Fatigue Performance of Orthogonally Reinforced Concrete Slabs

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Fatigue performance of orthogonally reinforced concrete slabs

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Abstract

The majority of concrete bridges in Switzerland was constructed prior to the introduction of explicit guidelines concerning fatigue of reinforced concrete to the Swiss design standard. Furthermore, the remaining service life of a number of concrete structures on the Swiss highway network may be jeopardised by the increasing frequency and axle load of heavy vehicles, thus reaching the end of their fatigue design lives in the next 10 to 20 years. The fatigue performance of reinforcing steel bars embedded in concrete is currently under investigation in preliminary tests. The aim is to develop a physical-mechanical model for prediction of the structural response and fatigue performance of orthogonally reinforced concrete slabs under arbitrary combinations of the components of bending. Finally, the numerical results will be verified with a series of fatigue tests on slab specimens.

1 Introduction

Around 75% of the concrete bridges in Europe were constructed before 1988 [7]. In Switzerland, the majority of bridges was constructed prior to 1976 [4]. It is therefore surprising to note that the first explicit structural design guidelines for the fatigue of reinforced concrete were only introduced in the Swiss standard in 1989 [13]. Hence, a number of concrete bridges, underpasses and culverts on the Swiss highway network may reach the end of their fatigue design lives within the next 10 to 20 years and fatigue induced damage could be expected [4]. In addition, traffic measurements in Switzerland have indicated a yearly increase in the total number of vehicle-kilometres over the last 10 years, with a significant increase in heavy traffic [2].

The current Swiss standard often predicts an insufficient fatigue safety in the evaluation of existing structures. However, no observable damage, which is attributed exclusively to fatigue processes, has been identified for concrete bridges in Switzerland so far. It has been inferred that this could be attributed to most concrete structures having been in service for less than 40 years, whereas damage due to fatigue processes only becomes visible near the end of the service life [13]. Alternatively, a number of concrete structures may already be damaged due to fatigue processes. Such damage may simply not be visible or may have been attributed to other actions, such as overloading or corrosion of the reinforcement.

Reinforced concrete elements subjected to cyclic loading are known to exhibit different failure modes than those predicted under static loading [3]. This fact necessitates the explicit design for fatigue action, in addition to the ultimate and serviceability limit states. Furthermore, the development of high tensile strength reinforcing steel was not accompanied by a corresponding improvement on the fatigue strength of the steel [11]. Hence, the applicability of this material is limited by the fatigue strength where large stress ranges are expected. In the case of highway traffic bridges, the deck slabs are known to be susceptible to fatigue damage [1]. This has been attributed to a direct contact with the wheel loads, large slenderness ratios, light reinforcement content and small ratio of dead load to live loads [12; 14]. Our current knowledge of fatigue in reinforced concrete is limited and does not allow the current state of damage within an existing structure to be determined, nor to predict the remaining service life [4].

2 Overview of the investigation

The fatigue performance of reinforcing steel bars embedded in concrete are currently under investigation in a series of preliminary tests (Section 3). The primary objective, however, is to investigate the structural response and fatigue performance of orthogonally reinforced concrete slabs under cyclic loading. The development of a numerical model, to predict this response for a general state of flexure,
is described in Section 4.1. Finally, the results will be verified with experimental results from a series of fatigue tests on slab specimens (Section 4.2).

3 Preliminary tests

3.1 Background

The fatigue strength of reinforcing steel is a vital parameter on the resistance side of reinforced concrete members subjected to cyclic loading. The majority of investigations on the fatigue strength of reinforcing steel have been performed with constant-amplitude cyclic tests of bars in air [5; 6; 10]. Steel bars tested in air experience a stress range ($\Delta \sigma$) which is constant along the bar length and any surface imperfections will be potential crack initiation sites. Hence, the critical surface imperfection governs the fatigue strength of the bar. In contrast, cyclically loaded steel bars embedded in concrete experience a stress range which varies along the bar length due to the tensile strength of the concrete and resulting bond stresses. Concrete cracks form where the tensile strength is exceeded and the steel stress increases as the bar is required to resist the full load. The concrete between cracks, however, remains intact and the steel stress is reduced through tensile stiffening. The probability of the critical surface imperfection coinciding with the maximum stress range at the concrete cracks is small and a higher steel fatigue strength could be expected. This effect has previously been observed in experimental tests [9].

3.2 Test specimen

The test specimen consists of a concrete cylinder, concentrically reinforced with a single steel bar of diameter 16 mm (Fig. 1 (a)). In order to reduce the likelihood of a fatigue fracture occurring in the region of the testing machine clamps, bars of diameter 20 mm were connected at either side of the central bar through threaded couplers. The increased steel cross section of the larger bar results in a stress reduction of 36%, which increases the predicted number of load cycles to failure by a factor of approximately 6. Circular grooves or notches of 5·5 mm, width and depth respectively, were sawed at the quarter-points into the concrete surface to ensure cracking of the concrete at specified locations.

Fig. 1  Test specimen: (a) Geometry and measurement instrumentation; (b) Side and top view of the strain gauge application; (c) Threaded couplers on the Ø20 (top) and Ø16 (bottom) bars. Dimensions in mm
3.3 Instrumentation and testing

Strain gauges were applied directly to the reinforcing steel over the bar length on surfaces of 20·5.5 mm milled into the bar (Fig. 1 (b)). Linear Variable Differential Transformers (LVDT) were placed on the concrete surface and across the central concrete notch. In addition, Infrared light-emitting diodes (IRED), were applied in a grid pattern to the concrete surface.

The first fatigue test, completed at the time of writing this paper, was conducted in a Schenck servo-hydraulic testing machine. Initially, the specimen was subjected to a displacement-controlled loading to obtain a cracked, elastic response. Subsequently, the specimen was subjected to increments of 100 load cycles, separated by a quasi-static load ramp, and later to increments of 1000 load cycles at a frequency of 5 Hz.

The primary parameter to be varied in the series of tests is the upper load level. Three series of five specimens each will be tested under constant-amplitude cyclic loading with different upper load levels, resulting in stress ranges ($\Delta \sigma_e$) of 330, 275 and 230 N/mm$^2$, respectively.

3.4 Testing material

3.4.1 Concrete

Specimens were cast in the vertical position with a self-compacting concrete to avoid internal vibration. The mechanical properties of the concrete will be determined after completion of the fatigue tests.

3.4.2 Reinforcing steel

All reinforcing bars were of the steel type BSW Tempcore. A set of five bars were tested in a servo-hydraulic testing machine to determine the mechanical properties. The stress-strain characteristics for the steel tests are shown in Fig. 2. The mean static yield and ultimate strength of reinforcing steel was found to be 496.6 and 621.2 N/mm$^2$, respectively.

3.5 First results

In the following discussion only the preliminary results for the first cyclically loaded specimen ($\Delta \sigma_e = 330$ N/mm$^2$) are shown.

The steel strain measurements from the three strain gauges are shown in Fig. 3. The longitudinal axis of the specimen is defined by the x-coordinate with the origin at mid-height and the positive direction oriented upwards (Fig. 3 (a)). Initial measurements at the upper load (cracked, elastic state) indicate that the central strain gauge ($x = 0$), located at the central concrete crack, shows a steel strain equal to what the steel would experience without the concrete cover. The initial strains within the uncracked concrete zones ($x = -100; 100$ mm) were lower by 0.9703 and 0.8180‰, respectively. This steel strain reduction corresponds well to the analytical prediction of the tensile stiffening influence of the concrete.

![Stress-strain characteristics](image)

Fig. 2 Stress-strain characteristics of the steel: (a) Strain over the free length of 420 mm; (b) Strain in the elastic region with a displacement transducer of base length 300 mm
The central strain gauge measurement ($x = 0$) remains constant with increasing load cycles ($N$) as can be seen in Fig. 3 (b). This strain gauge, however, was damaged after about 200 load cycles, illustrated by the sudden strain decrease. It was observed that the steel strain within the uncracked zones increased with increasing load cycles. This increase can be attributed to a deterioration of bond between the concrete and steel under cyclic loading, thereby reducing the tensile stiffening effect. This deterioration of bond resulted in a steel strain increase of 0.0606 to 0.1302‰ or an average stress increase of 18.5 N/mm² just prior to fatigue fracture of the specimen ($N = 97'724$) under the specified stress range. The bar failed by fatigue fracture at the position of the bottom concrete crack ($x = -200$ mm).

4 Main investigation

Slabs are one of the most widely used structural elements and are often subjected to high-cycle loading as in the case of highway bridge deck slabs. Previous tests have indicated that the fatigue strength of slabs, subjected primarily to bending, is restricted by the fatigue strength of the reinforcing steel and rarely by the concrete in compression [12]. Therefore, the effective stress range ($\sigma_{eff}$) in the reinforcement has been identified as the primary parameter to be investigated.

4.1 Numerical investigation

The cross sectional analysis and prediction of the structural behaviour of reinforced concrete slab elements, relative to beams, poses a considerable challenge. Simplified procedures, conservatively overestimating or sometimes completely neglecting the influence of the torsional moment components, are generally applied. Therefore, the uncertainty regarding fatigue life prediction, based on code defined S-N curves, becomes evident due to the sensitivity of an “accurate” calculation of the steel stress range.

A refined approach for the analysis of slabs, namely the *sandwich model*, will be employed in combination with the compression field theory to develop a physical-mechanical model. Subsequently, the numerical results will be compared to published fatigue test results on reinforced concrete slabs and own tests under critical combinations of flexural and torsional moment.

4.1.1 Structural analysis

Analogous to the typical modelling of beams, namely assigning the flexure to tensile and compressive chords and the shear to the web, slab elements can be represented with the sandwich model [8] by discretization into three layers, parallel to the central plane. In-plane effects such as membrane forces and the components of bending moment ($m_{xx}$, $m_{yy}$ and $m_{xy}$) are assigned to the outer two fictitious reinforced concrete layers, whereas the components of shear ($v_{xy}$ and $v_{yx}$) are carried by a central concrete core (Fig. 4 (a)). Subsequently, the outer layers can be analyzed as reinforced concrete plates with the use of the compression field theory to obtain the steel stress under service conditions.

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Fig. 3 Strain gauge measurements at upper load: (a) Steel strain distribution along the bar length; (b) Change in steel strain with increasing load cycles

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4.1.2 Modelling assumptions

The model will enable a prediction of the fatigue performance of slabs for arbitrary reinforcement directions and combinations of the components of bending. The tensile stiffening effect of the concrete will be included to more accurately model the response. A fatigue failure prediction of the individual bars will be based on a linear damage accumulation law, as proposed by Palmgren-Miner. Furthermore, the fatigue strengths of the bars will be assigned according to a stochastic distribution, based on experimental results, similar to the approach taken by Fehlmann [4]. This will enable an investigation of the remaining slab capacity and performance after fatigue fracture of the first bar.

4.2 Test specimen and test setup

A series of reinforced concrete slab strips will be tested under service-like cyclic loading. Statically determinate boundary conditions in the test setup will ensure that the flexural demand is known from the load measurements and remains constant during cyclic loading. A standard orthogonal reinforcement layout on the flexural tension slab side will be investigated. Critical combinations of the components of bending in the reinforcement ($m_x$, $m_y$ and $m_{xy}$) will be simulated for a constant applied principal moment ($m_2$ and $\phi$) by varying the reinforcement direction in the slab. This effect is illustrated with the Mohr’s circle for the bending demand on the slab (Fig. 4 (b)) for the arbitrary reinforcement directions $n$ and $t$ (Fig. 4 (c)).

The slabs will be subjected to constant-range cyclic loading until fatigue failure of individual reinforcing bars is observed. The applied loading, deformation and reinforcing steel strains will be monitored continuously. In addition, the concrete strains, crack widths and cracking pattern will be recorded at regular intervals. Collaboration with on-going investigations of non-destructive testing methods, such as acoustic emission and the magnetic flux leakage method, could enable the detection and localization of individual reinforcing bar fractures.

![Diagram](https://example.com/diagram.png)

Fig. 4 Schematic representation of the main investigation: (a) Sandwich model with the components of bending transformed to membrane forces in the outer layers, according to [8]; (b) Mohr’s circle for the applied moment; (c) Outer sandwich layers for the standard ($\phi = 0$) and arbitrary ($0 < \phi < \pi / 2$) reinforcement directions with the corresponding state of bending.

5 Conclusion and outlook

The design of new structures and the evaluation of existing structures for fatigue action currently relies on conservative models. Fatigue thus frequently governs the design or structural evaluation process when high live loads are expected. For existing structures, evaluations based on simplified...
analyses frequently lead to costly retrofitting or replacement measures. Such results are often viewed with scepticism by engineers and owners because of the absence of visible damage to these structures even where current evaluations predict insufficient fatigue resistance. However, it has been shown that fatigue in reinforced concrete is a continuous damaging process, which accumulates over years and exhibits a highly non-linear behaviour [4]. Fatigue could lead to sudden, unannounced structural damage to elements near the end of their design lives.

The proposed numerical approach for the evaluation of reinforced concrete slabs will enable an improved prediction of the reinforcing steel stress range and resulting fatigue performance by applying a combination of established analytical approaches. A comparison of the numerical prediction to the experimental results and test results from literature will illustrate whether unexploited structural and material reserve is still available in reinforced concrete slabs.

References


