Fatigue behavior of HPC and FRC under cyclic tensile loading: Experiments and modeling

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Abstract
Systematic investigations of hardened cement paste, high-performance concrete and mortar with and without microfibers, subjected to static and cyclic tensile loadings, were conducted. The material degradation was investigated by means of microscopic analyses of the microcrack development. Notched specimens were subjected to a predefined number of load cycles. A nonsteady increase of microcracking with increasing load cycles was observed in high-strength concrete, whereas the addition of steel fibers lead to a steady increase of microcracks. High-strength mortar often showed premature failure, while addition of steel micro fibers allowed completion of the cyclic tests. To obtain a deeper insight into physical mechanisms governing fatigue and structural failure, high-performance concrete (HPC) and fiber-reinforced concrete (FRC) under static and cyclic tensile loadings have been modeled using cohesive interface finite elements, micromechanics, and a fiber-bundle model. Analysis of model predictions shows the significance of strength disorder and fiber properties on the structural behavior.

KEYWORDS
cyclic loading, discrete crack model, disorder, finite element method, steel micro fibers

1 | INTRODUCTION

The growing demand to create slender constructions makes the use of high-performance building materials indispensable. The consequence of such lightweight constructions is an increasing vulnerability to fatigue loads, caused by time variant loadings, which may ultimately lead to earlier fatigue failure. Fatigue can be defined as a process of mechanical weakening, which culminates in the complete failure of a construction.\(^1\) Examples include bridge girders, onshore, and offshore installations,\(^2\) which are affected by time variant loading such as traffic, wind, and waves simultaneously.\(^3\) The design of filigree and slender constructions implies an increased sensitivity to vibrations due to variable external loads.\(^4\) This, however, may cause higher fatigue loads under cyclic stresses which may further lead to damages or even failure of the concrete components before the maximum static strength is achieved.\(^5\)

Fatigue in concrete and concrete structures has been investigated already for a long time, and the general context is well known.\(^3\) Up to now in most of the investigations dealing with fatigue of plain concrete the maximal bearable number of cycles is determined for various stress–strength
ratios. In this type of investigations the fatigue state of plain concrete is described in terms of Wöhler curves. When subjected to compression, ambivalent conclusions concerning the effect of steel fibers are drawn. While in low cycle fatigue tests macro-fibers substantially increase the number of cycles to failure, the effect of fibers in the high cycle regime has been reported as negligible. In bending tests it has been demonstrated that fibers extend the crack resistance and the number of cycles to failure, a fact which correlates with the static behavior of fiber-reinforced concrete (FRC). In cyclic bending tests on high performance concrete (HPC) reinforced with microfibers showed, that a content of 1.6% shows the best performance.

In respect to the detailed mechanisms acting on the different scales of concrete, there are still many questions open. It is well established that in conventional concrete microcracks evolve in the mortar matrix during cyclic loading, which result in a continuous degradation process and eventual localized failure. However, in which way such microcracking takes place in high-strength concrete, and how fibers would influence this process, and the question, what the most important parameters are in this case is still unknown.

Due to inherent complexity of the process of fatigue degradation, it is rather beneficial to analyze it also from a theoretical point of view by introducing certain simplifying assumptions and subsequently verifying them against experimental data. Often, for highly cycle fatigue, cycle-based models, calibrated from experimental S-N-curves are applied. This type of models involves the use of empirical formulas that stem from the experimental data itself which leads to models that are not predictive in the sense of mechanism-based prognoses. On the other hand, in case of models on lower spatial scales (i.e., nano and microscales), the difficulty is transferred to obtain the required parameters that control the assumed behavior on the respective scales (c.f., Altus in the context of fatigue of polymers). The challenge is to model the fatigue behavior with a reasonably small number of additional parameters and to devise an adequate experimental program that allows a unique identification of these parameters. The majority of existing fatigue models for plain concrete, although sound on a theoretical basis, are based on a damage accumulation rule, which eventually leads to fatigue induced material degradation. This type of models, however, does not contribute to a better understanding of the mechanisms of growth and coalescence of microcracks acting on the microlevel.

In this work, an attempt is made to analyze the observed behavior of concrete under cyclic loading and to identify the main causes for this behavior on the microlevel. The identified cause has been fine microcracking of the matrix which leads to steady degradation of material integrity. A computational model, validated by experiments, is presented, which is able to replicate the evolution of microcracking before the peak load. Based upon a micromechanics approach, also the factors that govern failure of FRC under high cycle fatigue are shortly reviewed. It must be noted that micromechanics based models introduce cyclic degradation of the material using Paris Law type expressions in conjunction with fracture mechanics. However, fracture mechanics describes the evolution of an existing crack and does not explain the initiation of new cracks which is a predominant failure mechanism in high-cycle fatigue of concrete. Initiation of new microcracks in concrete under cyclic loading is strongly governed by material disorder. While a fracture mechanics based analysis can help in the design of fatigue tolerant high performance FRC, it does not provide insight into the role of disorder on the microscale level of heterogeneous materials such as concrete. Introducing disorder into a homogeneous material has important consequences on the stress that the material can withstand before loss of material integrity. One approach to account for the mechanics of disorder is to introduce a certain strength distribution into a homogeneous solid. Analytical approaches include the fiber-bundle model, while computational approaches include the random fuse network model, lattice models, or voxel models. In Section 4.3 of this paper the matrix-fiber-bundle approach is used for the sake of simplicity to capture the most relevant qualitative characteristics that govern failure of FRC under fatigue loads. Finally, we summarize the findings from the paper and provide conclusion in Section 5.

## 2 | EXPERIMENTAL INVESTIGATIONS

As part of the conducted investigations, the static tensile strength of cement-bound specimens was investigated in the first place. To this end, cyclic tests were carried out on the specimens, in which three different compositions were investigated that were characterized by the stepwise elimination of the aggregate. The basis was a high-strength concrete composition, from which a mortar composition and a cement paste composition were developed. As a further variation, steel microfibers that featured different lengths were mixed into two of the three compositions and examined in an additional test series. Before and after the cyclic tensile load was applied, the test specimens were examined on two sides in order to identify existing and newly formed micro cracks. Furthermore, the influence of steel micro fibers on the tensile behavior, the formation and the development of cracks was to be determined.
2.1 | Materials and composition

The composition of the investigated cementitious specimens is summarized in Table 1. For all compositions, a Portland cement CEM I 52.5 R was used. Fine quartz sand, mineral sand, and basalt with a maximum grain size of 8 mm were used as aggregates, while additionally a superplasticizer and a stabilizer were added. From the basic composition (HPC-08), where the two numbers 08 represent the maximum grain size of 8 mm, a high-strength mortar composition (HPC-02) was derived by eliminating all aggregates with a maximum grain size of above 2 mm. Consequently, the composition HPC-02 mix did not contain any basalt aggregate. The third composition is cement paste (HPC-00). The water–cement value (w/c value) of 0.35 was kept constant. To two compositions (HPC-02, HPC-08) short Bekaert steel fibers (denoted by SF suffix in specimen name) with a diameter of 0.160 mm and a length of 6 mm (Dramix OL 6/.16) were added (see Table 2). Due to experiences, that in fresh concrete mixes, fibers only in an amount of about 70 to 100 kg/m³ can be mixed reliably, fiber dosage of 1% by volume had been chosen. In addition, the influence of one long single micro fiber (denoted by LF suffix in specimen name) extending through the center of the entire length of the test specimen was also investigated (HPC-08-LF, HPC-02-LF).

2.2 | Test method

Figure 1 shows the experimental setup including the specimens (1), the two adhered test stamps (bottom/top) (2), the lower/upper clamping in the machine (3), and the strain gauge (4). In displacement-controlled experiments, the test specimens were loaded with a constant displacement rate of 0.1 mm/min until failure of the specimen occurred. In force-controlled fatigue tests, the test specimens were subjected to tensile stresses at half-sinusoidal and sinusoidal load functions (Figure 2) with an upper load level of 70% of the maximum static tensile strength $f_{ct,max}$ and a lower level of 10% $f_{ct,max}$. These levels were chosen in dependence on common cyclic investigations at normal concrete specimens. The cyclic loading was completed after 1, 10, 100, 1,000, 100,000, and 200,000 cycles. For cycles 1, 10, 100 the test frequency was 1 Hz with a half-sinusoidal load function, whereas for 1,000, 100,000, and 200,000 cycles the test frequency was 10 Hz with a sinusoidal load function. For the static and cyclic investigations, prismatic (40 mm × 40 mm × 160 mm) specimens with two notches (5 mm in width, 10 mm in depth) in the middle of the specimens were produced (Figure 3). The displacement in the static tensile tests were measured by a clip-on-gauge (Figure 1a), whereas in the cyclic tensile tests the displacements in the predetermined breaking points were recorded by means of strain gauge (Figure 1b).

3 | EXPERIMENTAL RESULTS

3.1 | Static tensile tests

The stress-displacement diagrams obtained from the static tensile tests are summarized in Figures 4 and 5. In each test

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**TABLE 1** Compositions by weight (unit: kg/m³)

| Materials       | HPC-08 | HPC-02 | HPC-00 | HPC-08-SF | HPC-02-SF | HPC-08-LFa | HPC-02-LFa |
|-----------------|--------|--------|--------|-----------|-----------|------------|------------|
| CEM I 52.5 R    | 500    | 646    | 1,460  | 500       | 646       | 500        | 646        |
| Quartz sand     | 75     | 120    | -      | 75        | 120       | 75         | 120        |
| Mineral sand 0/2| 850    | 1,333  | -      | 850       | 1,333     | 850        | 1,333      |
| Basalt 2/5      | 350    | -      | -      | 350       | -         | 350        | -          |
| Basalt 5/8      | 570    | -      | -      | 570       | -         | 570        | -          |
| Superplasticizer| 5.0    | 4.845  | -      | 15.0      | 9.69      | 5.0        | 4.845      |
| Stabilizer      | 2.85   | 2.762  | -      | 4.28      | 4.60      | 2.85       | 2.762      |
| Short micro fiber| V_f = 1.0%| -    | -      | 78.6      | 78.6      | -          | -          |
| Water           | 176    | 227.39 | 513.92 | 176       | 227.39    | 176        | 227.39     |

*One long single steel micro fiber added.

**TABLE 2** Properties of the fibers

| Material (−) | Description (−) | Brand (−) | Length (mm) | Diameter (mm) | Tensile strength (MPa) |
|--------------|-----------------|-----------|-------------|---------------|-----------------------|
| Steel        | Short micro fibers | Dramix OL 6/.16 | 6          | 0.160         | 2,600                |
| Steel        | Single long micro fiber | -         | 250 (cut from wire coil) | 0.155 | 2,345 |

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series 6 specimens were tested. The specimens of composition HPC-08 and HPC-02—with and without steel fibers—all failed at the notch. For HPC-02 two stress displacement characteristics were observed (Figure 4b). Specimens III, IV, and VII showed a much more rapid increase in stress at a relatively small crack opening, whereas the remaining specimens (II, V, VI, VIII, and IX) displayed a less stiff stress-crack opening relationship. The addition of a single continuous microfiber (HPC-08-LF) to the high strength concrete specimen (HPC-08) caused in nearly all specimens a sudden failure at the notch, induced by the sudden failure of the fiber. If the bond strength acting on the fiber exceeds its tensile strength, the fiber breaks before it is pulled out—a condition which can be described as supercritical fiber length.26

Also, for the high-strength mortar composition with the addition of a single long microfiber (HPC-02-LF), all specimens abruptly failed at the notch (Figure 4d). The addition of short steel fibers showed no significant increase in tensile strength, whereas the postcracking branch was considerably influenced as the steel fibers were activated and slowly pulled out of the matrix (c.f., Figure 5e), a behavior typical for a subcritical fiber content.27,28 The addition of steel fibers to the high-strength mortar composition leads to a similar behavior until failure of the specimen. The postfracture behavior, however, was similar to the composition HPC-08-SF. The stress-displacement diagram shows, that after reaching the maximum stress, two groups of curves could be distinguished (c.f., Figures 4f and 5g).

The investigations on hardened cement paste (HPC-00) showed a large scatter in the stress-displacement diagrams (Figure 5h); also the fracture behavior varied significantly. Some specimens failed at the notch. In some specimens, cracking started at the notch, but continued at different
regions above or below. Until shortly before peak load, in agreement with the literature, a nearly linear load-displacement diagram is recorded. The nonlinear portion before the peak stress recorded in some diagrams is attributed to the accumulation of micro cracks in the fracture zone as the strains in the notched region increase, which form a macrocrack leading to failure of the specimen. This observation is confirmed by the numerical simulations in Section 4. In addition, particle interlocking could lead to a further absorption of the tensile forces, contributing to the nonlinear prepeak behavior. According to König et al., particle interlocking is lower for high-strength concrete than for normal-strength concrete, as the interfacial transition zone is improved.

For the short fiber compositions (HPC-08-SF, HPC-02-SF), it is observed that after the initiation of micro-cracks, the fibers were activated, causing a slow extraction from the matrix upon further loading (subcritical fiber length) in the postpeak regime, indicating a ductile failure behavior.
3.2 | Cyclic tensile tests

The cyclic tensile tests were complemented by means of a microscopic crack analysis before and after the cyclic loading of each specimen. To this end, up to 200,000 load cycles were applied. The cyclic loading was completed after 1, 10, 100, 1,000, 100,000, and 200,000 cycles. After 1, 10, 100, and 1,000 cycles, each of the six test specimens was tested, after 100,000 cycles three specimens were tested and after 200,000 load cycles one specimen was investigated, which lead to 27 to 28 test specimen per composition. The applied upper, middle and lower load levels were adjusted to the respective tensile strengths (c.f., Table 3). With the exception of two specimens, all specimens reached 1,000 load cycles without premature failure. All specimens of compositions HPC-02 and HPC-00 failed before 100,000 cycles. Specimens from composition HPC-00 did not fail at the notch. All other specimens reached the specified number of load cycles.

Figure 6 shows force-displacement curves obtained from the HPC-02 specimen after the first cycle and immediately prior to failure (after 17,627 cycles), exhibiting hysteresis. The other specimens of series HPC-02 failed before passing the 100,000 load cycles, while the test specimens of the HPC-02-SF series all reached the designated 100,000 load cycles. Evidently, the microfibers arrested the propagation of the micro cracks and avoided crack localization.33

The series of HPC-08 specimens all passed the designated number of load cycles. In the case of the short fiber compositions HPC-08-SF, premature failure occurred in two cases only. The observations made during the experimental investigations suggest that the bond between the matrix and the fiber failed, such that the steel fibers could no longer absorb the tensile stresses after failure of the concrete matrix.34,35 Moreover, a nonhomogeneous fiber distribution might also contribute to the brittle failure.36 In the HPC-08 series all tested specimens reached the designated number of load cycles, whereas the test specimens of the HPC-02 series all failed prematurely. This might result from the crushed aggregate in the composition, which, as compared to round aggregates, improves the bond strength between matrix and aggregate.32

3.3 | Microscopic investigation

The microscopic analysis was conducted before and after the cyclic loading of the specimens. For this purpose, the notched region was investigated. For each number of load cycles and each composition, the average number of cracks was determined visually under a microscope. This was performed for the high-performance concrete and high-performance mortar, both with and without short micro fibers where the high-performance concrete is named HPC-08 and the high-performances mortar is named HPC-02, additionally marked with -SF when fibers are included in the mixture. For high-strength concrete with and without micro steel fibers, the increase in cracks after the defined number of load cycles is depicted in Figure 7. The diagram indicates that the addition of steel micro fibers leads to a slight increase of cracks at less than 100,000 load cycles. After 100,000 cycles, the number of cracks increased significantly. High-strength concrete without the addition of steel micro fibers showed a nonsteady crack increase below 1,000 load cycles. After this point, however, the number of cracks increased considerably. The results for the high-strength mortar are shown in Figure 8. The specimens failed before the designated 100,000 load cycles were completed. The addition of steel micro fibers leads to a higher number of new cracks below 1,000 cycles. These cracks did not lead to failure before 100,000 cycles. The high-strength mortar (HPC-02) showed a continuous crack increase between 1,000 to 100,000 load cycles until the specimen failed.

![Figure 6](image-url)
4.1 Numerical simulations of static tensile tests

The direct tensile tests on the notched specimens were simulated using the finite element method. Cracking is modeled by means of zero-thickness interface elements equipped with a linear cohesive traction–separation relation inserted between linear elastic bulk elements. The interfaces break when the tensile strength ($f_t$) is reached, and they experience gradual softening until all fracture energy ($G_f = 0.075 \text{ Nmm/mm}$) is released\(^{37,38}\) (see Figure 10).

The model is implemented in the general purpose finite element program KRATOS.\(^{39}\) The global equilibrium equations are solved implicitly by means of Newton–Raphson iterative procedure with interface element tangent contributions obtained by a consistent linearization of element tractions.

Figure 10 shows the finite element discretization with mesh size in the notched area of the specimen of 0.25 mm. This allows to explicitly resolve the microcracks. The bottom and top surfaces are fixed to simulate the glued conditions in the experiment.

The tensile strengths prescribed in the integration points are assumed to follow two stochastic distributions—Normal and Weibull. Normal distribution parameters are taken as mean strength 5.77 MPa and standard deviation 0.9 MPa. The Weibull distribution parameters are taken as: scale parameter 5.77 MPa and shape parameter 6.6, which results in a mean value of the sample of 5.38 MPa and the standard deviation of 0.95 MPa (c.f., the histograms of the sampled strengths illustrated in the Figure 11).

The load-displacement curves obtained from the displacement controlled numerical simulations using the two distributions are depicted in Figure 12. The range of experimental results for HPC-02 is also included as gray areas. The peak loads for both test cases are within the experimental range. More important, however, is the qualitative difference in the microcrack pattern obtained for the two distributions. In both cases, first microcracks initiate at the corners of the notch at the nominal stress of around 30% of the peak load due to stress concentrations at the corners (Figure 13 (upper left) and Figure 14 (upper left)). Microcracking proceeds gradually as the load is increased. The maximum number of microcracks is reached at the peak load (Figures 13 and 14 [upper right and bottom left]). After the peak load, distributed damage localizes into a single crack that spans the whole cross section leading to failure (Figures 13 and 14 [bottom right]). Since the simulations are

**FIGURE 7** Crack increase in specimens HPC-08 and HPC-08-SF during cyclic loading

**FIGURE 8** Crack increase in specimens HPC-02 and HPC-02-SF during cyclic loading test

Figure 9 shows an example of the HPC-08 series with a freshly formed crack at the end of the first load cycle.
conducted under monotonic loading, no comparison with crack numbers in cyclic tests was performed.

This observation is important as a basis for the further development of the finite element model, where each of the open microcracks undergoes the mechanisms of frictional sliding, degradation of the aggregate-matrix bond and possible arrest in case of bridging fibers.

4.2 Strengthening due to fibers—a micromechanics view

Assuming that the failure mechanism is predominantly Mode-I, fibers arrest microcrack growth by reducing the stress-intensity factor $K_I$ at the microcrack tip. By bridging the stresses, across a microcrack, the stress-intensity factor at the microcrack tip is reduced. For a penny-shaped microcrack of size $a$, the stress-intensity factor is given by the expression:

$$K_I = \frac{2}{\sqrt{\pi a}} \int \frac{\Sigma - \Sigma_f}{\sqrt{a^2 - x^2}} dx$$  \hspace{1cm} (1)

Here, the applied stress is $\Sigma$ and the fiber bridging stress is given by $\Sigma_f$. Using a multiscale micromechanics approach\textsuperscript{40,41} as illustrated in Figure 15, the fiber bridging stress is obtained as a function of the material and geometrical properties of the concrete, fibers and the interface bond strength $t_{\text{max}}$.

While failure under monotonic loading occurs when $K_I \geq K_{Ic}$, where $K_{Ic}$ is the toughness of concrete, subcritical failure under cyclic-loading is generally described by a phenomenological rate equation for the crack growth per cycle\textsuperscript{42}.
as proportional to the amplitude of the stress-intensity factor $\Delta K_I$ and to $K_{I - \text{max}}$:

$$\frac{da}{dN} \propto (\Delta K_I)^p (K_{I - \text{max}})^n.$$  \hspace{1cm} (2)

In contrast to fatigue failure in metals, for brittle and quasi-brittle materials like concrete, the exponent $n > p$, that is, fatigue is more sensitive to peak load than to the amplitude of loading.\textsuperscript{42} Nevertheless, the rate of cracking is reduced if there is a reduction in the crack-tip stress intensity. In order to analyze the influence of various material properties on the overall damage of the FRC, we investigate the properties governing the growth of a representative microcrack bridged by fibers.
Micromechanics model predictions for the reduction of the stress-intensity factor in a single microcrack by introducing fibers of various length $L$ and increasing bond strength for various crack sizes are shown in Figure 16. Having characterized the mechanics of the growth of a single representative microcrack, the macroscopic evolution of damage can be obtained in a straightforward manner using the framework of continuum micromechanics (see Refs. 40, 41 for further details). The increase in the fiber content and the bond strength is expected to improve service life of the FRC. It is also seen that increasing the length of the fibers from 25 to 30 mm would not significantly increase the service life. However, for the same relative increase in fiber length, from 10 to 15 mm would significantly decrease the peak stress-intensity factor and subsequently increase the service life of the material.

4.3 | Modeling failure due to fatigue loads using fiber-bundle approach

While a fracture mechanics based analysis as shown in Figure 16 can help in the design of fatigue tolerant high performance FRC, it does not provide insight into the role of disorder on the microscale level of heterogeneous materials such as concrete. The matrix-fiber-bundle model idealizes the concrete matrix with a disordered strength distribution. The individual fibers have a linear elastic behavior until they completely break at a stress larger than the strength of an individual matrix-fiber. The breaking of matrix-fibers is assumed to be irreversible and instantaneous. After failure the load carried by the failed fiber is redistributed to the rest of the fibers (see Figure 17). The strength of the individual fibers is assumed to be an uncorrelated random variable whose cumulative strength distribution is assumed to be of the form $F(\sigma) = \sigma^\beta$. This distribution is a generic
distribution with a scale-invariant power-law tail at the origin. \( \beta \) is a parameter that characterizes the strength disorder. If \( \beta = 1 \), the strength distribution is uniform characterizing maximum disorder while \( \beta \to \infty \) characterizes a homogeneous strength in the material. The applied stress \( \sigma_a \) is normalized with respect to the maximum stress \( \sigma_{\text{max}} \) in the bundle. Denoting the fraction of matrix-fibers (whose strengths are smaller than the applied stress) that fail due to a certain level stress \( \sigma \) as \( \phi_{n+1} = F(\sigma_n) \), this evolution of damage of the matrix-fiber bundle can be recursively written as:

\[
\phi_{n+1} = \left( \frac{\sigma}{1 - \phi_n} \right)^\beta
\]

(3)

The above expression is a recursive equation for the state of damage that can be solved numerically. It can be seen that the overall (structural) strength is not just an average of the individual (material) strengths (see Gudzulic et al.\(^{25}\) for a discussion on the influence of the redistribution mechanics). For small values of \( \sigma \), damage evolves up to a certain level and thereafter remains constant. However, beyond a certain critical value of the applied stress, damage increases monotonically and the material fails. Thus, there exists a critical value for the stress level below which the material does not fail. This critical stress is the overall structural strength of the material. It depends on the strength distribution (i.e., \( \beta \)).

We assume that under cyclic loading the disorder in the material increases, that is, \( \beta \) decreases. This represents microscopic weakening in the material during repeated loading. The rate of increase of disorder (or reduction in \( \beta \)) is assumed to be proportional to the current state of disorder, that is, \( \frac{d\beta}{dN} \propto -\beta \). Solving this differential equation, we obtain an exponential decay of order (in strengths) in concrete due to cyclic loading as: \( \beta = \beta_0 e^{-aN} \). Here \( a \) is the rate of material restructuring, that is, increase of strength disorder and \( \beta_0 \) is the initial strength exponent. The number of cycles is parametrized in terms of the recursion levels as \( N = Cn \).

Assuming \( C = 1 \), the parameter \( a \) is calibrated from experimental data to give \( 2.5 \times 10^{-6} \) /cycle for HPC-08 and \( 8 \times 10^{-7} \) /cycle for HPC-08-SF. \( \beta_0 = 4.5 \) for HPC-08 and \( \beta_0 = 5 \) for HPC-08-SF. These values for \( a \) and \( \beta_0 \) are consistent with the material composition as addition of steel fibers reduces the apparent strength disorder and the restructuring rate in concrete. It must be noted that this choice of parameters is dependent on the type of the chosen distribution. Nevertheless, it would not change the qualitative predictions of the model.

Figure 18 (left) shows the predicted damage as a function of loading cycles for the compositions HPC-08 and HPC-08-SF (upper load level 70% of tensile strength) with (gray curve) and without steel fibers (black curve). The agreement

**FIGURE 16** Micromechanics predictions for the effect of fibers on the crack-tip stress-intensity factor with increasing crack-size. Left: influence of fiber-length \( L \), Right: fiber-matrix interface bond strength \( \tau_{\text{max}} \) (Fiber Vol. %: blue—0 %, orange—1% and green 1.5%).

**FIGURE 17** Illustration of the breaking of a matrix-fiber and load re-distribution in a matrix-fiber-bundle.
of the computed curve and the measurements during the complete load history is excellent. Figure 18 (right) shows new predictions for upper load levels of 60 and 80% of the tensile strength. It is noted, that the damage due to an increase of the upper load level from 60 to 70% is considerably smaller than due to an increase from 70 to 80%.

5 | CONCLUSIONS

In order to investigate the degradation of different high-performance compositions, static and cyclic tests were carried out. Furthermore, a microscopic analysis of the tested specimens was conducted. Regarding the specific stress level and stress amplitude, the described test procedure lead to the following conclusions:

1. High-strength concrete (HPC-08) caused higher tensile strengths than the high-strength mortar composition (HPC-02), both with and without addition of fibers. The test specimens without fibers showed a brittle failure behavior. Adding a single long fiber (HPC-08-LF, HPC-02-LF) had no influence on the postcracking behavior. Short fibers led to a ductile postpeak behavior.

2. High-performance concrete always reached the designated number of load cycles, whereas the high-performance mortar failed prematurely after a certain number of load cycles. The addition of steel micro fibers enabled the specimens to reach the designated number of load cycles.

3. The microscopic crack analysis showed an increased formation of new micro cracks during cyclic loading. An extension or widening of pre-existing cracks was rarely observed.

4. The cracks in the high-performance concrete (HPC-08) already formed after a small number of load cycles and increased only slightly during cyclic loading.

5. The addition of steel fibers to the high-performance concrete revealed that, with an increasing number of load cycles, there was no significant increase in microcracks. However, the high-strength mortar composition that included fibers showed an increasing number of microcracks.

6. Clear conclusions regarding the hardened cement paste (HPC-00) are difficult to draw, as the results varied strongly and no clear failure pattern could be observed. The observed results require further investigations.

7. The cohesive interface finite elements model with a stochastic distribution of strength is able to predict the transition from diffuse microcracking to localized failure. This mechanism is governed by the nonhomogeneous spatial strength distribution that characterizes the material disorder observed in concrete.

8. Analysis of a micromechanics model for FRC has provided insights into the mechanism of toughening that can help in the design of fatigue tolerant high-performance concretes.

9. The role of disorder and its evolution during cyclic loading was investigated by means of a matrix-fiber-bundle model. The model was calibrated to the experimental data for high performance concrete with and without short steel fibers. An excellent qualitative and quantitative agreement was observed during the complete loading history up to 200,000 cycles. Predictions for additional upper load levels showed a nonlinear dependency of the damage level and damage evolution with respect to the upper load level.

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