PULL-OUT TESTS TO DEMONSTRATE THE INFLUENCE OF CONCRETE HUMIDITY ON THE FATIGUE OF BOND

AUSZIEHVERSUCHE ZUM EINFLUSS DER BETON-FEUCHTE AUF DIE VERBUNDERMÜDUNG

Christoph Walther, Veit Birtel

Material Testing Institute (MPA), University of Stuttgart, Otto-Graf-Institute

SUMMARY

Cyclic loaded pull-out tests were carried out to demonstrate the fatigue damage of bond at two different concrete humidity levels (under water stored and oven dried). The specimens were concrete cubes with a centrally embedded reinforcing bar and a fixed bond length l_v = 28 mm. The fatigue tests were carried out with a sinusoidal loading and were related to the bond strength of static pull-out tests (F_{stat}) to achieve a constant min. load level ($S_{min} = F_{min}/(F_{stat}) = 0.05$) and different max. load levels ($S_{max} = F_{max}/F_{stat} = 0.6; 0.7; 0.8$). The test results show a strong effect of concrete humidity on the number of cycles to failure. Usually failure was observed by pull-out the reinforcing bar. The fracture surfaces of the different humidity-conditioned specimens have different roughness surfaces.

ZUSAMMENFASSUNG

Es wurden zyklische Pull-Out Versuche zur Untersuchung der Ermüdungsschädigung des Verbundes bei zwei unterschiedlichen Betonfeuchten durchgeführt (Unterwasser gelagert und Ofen getrocknet). Als Probekörper dienten Betonwürfel mit einem zentrisch einbetonierten Bewehrungsstab und einer festgelegten Verbundlänge l_v = 28 mm. Die Versuche wurden mit einer sinusförmigen Belastung durchgeführt und auf die statische Verbundfestigkeit (F_{stat}) bezogen, um eine konstante Unterlast ($S_{min} = F_{min}/(F_{stat}) = 0.05$) und variierende Oberlasten ($S_{max} = F_{max}/F_{stat} = 0,6; 0,7; 0,8$) zu erreichen. Die Ergebnisse zeigen einen starken Einfluss der Betonfeuchtigkeit auf die Ermüdungstragfähigkeit. Das Versagen erfolgte in der Regel durch Herausziehen des Bewehrungsstabes. Die Bruchflächen der verschiedenen feuchtekonditionierten Probekörper weisen unterschiedliche Oberflächenrauigkeiten auf.

1. INTRODUCTION

As a result of the research work in recent decades the use of high-performance concretes in practice are common now. The increasing compressive strength of concrete enables the realization of increasingly slender and aesthetic concrete structures in civil engineering. Therefore a reduction of the dead load and a proportional increase in the variable live loads are given. The structural vibrations under live loads increase and the fatigue verification according to DIN EN 1992 – 1 - 1 becomes important or decisive for the design in the ultimate limit state. In the current standardization, this verification has so far been carried out separately for the materials steel and concrete. The fatigue of bond is not part of the design concept.

Current research projects (SPP2020) are already dealing with the fatigue of concrete at the material level to understand the expiring damage processes depending on loading and environmental impacts. For example, current research work points out that the influence of concrete humidity significantly accelerates fatigue damage of concrete [2], [3]. The influence of cyclic loads on the bond between reinforcement and concrete was investigated in [1], [4]. There it could be shown that the fatigue damage of bond substantially corresponds to the material damage of concrete. In this context, the research results at the material level give reason to investigate the influence of concrete humidity on bond fatigue. Therefore, in preparation for a proposed research project, two small test series were carried out.

2. EXPERIMENTS

2.1 Test program

The test program was subdivided into two series with specimen of dry conditioned concrete (D) and wet conditioned concrete (UW) according to Table 1. For each test series, three fatigue pull-out tests and one static loaded pull-out test were carried out. The fatigue tests were carried out with a sinusoidal loading by applying a static load F_{mean} and a cyclic amplitude ΔF. The loads $F_{max} = F_{mean} + \Delta F$ and $F_{min} = F_{mean} - \Delta F$ were related to the bond strength of static pull-out tests (F_{stat}). The load level $S = F_{cyc} / F_{stat}$ for the fatigue tests was normalized to enable a direct comparison of the results of dry and wet conditioned specimens. Three load levels ($S_{max} = F_{max}/F_{stat} = 0.6$; 0.7; 0.8) and a constant minimum load level

$S_{min} = F_{min} / F_{stat} = 0.05$ were applied. The loading frequency was f = 5 Hz for all tests.

Table 1: Test program

Test series	Number of specimens	load level S_{max}	load level S_{min}	Test frequency [Hz]
Dry - D	3	0.8; 0.7; 0.6	0.05	5
Wet - UW	3	0.8; 0.7; 0.6		

2.2 Test specimen

As test specimen concrete cubes with an edge length of a = 150 mm and a centrally situated reinforcing bar (d_s = 14 mm) with a fixed bond length of 2 d_s = 28 mm, were used according Fig. 1. The test specimen were cast in a horizontal position. Therefore, the rebar could be guided centrally through the formwork to prevent unwanted movements of the rebar during concreting. The bond free length was made with dimensionally stable PVC pipes on both sides of the specimen. In load direction, a small outer pipe diameter d = 25 mm was selected to reduce notch effects at the transition of the bond zone. On the other side of the specimen a pipe with outer diameter of d = 32 mm was chosen to ensure sufficient humidity conditioning of the bond area. For the tests a reinforcing bar B500B with a nominal diameter d_s = 14 mm and a relative rib area of f_R = 0.071 were used.

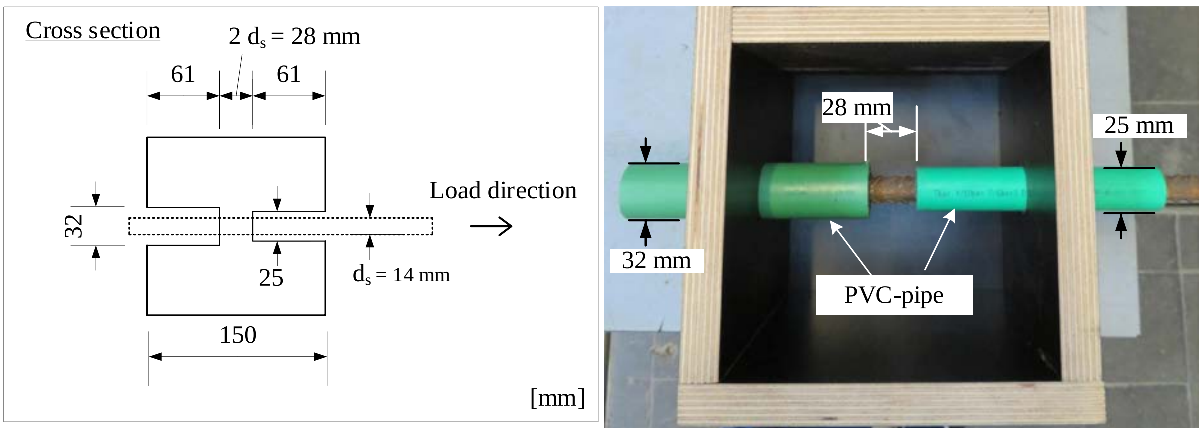

Fig. 1: Drawing of the test specimen and formwork

2.1.1 Material and storage condition

The test specimen were made by an high performance concrete with a water (w)/cement (c) ratio of w/c = 0.35 using a conventional single-shaft mixer.

The concrete composition is listed in Table 2. This corresponds to the concrete composition in the DFG SPP 2020 [3].

Table 2: Concrete composition with w/c = 0.35

Components	Amount [kg/m³]
CEM I 52.5 R-SR3 (na)	500
Fine sand	75
Sand 0/2	850
Basalt 2/5	350
Basalt 5/8	570
Concrete plasticizer	4.25
Stabilizer	2.42
Water	176

Before stripping the formwork the test specimens were stored for 24 h in a damp room (approx. 95 % relative humidity). Afterwards, all specimens were stored under water for 28 additional days to ensure optimal hydration and minimal shrinkage effects.

In order to achieve the highest possible saturation of the concrete pores, the test specimens of the wet test series (UW) were stored under water until testing. To minimize the effect of humidity reduction during the fatigue test these specimens were wrapped with cling film before they were adapted into the testing machine.

The specimens for the dry test series (D) were removed after 28 days from water storage and dried in an oven at 105 °C for 68 additional days until testing. It is assumed that the concrete humidity was nearly f = 0 % after oven drying. Based on the test specimen weights after 28 days, a humidity content f = 4.9 % is calculated for the test series UW. The storage conditions and the concrete humidity in mass percent are summarized in Table 3.

Table 3: Storage conditions

<table>
<tr><th>Series</th><th>Day 1</th><th>Day
1 - 28</th><th>Day
28 - 96</th><th>Humidity content [mass %]</th><th>Testing preparation</th><th>Testing</th></tr>
<tr><td>Wet (UW)</td><td rowspan="2">strip the form-work</td><td rowspan="2">Under-water storage</td><td>Underwater storage</td><td>4.9</td><td>Sealing with cling</td><td rowspan="2">25 °C – room tempera-ture</td></tr>
<tr><td>Dry (D)</td><td>Drying at 105 °C</td><td>0</td><td>-</td></tr>
</table>

The development of the concrete compressive strength of under water stored concrete was determined after 28 and 96 days using three cubes (a = 100 mm). After 28 the average concrete compressive strength was $f_{c,28d,UW}$ = 100.9 N/mm² and after 96 days $f_{c,96d,UW}$ = 116.6 N/mm².

Supplementary the concrete compressive strength of oven dryed concrete was determined at time when the fatigue testes were started (96 days). The compressive strength was $f_{c,96d,D}$ = 137.5 N/mm². All tests were carried out by 25°C room temperature.

2.3 Test procedure

A servo-hydraulic 400 kN testing machine from Schenk was used to perform the force-controlled fatigue tests. The test specimen was supported in a steel case, which was fixed in the upper chuck jaws of the machine, see Fig. 2. Possible misalignments could be compensated by means of a spherical cap, located on the upper steel plate.

The rebar was passed through a hole in the lower plate of the steel case, the concrete surface rested with its full area on the steel plate. With the help of the lower chuck jaws of the testing machine, the rebar could then be pulled from below.

During the tests the displacements were measured with three inductive displacement transducers on the unloaded side of the specimen. One of them measured the defection of the concrete surface itself. The other two measured the displacement of the unloaded end of reinforced bar. Therefore an adaption component was used as measuring point.

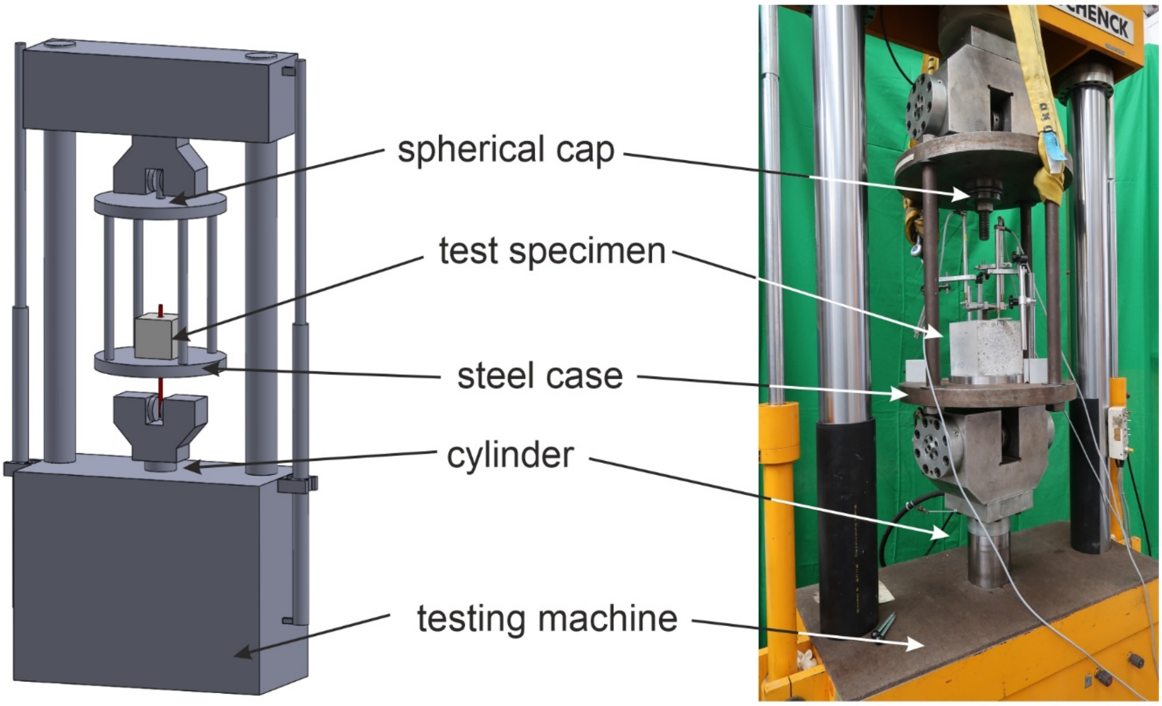

Fig. 2: Test setup

3. RESULTS

3.1 Number of load cycles and slip increase

An overview of the numbers of cycles to failure N_{max}, the slip and the failure mode of all fatigue tests is given in Table 4 with respect to the applied maximum load level S_{max}. The relative displacement (slip) between rebar and concrete was calculated from the difference of the measured displacements of rebar and concrete. Failure was observed by pull-out the reinforcing bar with accompanying shearing of the concrete brackets. Only the test with dry concrete and load level $S_{max} = 0.6$ failed due to steel failure.

Comparing the number of cycles to failure between the oven dried and wet stored concrete specimens at the same load level S_{max} it becomes very clear that the concrete humidity reduces the receivable load cycles significant. In every case the dry concrete specimen achieved a multiple of the number of cycles. Even assuming that the test with steel failure corresponds to the number of cycles for bond failure, the factor $N_{max(D)}/N_{max(uw)} \approx 3$. The comparison of individual ratio values $N_{max(D)}/N_{max(uw)}$ is not representative due to the expected scatter of test results, nevertheless a basic tendency of accelerated damage in the test series UW can be recognized. This trend can also be seen in Fig. 3. There, the numbers of cycles to failure N_{max} are plotted logarithmically with respect to the maximum load level S_{max}.

Table 4: Results of the fatigue tests

S_{max}	cycles to failure N_{max} [-]		max. slip [mm]		failure mode	
	D	UW	D	UW	D	UW
0.6	349,900	124,930	1.41	5.33	Steel	Pull out
0.7	62,314	7,513	3.67	5.62	Pull out	Pull out
0.8	8,632	132	4.60	-	Pull out	Pull out

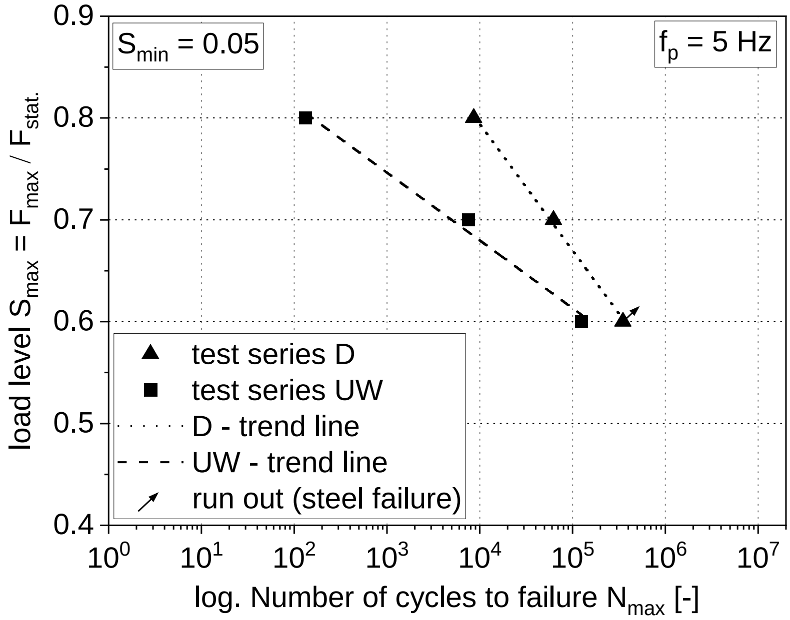

Fig. 3: load level S_{max} verses number of cycles to failure

The different bond bearing behavior during the test can be analyzed by comparing the slip for the test with different concrete storage conditions and same loading levels S_{max}. Fig. 4 shows the slip development of the fatigue tests of S_{max} = 0.6 and 0.7 plotted over the number of all load cycles. It becomes visible that tests of the UW test series are characterized by a larger slip in all phases until failure. Furthermore the specimen UW achieve a significantly larger final slip before failure, although a lower numbers cycles can be applied. It can be assumed that the damage processes run at an accelerated rate over the entire duration of the experiment.

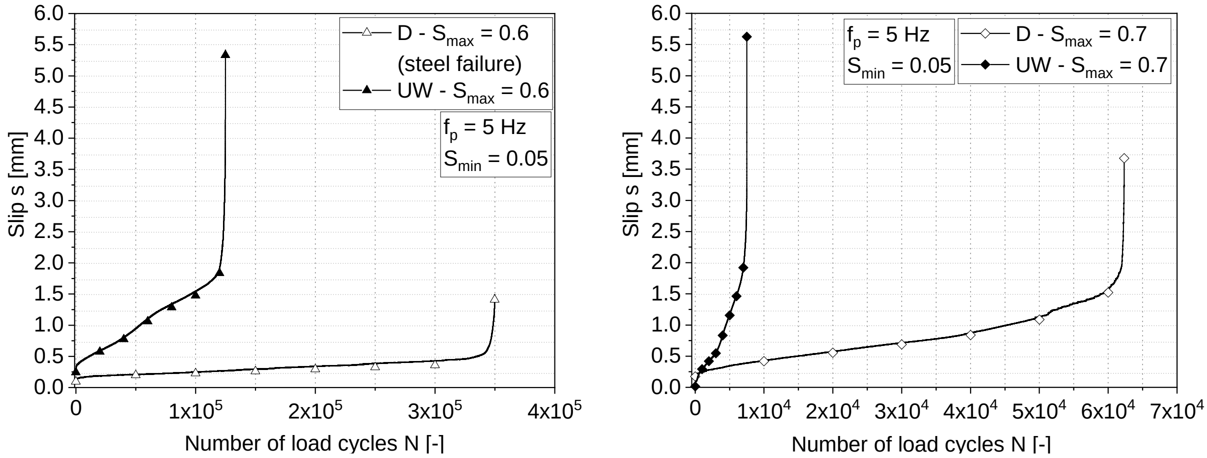

Fig. 4: Slip increase of load level S_{max} = 0.6 and 0.7

In Fig. 5, the slip increase of all performed cyclic pull out tests is plotted over the service life (N / N_{max}) by normalizing the applied load cycles N with the number of cycles to failure N_{max}. The slip curves are s-shaped and characterized by a significant increase at the beginning of the test (N / N_{max} < 0.1) and the end (N / N_{max} > 0.9). In the middle range between, there is an almost constant slip increase. If the increase in slip is equated with the course of damage, it can be concluded that damage processes occur particularly quickly in the start and end phases of the test. Consequently, a relatively stable condition with little damage progress is established in between. It is currently unclear why the absolute slip values are fundamentally greater with humid concrete.

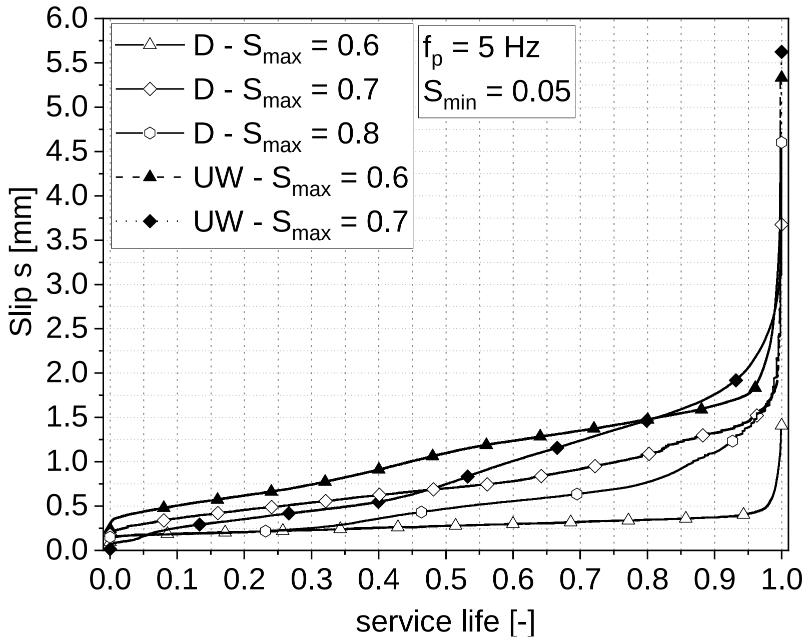

Fig. 5: Slip increase of cyclic pull out tests over service life

3.2 Fracture surface

In order to obtain further information about the damage process, the test specimens were sawed out after the end of the test. It becomes clear, that in case of pull-out failure the concrete brackets failed in shear for both test series. But the characteristics of the fracture surface were obviously different. A subjective roughened surface in the dry concrete specimens and a smoother surface in the humid specimens is recognizable in Fig. 6. This is also confirmed by images taken with a Keyence VHX 600 reflected-light microscope. Clear differences in the fracture surfaces can be observed at the 100x magnification. The investigated specimen of the test series UW show fine loose particles in the fracture zone and a rather abraded surface. The dry reference sample show a clearly roughened fracture surface and, in contrast to the test UW, no loose fine particles in the fracture surface. Therefore, an explicit determination of the surface roughness is planned to quantify these observations.

Furthermore, in the proposed research project it is planned to perform CT scans of the bond zone between the reinforcing bar and the concrete at different damage levels. The aim is to make the damage state visible.

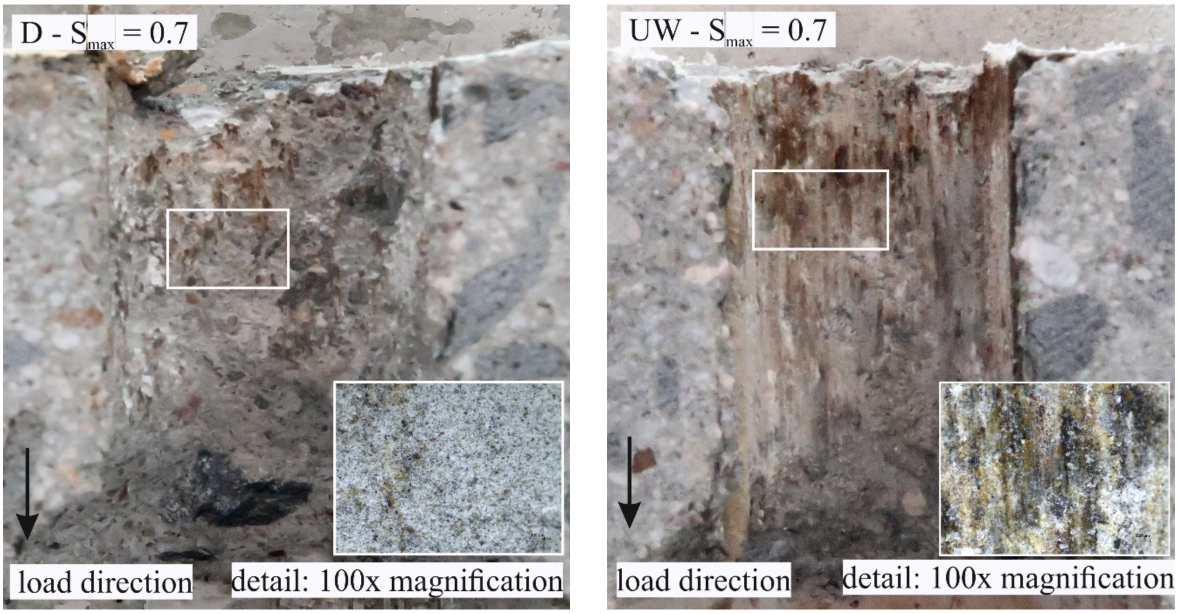

Fig. 6: Fracture imagines of load level S_{max} = 0.7 and detail 100 times magnification

4. CONCLUSION

Basically, the test results show a significant influence of the concrete humidity on the number of cycles to failure. In addition, the differences in the fracture surfaces and the damage rate per load cycle indicate deviating damage processes, which are to be investigated in more detail in a proposed research project using optical measurement technology, acoustic emission analyses and CT scans.

Comparable to the damage-related increase in e. g. the deformation of concrete in fatigue tests, the bond slip curves were s-shaped and characterized by a significant increase at the beginning of the test and the end. It becomes visible that tests of the UW test series are characterized by a larger slip in all phases until failure. Consequently, it can be assumed that the storage conditions of concrete have a significant influence on the bond damage progress during cyclic loading.

Overall, the identified effects of the bond fatigue behavior demonstrate a new phenomenon, which should be researched in future work. It is essential to consider both the fatigue damage of concrete and the influence of the other parameters relevant to bond, such as bond length or specimen form.

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