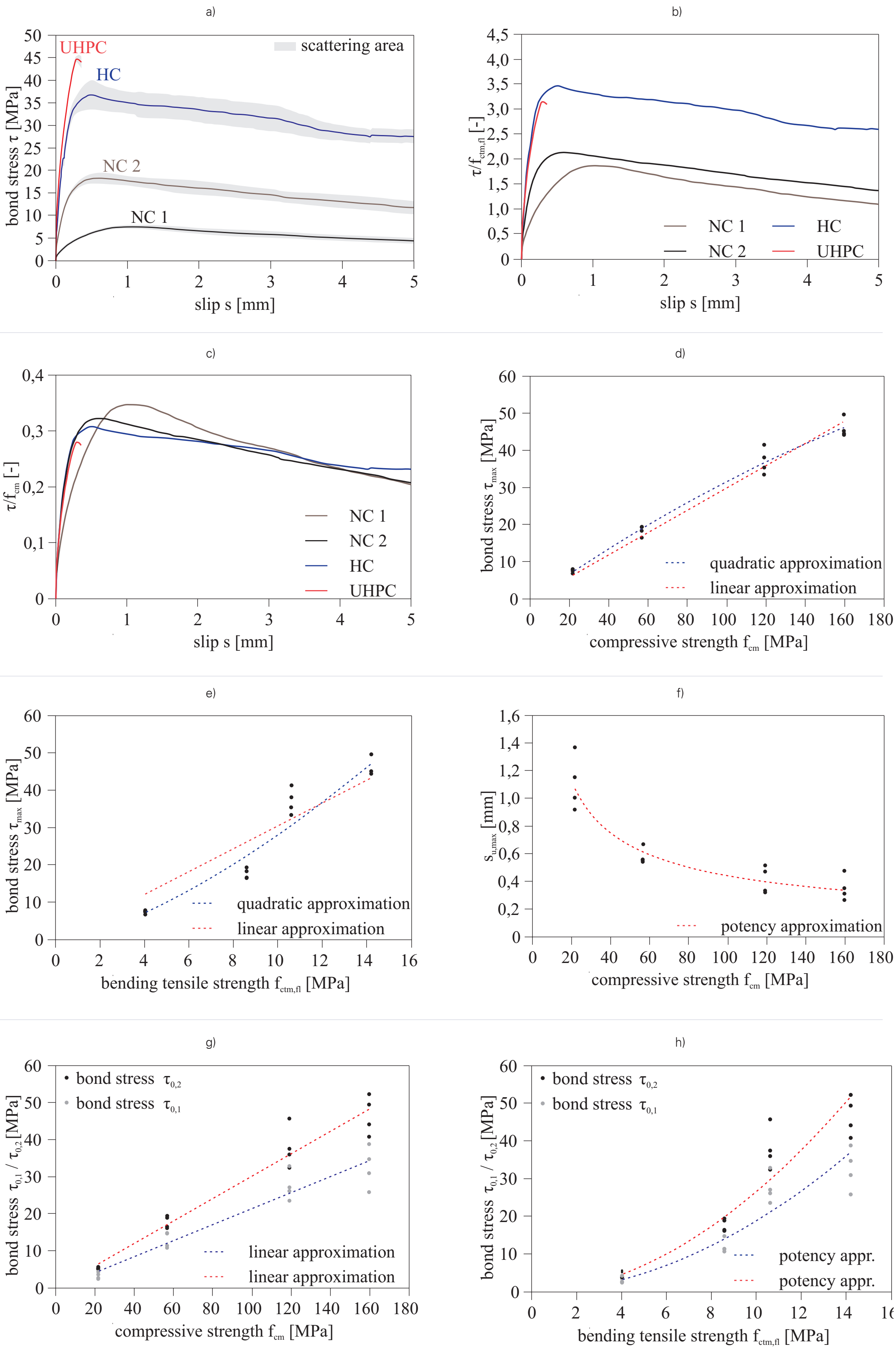

Figure 9: Comparison of the test results | graphic: Alexander Schumann

carbon ribs were sheared off, whereas the carbon ribs were completely destroyed when UHPC was used. In the range between the failure forms, mixed failures occur, a partial destroy of the carbon ribs and a shearing of the concrete consoles. The results obtained show that for the carbon rebar the maximum bond stresses increase with increasing concrete strength, as it is known from steel-reinforced concrete. Therefore the findings obtained are transferable, when sufficient data quantities are at hand.

Based on these results it is intended to study further factors of influence on the bond behavior, including the rebar batch, the bond length and the maximum grain size as well as the composition of the concrete. The results shall be used to develop a number of approaches for the description of the influence factors, to describe the bond behavior of structural components made of carbon concrete in greater detail.

7 References

[1] Schütze, E.; Bielak, J.; Scheerer, S.; Hegger, J.; Curbach, M.: Einaxialer Zugversuch für den Carbonbeton mit textiler Bewehrung. Beton- und Stahlbetonbau. 2018;113, Vol. 1:33-47.

[2] May, M.; Riegelmann, P.; Schumann, A.; Curbach, M.: Carbonstäbe im Bauwesen – Teil 3: Bestimmung der Zugtragfähigkeit. Beton- und Stahlbetonbau, submitted. 2020.

[3] Schmidt, A.; Bielak, J.; Hegger, J.: Large-Scale Tests on the Structural and Deformation Behaviour of I-Beams with Carbon Reinforcement. In.: International Institute for FRP in Construction (FRPRCS-14), Belfast 2019.

[4] Schumann, A.; May, S.; Curbach, M.: Design and Testing of various Ceiling Elements made of Carbon Reinforced Concrete. Proceedings (2018), Vol. 2:1-6.

[5] Kromoser, B.; Preinstorfer, P.; Kollegger, J.: Building lightweight structures with carbon-fiber-reinforced polymer-reinforced ultra-high-performance concrete: Research approach, construction materials, and conceptual design of three building components. Structural Concrete 20 (2018), Vol. 2:730-744.

[6] Schumann, A.; May, M.; Schladitz, F.; Curbach, M.: Carbonstäbe im Bauwesen. Teil 2: Verbundverhalten – Verbundversuche an unterschiedlichen Carbonstäben. Beton- und Stahlbetonbau. Submitted. 2020.

[7] Schneider, K.; Butler, M; Mechtcherine, V: Carbon Concrete Composites C3 – Nachhaltige Bindemittel und Betone für die Zukunft. Beton- und Stahlbetonbau 112 (2017), Vol. 12.

[8] Böhm, R.; Thieme, M.; Wohlfahrt, D.; Wolz, S. S. J.; Richter, B.; Jäger, H.: Reinforcement Systems for Carbon Concrete Composites Based on Low-Cost Carbon Fibers. Fiber 6 (3) (2018), Vol. 56:1-21.

[9] Schumann, A.: Experimentelle Unter-suchungen des Verbundverhaltens von Carbonstäben in Betonmatrices. TU Dresden, Dissertation. Submitted 2020.

[10] DIN EN 196-1:2016-11: Prüfverfahren für Zement – Teil 1: Bestimmung der Festigkeit; Deutsche Fassung EN 196-1:2016. 2016.

[11] Ritter, L.: Der Einfluss von Querzug auf den Verbund zwischen Beton und Stahl. Technische Universität Dresden, Diss., 2014.

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