SHEAR FATIGUE FAILURE OF REINFORCED CONCRETE ELEMENTS WITHOUT SHEAR REINFORCMENT

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Concrete bridge elements, and in particular deck slabs, are subjected to repeated moving wheel loads. This fatigue load may lead to damaging characterised by a shear mode type failure. To improve the prediction of the remaining fatigue life of existing concrete bridges, fatigue tests on slab-like concrete beams without shear reinforcement under combined bending and shear loading have been conducted.

The results of these tests show that a discrete shear crack crossing bending cracks is formed. Once formed, this crack increases in length until it extends to the top of the specimen, followed by excessive crack opening. Fatigue fracture of the reinforcement and debonding of the reinforcement and concrete cover from the specimen, due to dowel action, finally lead to beam failure.

INTRODUCTION

Using current code provisions to assess the fatigue safety of existing bridges in Switzerland, deck slabs are identified as the most fatigue loaded elements, with the determinant failure mode being the shear loading of the concrete (Brühwiler et al (1)). The fatigue loading of bridge deck slabs is due to moving wheels loads and is characterised by a high number of load cycles. The number of load cycles may exceed 100 million over the service life of a bridge. Despite this fact, reinforced concrete deck slabs have commonly not been designed for fatigue until the first code provisions for fatigue of reinforced concrete were introduced a few years ago. Fatigue is both a load cycle and time dependent phenomenon and for most existing bridges, the expected service life has not yet been reached by far. Consequently, fatigue damaged bridges may only become a major problem in a few decades from now.

Most previous investigations regarding the fatigue behaviour of reinforced concrete focused on the fatigue strength of the reinforcement and the concrete subjected to compressive stress (S-N (Wöhler)-curves), i. e. the relationship between stress range and number of load cycles at fatigue fracture. During the last decade, the fatigue-strength in tension and alternating tension-compression loading of plain concrete has been studied as well as the behaviour of concrete under variable amplitude fatigue loading, but no realistic damage accumulation law could be found.

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A number of shear fatigue tests were performed on structural members without stirrups (Markworth et al (2), Frey and Thürlimann (3), Ueda and Okamura (4)) and several researchers investigated the fatigue behaviour of deck slab elements under stationary pulsating and moving wheel loads (Sonoda and Horikawa (5), Perdikaris and Beim (6)). These investigations were motivated by the severely fatigue damaged deck slabs of highway bridges in Japan (Matsui (7)).

To develop a methodology for the determination of the remaining fatigue life of existing concrete bridge deck slabs, a research program was started in 1995 at the Swiss Federal Institute of Technology in Lausanne. This research includes fatigue tests on reinforced concrete elements without shear reinforcement. The objective of this research was to study the fatigue behaviour of slender beam elements showing 1) bending failure (Schläfli and Brühwiler (8)) and 2) shear failure. In the following, the results of shear fatigue tests are described.

EXPERIMENTS

Specimens and test program

To investigate the shear fatigue behaviour, ten slab-like beams (without shear reinforcement) were subjected to eccentric three-point-bending (Figure 1). These specimens represent – in a simplified way – slabs of box girder bridges which typically have strong reinforcement (and thus a main load bearing behaviour) in the transverse direction of the traffic.

After one quasi-static test to determine the static ultimate load F_u and the cracking behaviour, eight specimens were subjected to fatigue loading. Fatigue loading was applied by hydraulic actuators providing a sinusoidal load history at a frequency of 9 Hz. The main test parameter was the maximum load. The minimum load was 20% of the maximum load. The last specimen was subjected to slow fatigue loading to investigate crack formation by means of speckle interferometry up to 32000 cycles after which the specimen was loaded up to failure under quasi static conditions. All tests were conducted under force control and beams were more than 90 days old when tested.

Concrete was made with Portland cement (325kg/m^3) and rolled aggregates with a maximum size of 32mm. The concrete had an average compressive cylinder strength f_{cc} of 35 MPa and a tensile strength of 2.5 MPa at 28 days. Yield and ultimate strengths of the steel rebars were 490 MPa and 585 MPa, respectively.

A quasi-static load cycle was performed at given intervals, and the force, the deflection at midspan and the deformations at three different locations over the specimen height were measured. In addition, the crack pattern on the concrete surface was mapped and in the zone of maximum shear stresses, the diagonal deformations were measured (Figure 1).

Fatigue behaviour

Five distinct phases and load bearing modes have been identified during the fatigue life of the specimens subjected to F_{max} greater then 45% of F_u:

(1) Initiation: In the first load cycle, the formation of flexural cracks is observed.

(2) Propagation: Within approximately one hundred thousand cycles, the crack tip of the bending cracks propagate and incline to coalesce into a main diagonal crack which develops up to the specimens' compressive strut (Figure 1).

(3) Shear crack opening: After the formation of the main diagonal crack, the strains and (residual) deflection increase with continued fatigue loading at a very slow rate and result in a notable reduction of the specimen stiffness (Figure 2). The shear crack opening continues to increase steadily and slowly and the crack tip propagates into the compressive strut and may even reach the top of the specimen.

(4) Parallel crack initiation: As the opening of the diagonal crack gets larger, a crack develops along the (horizontal) flexural reinforcement (Figure 1). This horizontal crack, caused by the dowel action of the reinforcement, separates the cover concrete from the specimen. Dowel action increases as stress transfer normal to and along the steadily opening diagonal crack decreases, until the opening of the diagonal crack is large enough such that stress transfer is no longer possible.

(5) Failure: In the final phase, there is no longer stress transfer along the diagonal crack and the shear load is transferred by dowel action alone. Failure is caused by rebar fracture, followed by fracture of the compression strut in the upper flange.

Remarks:

- The duration of phases 2-4 depends on the location of the first bending cracks. The closer the tips of the bending cracks are to the ideal path for a diagonal crack, the less time it takes to them to coalescence to a diagonal crack.
- The shear slenderness (ratio of load to support distance and specimen depth) of the tested specimens is relatively small (=2.25). For larger shear slenderness, the horizontal crack increases in length and the failure mechanism can be increasingly attributed to the "peeling off" of the rebar from the specimen.

For 7 of the 8 specimens, final fatigue failure was either the result of fracture of the reinforcement (6/7) or a "peeling off" of the reinforcement due to dowel action (1/7) according to the failure process described above. Rebar fracture was detected by measurements (deflection and strain) and by observing the crack pattern and crack openings. In the other test, fatigue fracture of the reinforcement occurred because of the normal tensile stresses in the rebar at a flexural crack under the maximum bending moment. Similar fatigue behaviour has been reported in the literature (3).

The quasi-static tests showed the same phases, load bearing modes and failure processes as the fatigue loaded specimens, although the failure was due to “peeling off” of the reinforcement from the specimens.

Fatigue strength in terms of S-N curve

Shear fatigue failure was only observed when the maximum fatigue load was greater than 45% of the static ultimate load F_u. A fatigue test showing no significant fatigue damage was stopped - in most cases - after ten million cycles; this result is considered as a "run-out". The "run-out" specimens were subsequently subjected to a higher fatigue load. Three single level and five multiple level fatigue tests gave the results shown in Figure 3.

Shear loading may be expressed by the nominal shear stress $\tau = F/A$, with A being the cross section (depth times width). In Figure 3, the results of this test program are compared with those of other investigations. As can be seen, the results of these studies do not intersect; indicating that there is no direct relation between these investigations. Consequently, the nominal shear stress appears to be an unsuitable property to describe shear fatigue loading. Instead, parameters such as specimen size and geometry, type of loading and concrete fracture properties appear to determine the fatigue behaviour and thus the shear fatigue strength of structural elements.

MODELLING

In order to model the observed fatigue behaviour, an analytical approach is currently being developed. The analytical approach:

- assumes one main diagonal crack and includes the dowel effect of the reinforcement.
- assumes that the crack tip of the diagonal crack is the centre of rotation of displacements (Fischer (9), Leonhardt and Walther (10)).
- describes concrete cracking using fracture mechanics. Hillerborg's Fictitious Crack Model describing stress transfer normal to the crack faces as a function of the crack opening is used.
- describes crack face stresses created by sliding displacements according to an aggregate interlock model (Walraven (11)).

As cracking may result in stress redistribution, a fatigue approach for slabs must consider the different load cases for both longitudinal and transversal sections and the interaction between them.

CONCLUSIONS

The preliminary results of this research and literature review lead to the following conclusions:

1. Shear fatigue behaviour is predominantly influenced by concrete cracking; final failure is due to extensive dowel action resulting in either rebar fatigue fracture (for small shear slenderness) or the "peeling off" of the rebar from the specimen (for large shear slenderness).
2. There is essentially no difference between shear failure under static and fatigue loading. Thus, a model describing static shear failure may be suitable to model fatigue failure.
3. The nominal shear stress appears to be an unsuitable property to describe fatigue strength.

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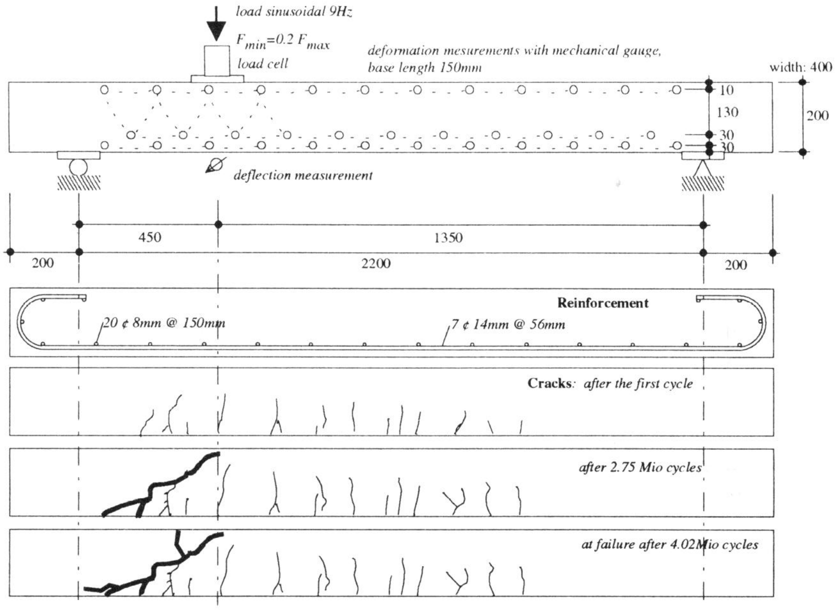

Figure 1 Specimen, test arrangement and typical crack patterns (all dimensions in mm)

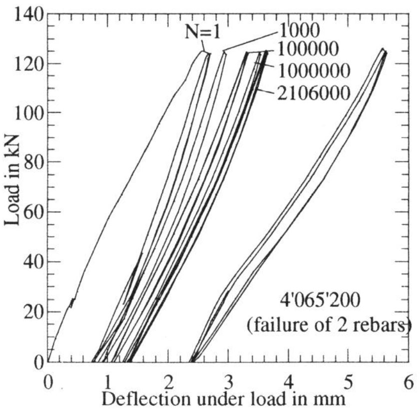

Figure 2 Typical structural response, as a function of the number of load cycles (single static load cycle).

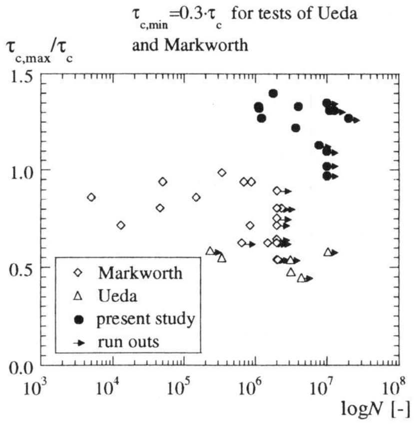

Figure 3 Shear fatigue strength (τ_c: nominal static shear strength)