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Experimental investigation of bond behaviour under repeated loading

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Abstract
The deterioration of bond between reinforcing steel bars and the surrounding concrete will be investigated under conditions of cyclic loading. An experimental campaign is planned in which a reinforced concrete tension chord will be subjected to axial cyclic tensile loading. The use of distributed optical fibre sensors applied directly to the surface of embedded reinforcing steel bars, will enable a continuous measurement of strains along the bar length with minimal disturbance of the bond properties. The variation of steel strains thus captured can serve as an indicator for the degradation of bond throughout the fatigue life of a structural member. The present paper provides a review of recent work on fatigue of reinforced concrete with particular focus on bond behaviour as well as an overview of the proposed experimental campaign.

1 Introduction
The aging of existing concrete bridges in combination with the increasing frequencies and maximum axle weights of traffic requires a more sound understanding of the damage mechanisms related to the fatigue of structural concrete. Often, the numerical examination of existing bridges indicates insufficient fatigue safety although the structure shows no visible damage. Furthermore, there are no reported cases of damage in Switzerland which can clearly be attributed to cyclic loading [1]. Consequently, many engineers suspect that the current code requirements underestimate the fatigue safety of concrete structures, thus promoting unnecessary retrofitting measures.

According to the Swiss and European guidelines, the verification of fatigue safety is to be performed independently for the reinforcing steel and the concrete. This approach is justified due to the vastly different fatigue behaviour of the constituent materials. Whereas the stress range is decisive for the reinforcement, the maximum and minimum stress levels are of interest for the concrete. The expected stresses in the materials are subsequently compared to the fatigue strength, which is typically defined by experimentally determined S-N curves. In this way, the maximum number of load cycles can be determined for a given stress or stress range. These S-N or Wöhler curves can be viewed as limit states; they provide no information on the actual state of damage in the material. Thus, the estimation of remaining service life of reinforced concrete structures remains a challenge, relying on strongly simplified damage accumulation calculations.

A verification of fatigue bond safety is currently not required in design practice, despite the fact that bond is essential for both the load-carrying capacity and the deformation behaviour of reinforced concrete members. Several experimental investigations underpin this, characterising failure either as rupture of the reinforcement or failure of the concrete in compression. However, a degradation of bond properties during the service life of specimens is often reported [1], [2], [3]. This deterioration manifests itself as an increase in deformations and crack widths. Hence, also the serviceability and durability of structures may suffer under the influence of repeated loads.

1.1 Fatigue of concrete members in bending
Fatigue of a structural concrete member subjected to bending moments is a complex and progressive process which takes place within the flexural compression zone and the flexural tension chord. The progression of this process is characterised by the fatigue behaviour of the concrete in compression and tension, the fatigue strength of the reinforcement as well as the deterioration of the bond properties. An increase in irreversible deformations as well as a reduction in stiffness of the concrete within the compression zone is typically observed. The concrete exhibits a large capacity to redistribute stresses within the compression zone. The contribution of the concrete between the cracks within the flexural tensile
chord, however, decreases and leads to a progressive reduction in stiffness. Tests on deck slab specimens [2] indicate a significant increase in deflections and strains within the initial thousand cycles. This initial phase is typically followed by a period of approximately constant increasing deflections and strains. The cyclic loading led to crack formation, an increase in the width of existing cracks and a continuous increase in deflection.

Fehlmann [1] conducted a large-scale experiment on a monolithic frame bridge. His observations confirmed the validity of fatigue as a hazard scenario for structural design since the fatigue damage remained mainly undetected until shortly before failure. The observed increase in deflection was attributed to crack growth, deterioration of bond as well as creep of concrete. Based on his own and other experimental investigations, Fehlmann developed a physical-mechanical model to describe the fatigue behaviour of structural concrete beams in bending which allows an estimation of the fatigue life. The bond deterioration was considered by introducing a factor for the tension stiffening effect. This factor is assumed to decrease logarithmically with increasing load cycles until the tension stiffening effect is neglected completely after one million cycles. This assumption remains to be verified by experimental tests. Spathelf [4] extended the model proposed by Fehlmann to consider combinations of bending and torsional moments in slabs using the same assumption for bond deterioration.

In addition to fatigue failure, Zanuy [3] warns that repeated loading may affect the serviceability of concrete structures. In his experiment, considering a reduced cross-section of a railway box-girder viaduct, a significant cycle-dependent reduction of tension stiffening effect was observed. Reinforcing steel strains were measured using Linear Variable Differential Transformers (LVDT) applied on the concrete surface at the level of the reinforcement. He noted that the steel strains tended towards the value expected in the fully cracked stage with the increase in the number of cycles.

1.2 Fatigue of steel-concrete bond

Bond properties are essential for the response of structural concrete. Both crack widths and crack spacings depend on the ability of the reinforcing steel bars to transfer forces to the surrounding intact concrete between the cracks via bond stress. Thus, the concrete also contributes to the load carrying behaviour and the steel strains are reduced. The activation of the concrete in tension increases the stiffness of the structure and significantly influences its deformation behaviour.

There are currently a considerable number of models to describe the bond stress-slip (τ-δ) relationship. A relatively simple but established one is the stepped rigid perfectly plastic bond stress-slip relationship of Sigrist [5] for monotonic loads (Fig. 1, left). Koppitz [6] amended this model to consider the previously mentioned changes in bond properties during unloading and reloading. He proposed a reduction of bond strength to 50 % of the initial value when subjected to cycles of unloading and reloading (Fig 1, right). This assumption was verified by the comparison to existing experimental data. However, it is suspected that a significant increase in load cycles may lead to an even greater irreversible reduction of bond.

Experimental investigations of bond under fatigue are mainly performed on pull-out tests similar to the ones under monotonic load. The rebar is cast with a defined, typically short bond length into a concrete prism and subjected to constant amplitude loading. The bond slip on the free end is measured. The aim of such tests is to derive a bond stress or slip versus number of cycles diagram comparable to the S-N curves for steel and concrete. Rehm and Eligehausen [7] performed extensive pull-out tests with varying bond lengths, bar diameters and concrete strengths at different maximum and minimum load levels.
Their tests indicate that the maximum number of load cycles to bond failure decreases with an increase in maximum load level for a constant minimum load. The resulting S-N diagram shown in Fig. 2 can be simplified to a straight line. Balázs [8] noted that the slip versus number of cycles diagram is S-shaped, which is analogous to the development of concrete strain under fatigue. The slip in the transition to the last segment corresponds roughly to the slip at the ultimate bond strength (τ_{bu}) in a monotonic pull-out test. He defined this slip as a failure criterion under repeated loading. Lindorf [9] observed that conditions of transverse tension accentuated this reduction in bond strength.

Fig. 2  S-N Diagram for bond. Adapted from [7].

Bresler and Bertero [10] examined the stress transfer between steel and concrete, the crack widths and the stiffness on four concrete cylinders with concentrically cast rebars. The bars were cut longitudinally and a groove was milled into one-half which was instrumented with strain gauges. The two halves were subsequently welded together. The experiment revealed that the tension stiffening effect is reduced with an increase in load cycles and load amplitude. The number of load cycles in the tests, however, were limited to only 65 repetitions.

2  Overview of the investigation

The present research project aims at contributing to a deeper understanding of the complex processes of the fatigue of reinforced concrete through an investigation of the mechanisms that take place in the tension chord. Fibre Optical (FO) sensing will be used to investigate the degradation of bond and the related decrease in tension stiffening throughout the fatigue life. The previously mentioned assumptions and observations can thus be verified.

In a first step, preliminary experiments are planned to assess the performance of fibre optical sensing under cyclic loading. At the time of writing this paper, the majority of the specimens have already been tested. The results, however, have not been analysed yet. The findings from this initial investigation will be used to optimise the test setup and measurement methods of the main experimental campaign. The results will be used to validate a model developed by the first author to describe bond deterioration under repeated loading.

Improved knowledge of the process of fatigue and the resulting changes in the stiffness properties of a structure will supplement the current design standards and contribute to an estimation of the actual degree of damage in existing structures.

3  Preliminary tests

3.1  Test programme

Before embedding the fibre in a reinforced concrete specimen, preliminary experiments were conducted to assess its performance in a fatigue test. The fibres were attached on opposing sides of the rebars.
Three different configurations of applying the fibres to a reinforcement bar were investigated. In series one, a groove of 1.0 x 1.0 mm was cut along the length of the bar and the fibres were glued inside with epoxy. In the second series, the same procedure was used, but with a more viscous two-component adhesive. The third series was prepared without grooves and the fibres were glued directly to cleaned surfaces along the longitudinal ribs to keep the fibres steady. The same adhesive as in series two was used. In order to compare the results, the elongation of the bars was measured with an LVDT mounted at mid-height of the bar with a base length of 300 mm.

Three bars were tested in each series in a uniaxial tensile test by increasing the force continuously until failure. Another four bars were tested under cyclic loading with constant stress ranges of $\Delta\sigma = 300 \text{ N/mm}^2$ and 200 N/mm$^2$ until fatigue failure. The bars had a length of 1.20 m, a free length between the grips of 968 mm and a nominal diameter of 14 mm. All bars classified as type B500B according to the Swiss Standard SIA 262:2013 were taken from the same production heat. A set of five bars was tested in a standard tensile test to determine their mechanical properties.

In order to prevent premature failure due to the transverse pressure of the clamps, the ends of each cyclically tested bar were sandblasted and glued with epoxy into metal sleeves. This ensured a uniform transfer of the applied forces. The alignment of the testing machine was controlled prior to each test. Nevertheless, some tests indicated secondary stresses due to lack of straightness in the bars. The fibre optic sensing clearly captured this effect.

### 3.2 Testing procedure

All of the preliminary tests were performed in a Schenck servo-hydraulic testing machine under force control. The test procedure is shown schematically in Fig. 3. The loading history included both monotonic and dynamic sequences. Initially, 10 cycles of monotonic loading and unloading were applied with a rate of 1.3 kN/s. The steel strains were measured with optical fibres at a sampling frequency of 1/3 Hz and with an LVDT at a sampling frequency of 5.0 Hz. Subsequently, the FO recording was discontinued and the LVDT was removed. A dynamic sequence was started with sinusoidal load cycles in the same force range at a frequency of 6.0 Hz. Herein, only the applied force and the testing machine stroke were recorded. After reaching a specified number of cycles, the dynamic loading was stopped and the LVDT was remounted at the marked position. The strains were recorded from the minimum to the maximum load level. This was followed by a new sequence of dynamic loading. The loading sequences were repeated alternately until fatigue failure of the bar.

![Fig. 3 Loading history for the preliminary tests.](image)

### 4 Main investigation

#### 4.1 Test description and setup

The deterioration of bond between reinforcing steel bars and the surrounding concrete under cyclic loading will be investigated in a series of large-scale tests on reinforced concrete wall specimens. Specimens will be subjected to axial tensile cyclic loading. The governing parameters for fatigue and bond behaviour such as stress amplitude, concrete strength, the geometry of the reinforcing steel bar ribs and the influence of transverse reinforcement will be investigated. Furthermore, one specimen will be tested under monotonically increasing loading to illustrate the response under quasi-static loading.
The setup was designed to ensure that the specimen is subjected exclusively to tensile loads. The actuator will be mounted with pinned connections at the top of the specimen. In this way, the reinforcing steel stresses at the concrete cracks can be determined directly from the equilibrium conditions. The test setup was adapted from the experimental campaign presented in [11]. In order to prevent fatigue fracture of the main reinforcement outside the specimen or within the transition zone, it is connected to larger diameter bars using fatigue-resistant threaded couplers. The threaded connector bars will be attached to a rigid steel plate, which will ensure a uniform distribution of the applied force over the reinforcing bars. Furthermore, the transition zone will be reinforced with four stirrups.

![Diagram of test setup](image)

**Fig. 4** Front view of test setup (left); views of a typical test specimen (right). Dimensions in cm.

### 4.2 Method of measurement – distributed fibre optic strain measurement

The variation of steel strain over the length of the reinforcement and throughout the fatigue life serves as an indicator of bond degradation and loss of the tension stiffening effect of concrete between the cracks. Until recently, it has been nearly impossible to measure the reinforcement strains at the concrete-steel interface without disturbing the bond properties. Such measurements could typically only be obtained at distinct points, e.g. by means of strain gauges. The crack location had to be predicted or induced by artificially reducing the concrete cross-section in order to define a suitable location for the strain gauge. These major drawbacks in previous measurement techniques are overcome with the use of the fibre optic sensing method. In this method, light fibres with a negligible diameter of 250 micrometres can be applied along the length of a reinforcement bar. A continuous strain measurement is possible over the entire length at a spacing of 5 mm.

In addition to FO sensing, established measurement techniques such as strain gauges and LVDTs will be used. The authors are not aware of other investigations into the fatigue behaviour of structural concrete members that have made use of FO sensing. The simultaneous recording of steel strains with different techniques will be used to confirm the measurements obtained from FO sensing. A further reason for the redundancy in steel strain measurements is to correct the results for the expected heat development in the specimen under cyclic load [12]. The scattering of light within the fibre is caused...
by elongation of the fibre or changes in temperature. Therefore, the relative contribution of each effect will have to be recorded. Further details on FO sensing are provided in [13].

5 Conclusion and outlook

The current knowledge about fatigue in structural concrete is still not satisfactory. The properties of the two components, namely the reinforcement and the concrete, are typically researched separately with emphasis on the ultimate fatigue strength only. The fatigue phenomenon, however, is characterised by a progressive damage accumulation which evolves over the lifetime of a structure. Increasing crack widths and deflections adversely affect the serviceability of structures. The findings of this project will contribute to a better understanding of the fatigue process at the interface between concrete and steel. The aims are to (i) clarify to what extent the tension stiffening effect is reduced under cyclic loading, (ii) investigate how this affects the deformation behaviour of reinforced concrete throughout its fatigue life, and (iii) develop a model to predict the loading and unloading response of a tension chord subjected to repeated loading. Subsequently, the relationship will be used to extend existing physical-mechanical models for the prediction of fatigue failure for beams [1] and orthogonally reinforced slabs [4].

Following the evaluation of the preliminary experiments, the parameters of the experimental campaign will be reviewed. The fibre optic sensing will generate a large volume of data during fatigue testing. Effective ways of post-processing the data will have to be developed.

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