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Fatigue Considerations in the Evaluation of Existing Reinforced Concrete Bridge Decks

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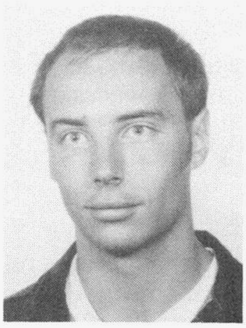

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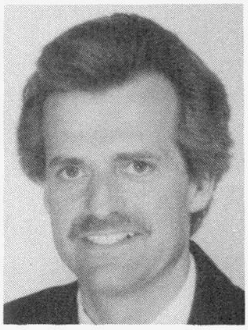

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Summary

Despite the fact that deck slabs are the most fatigue loaded elements of composite bridges, they are rarely designed or examined for fatigue. The fatigue safety of existing reinforced concrete deck slabs often cannot be verified if current fatigue design provisions are applied. Thus, there is a strong need to enhance knowledge of the fatigue behaviour of reinforced concrete deck slabs. The initial results of ongoing research with fatigue tests on slab-like reinforced concrete beams indicate that current fatigue design provisions appear to be too conservative and that the fatigue reliability of existing deck slabs is satisfactory if the principles of good fatigue design and construction practice have been respected.

1. Introduction

1.1 Motivation

Deck slabs are the most fatigue loaded elements of composite bridges. The fatigue loading is due to moving wheels and is characterised by a high number of heavy load cycles which may exceed 100 millions over the service life of a bridge. Despite this fact, reinforced concrete deck slabs are commonly not designed for fatigue and most attention is still given to the fatigue of the welded steel structure of composite bridges.

Fatigue loading of deck slabs may lead to progressive damaging of concrete and steel reinforcement, with subsequent failure. Although the fatigue phenomenon has been observed in many tests, few cases of concrete bridge damage in deck slabs due to fatigue are known [1, 2]. This may be explained by the fact that fatigue cracking of concrete cannot be clearly distinguished from cracks due to other concrete deterioration, and fatigue cracking of the steel reinforcement cannot be observed.

The objective of this paper is (1) to outline the question of fatigue of reinforced concrete decks of composite bridges and (2) to present first answers on the basis of results of current research.

Fatigue provisions have been introduced in design codes for concrete structures only during the last few years, for example in Switzerland in 1989 [3] or more recently in the pre-Eurocode 2 dealing with bridge design of concrete bridges [4]. These provisions rely on a narrow knowledge basis when compared to most other domains of concrete structures. They have led to a significant change in the design of railway bridges and deck slabs for road bridges; fatigue often is the determinant design criterion. As a result, considerable additional reinforcement, in particular shear reinforcement in slabs, and larger structural dimensions are necessary when compared to elements designed using former codes. This situation raises two questions: Are these fatigue design rules too conservative? Is the fatigue reliability of existing bridges in jeopardy?

1.2 Fatigue safety of existing concrete bridges

To investigate the second question, the fatigue safety of various concrete railway bridges and one composite road bridge has been examined on the basis of current code provisions [5]. The ratio $n_{fat} = R_{fat}/S_{fat}$ between fatigue resistance R_{fat} and fatigue action effect S_{fat} has been determined and a ranked list identifying fatigue critical structural elements for $n_{fat} < 1$ has been established. These structural elements do not fulfill the requirements of current codes regarding fatigue safety and thus the fatigue life may be shorter than the design service life of the bridge. The most fatigue critical elements of these bridges turned out to be the deck slabs and in particular when subjected to shear stress in the concrete.

In addition, examination of several existing concrete bridges in Switzerland allowed to make the following observations related to deck slabs :

- Typical calculated maximum stress values in the traverse direction of deck slabs due to the traffic model for fatigue in the Swiss code (4 concentrated wheel loads of 75 kN each in distance of 1.8 m and 1.4 m and a dynamic factor of 1.8) are 14 MPa for concrete normal stress, 0.45 MPa for concrete shear stress and 225 MPa for steel reinforcement. The minimum stress level is between 10% and 30% of the maximum stress.
- Due to the different load positions for fatigue safety and structural safety verification, fatigue safety can be insufficient in cross sections where structural safety is fulfilled and vice-versa.
- Thickness of pavement and deck have an important influence on load distribution and the determination of stresses in deck slabs. Distribution of concentrated loads through the pavement and deck under a 45 degree angle [4] may double the wheel print from a square of 0.4 m to 0.8 m which smoothes significantly the amplitude of local shear stresses.
- Verification of decks in the longitudinal direction gave values n_{fat} for shear stress reversals (Fig. 3) significantly smaller than 1.
- Normal stress reversals in the longitudinal direction lead to transversal cracking of deck slabs. This affects serviceability more than safety.

Whether the fatigue reliability of the investigated deck slabs really is in jeopardy cannot be answered now. It is speculated that sufficient fatigue safety may be determined on the basis of improved knowledge and a more realistic examination. Hence, a strong need to enhance knowledge in fatigue behaviour of concrete bridges is identified. Additionally, the steady increase of traffic loads demands a keener alertness to the fatigue phenomenon.

2. Fatigue of concrete bridge elements

The three most important fatigue relevant parameters are (1) the magnitude of stresses, (2) the number of load cycles and (3) discontinuities both in the cross section and the layout of the steel reinforcement resulting in stress concentration at possible fatigue damage locations. The stress magnitude due to fatigue loading and the number of load cycles determine whether fatigue damage occurs in these locations. Fatigue reliability of a structural element over its design service life is verified if the fatigue resistance R_{fat} is larger than the effect of fatigue loading S_{fat}. The fatigue safety of steel reinforcement and concrete are determined separately :

2.1 Fatigue of steel reinforcement

Similar to steel structures, the fatigue resistance of mild and prestressing steel reinforcement may be represented by the detail category $\Delta\sigma_{fat}$ which is defined as the fatigue strength at $2x10^6$ cycles (Fig. 1). Regarding the fatigue action effect, the stress range is the most important parameter and a correction factor is used to account for the cumulative fatigue damage caused by the stress spectrum of traffic models for a lifetime of a hundred years. This correction factor as calculated for steel bridges using the Palmgren-Miner damage accumulation rule is also applicable with sufficient accuracy to steel reinforcement in concrete bridges [6].

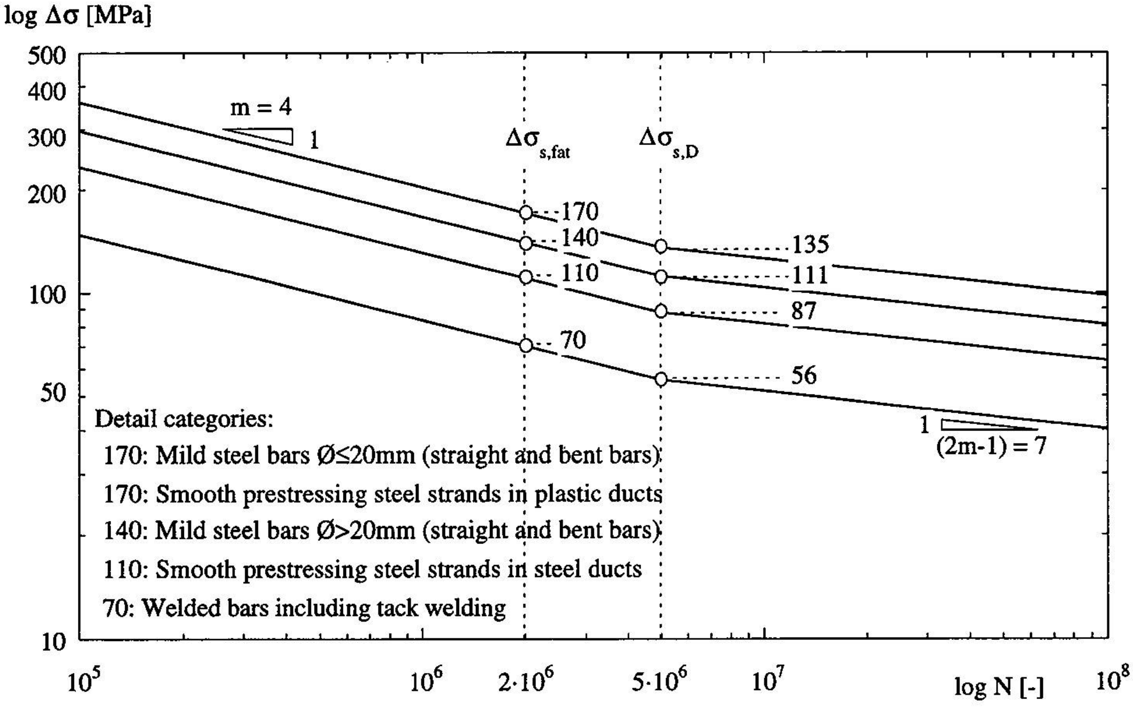

Fig. 1 Fatigue strength of steel reinforcement according to [6].

2.2 Fatigue of concrete

The fatigue resistance of concrete is in principle defined by a pair of stresses, i.e. the maximum and minimum stress values as the most important fatigue relevant parameters. The effect of this pair of stresses on the fatigue strength as a function of the number of load cycles is best represented by a Goodman diagram (Fig. 2). Other fatigue relevant parameters include the concrete strength and the structural size effect which are taken into account by the nominal design values f_c and τ_c for static compressive and shear strength respectively. The fatigue action effect in the concrete is described by the maximum and minimum stress values due to the fatigue loading and the dead load of the structure including permanent loads. No correction factor is introduced because of a lack of proven models for fatigue damage accumulation in concrete.

In the longitudinal direction of the deck slab, stress reversals may occur in a given section due to the passage of a moving load (Fig. 3). The effect of these stress reversals for shear is not conclusively known; the literature [7, 8] indicates a strong reduction of shear fatigue resistance which is accounted for in Fig. 2b. Since the fatigue strength of the rebars is not expected to be sensitive to stress reversals, the failure mode of the slab under normal stress reversals is likely to be characterised by concrete fracture alone.

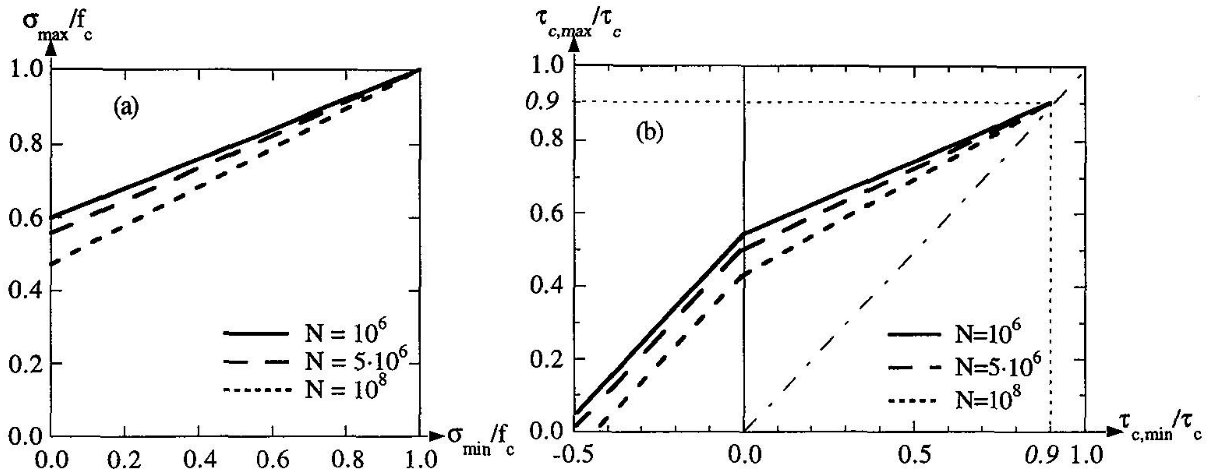

Fig. 2 Fatigue strength of concrete as represented by a Goodman diagram for (a) compressive and (b) shear stresses according to [6].

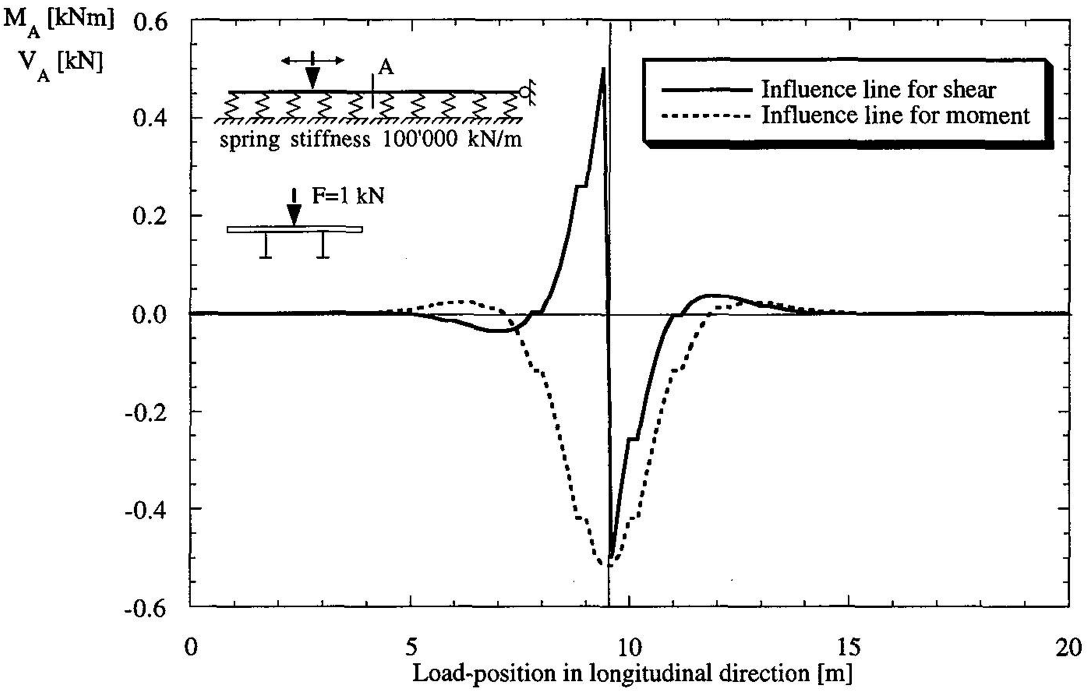

Fig. 3 Influence line of a moving load in the longitudinal direction of a deck slab.

3. Concept for the examination of existing bridge decks

In the examination of existing bridges, a stepwise procedure is normally adopted.

The *first step* is a verification of the structural safety, fatigue safety and serviceability of the existing structure based on the requirements of current codes. The objective of this first step is to identify determinant structural elements.

In the *second step*, the existence of the structure allows load and resistance models to be updated. Updating the information on a given bridge includes :

- more detailed assessment of past and future traffic loads (including their locations on the slab)
- determination of actual structural dimensions

- determination of in-situ material properties

If safety cannot be verified during the second step, stresses can be determined in a *third step* using more detailed methods, for example in-situ load testing or a refined FE model, and more advanced methods such as those based on probabilistic concepts.

4. Current research at the Swiss Federal Institute of Technology

4.1 Specimens and experiments

Research focusing on the remaining service life of existing concrete bridges has recently begun. Firstly, the fatigue behaviour of concrete slabs without shear reinforcement is investigated. Seventeen slab-like beams without shear reinforcement have been made (Fig. 4) using ordinary concrete with an average compressive cylinder strength f_{cc} of 35 MPa at the age of 28 days, which corresponds to a nominal compression design strength f_c of 19.5 MPa and a nominal shear design strength τ_c of 1.0 MPa. Three reinforcement ratios were chosen; the yield and ultimate strength of the mild steel bars is 490 MPa and 585 MPa respectively. All beams were older than 90 days when tested.

Before conducting the fatigue tests, two specimens have been tested under static loading to observe the crack pattern and to determine the ultimate static strength. Fatigue loading was applied by hydraulic actuators providing a sinusoidal load history at a frequency of 4.5 Hz. The first six specimens were tested with a minimum load equal to 10% of the maximum load. Since no concrete damage was detected, the minimum load was increased to 30 % of the maximum load. One specimen was even tested at a minimum load level of 54 % of maximum load but it was found that the maximum load must be less than 75-85% of the ultimate static strength to avoid yielding of the rebars with subsequent failure due to low cycle fatigue.

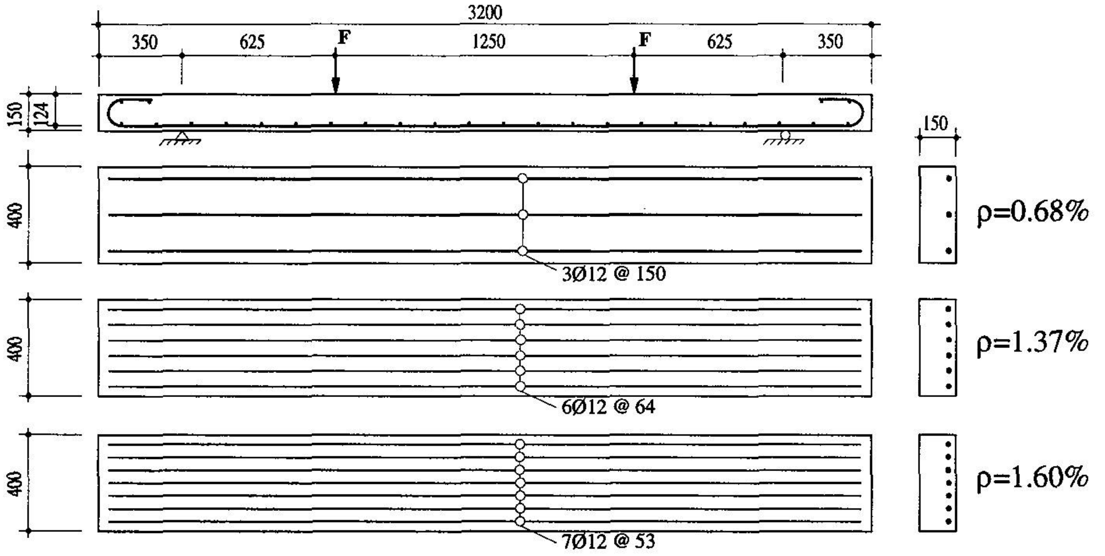

Fig. 4 Specimen dimensions and static system (all dimensions in mm).

The force, the axial strains in one rebar and the axial strains on the compressed concrete surface in the constant moment region were monitored during the test. Deflection was measured at mid-span. Two strain gauges with a length of 20 mm were glued to the lower side of one rebar of each specimen after casting the specimens. For this, the rebar surfaces were made accessible for the glueing of the strain gauges by an opening which was blocked out in the formwork. This hole created stress concentration so that cracks appeared without any exception in the cross sections with the strain measurements. In the same sections, strain gauges with a length of 100 mm were glued on the concrete top surface. Despite the long strain gauges, measurements varied strongly and consequently measurements using a mechanical dial-gauge are planned for the future experiments. A typical strain versus number of load cycles curve for concrete and reinforcement is shown in Fig. 5. To observe the development of cracks, the crack pattern of the concrete surface was mapped several times during each test.

4.2 Test results

For all 9 specimens tested under fatigue loading failure was always fatigue fracture of rebars.

The strains and the deflection strongly increased within the first thousand cycles followed by a sequence of constantly increasing strains and deflection at a much lower rate (Fig. 5). Increasing strain and deflection was accompanied by crack propagation (Fig. 6): during the first thousand cycles, the visible crack propagation at the surface was strong, i.e. about 1-2 cm. New cracks developed in particular in the region with shear loading. In the final phase of the tests, cracks often changed direction and propagated parallel to the neutral axis. One specimen was subjected to static loading after 10 million cycles on two load levels each; no further crack propagation was observed before the specimen started yielding, the yielding and ultimate load of this specimen was equal to the corresponding values obtained from the static experiments.

A reinforcement ratio of 0.69% is considered to be a low value for decks of two girder bridges. Four fatigue tests have been performed using specimens with this reinforcement ratio. Failure always occurred by fatigue fracture of rebars and concrete under compression showed no spalling at the surface under fatigue loading. Thus, because of the low reinforcement ratio, the rebars are significantly more loaded than the concrete which, as a result, does not show any distress due to fatigue loading.

Specimens with the high reinforcement ratio showed no or only minor local fatigue damaging of concrete under compressive stresses. On two specimens, compression peaks such as those at location A in Fig. 6 formed cracks which were closed when the specimens were loaded and open when unloaded.

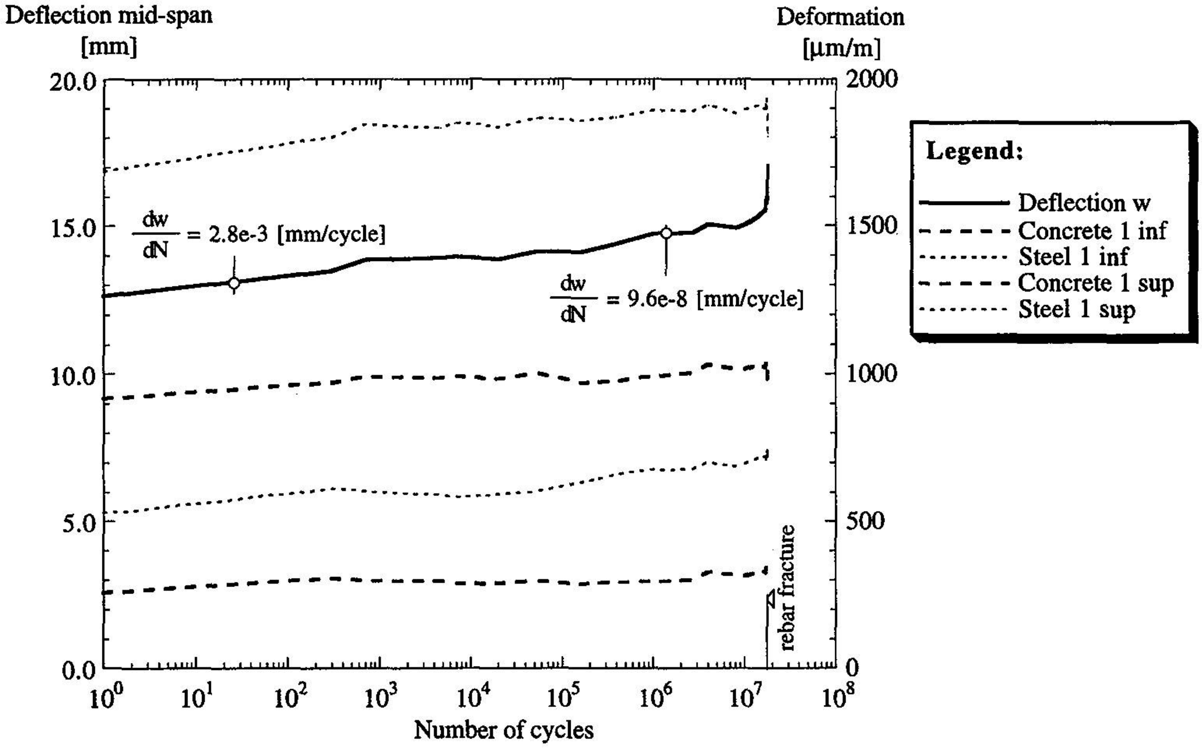

Fig. 5 Fatigue behaviour of a specimen with 1.6% reinforcement.

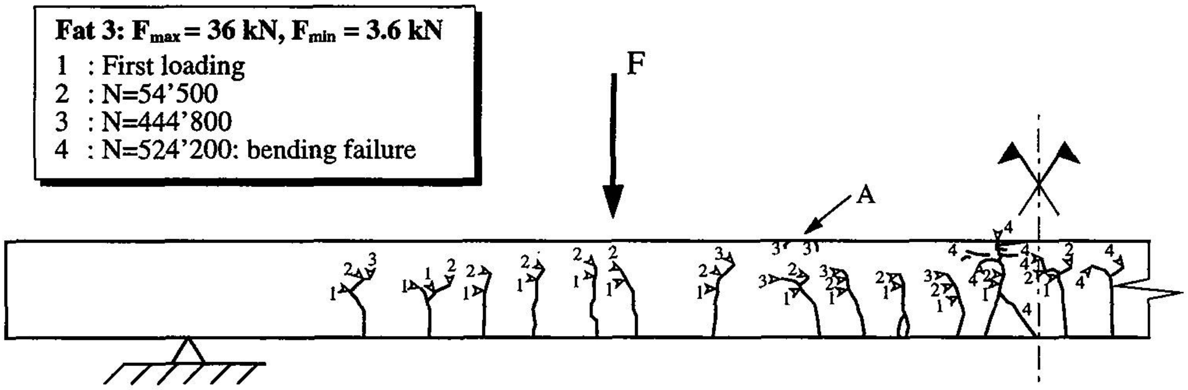

Fig. 6 Crack pattern of a specimen with 1.37% reinforcement as observed by visual inspection.

Although this research is still in its initial phase, the following initial observations can be made:

- Fatigue failure of concrete under compression is to be expected only if the stresses are extremely high, i.e. above 60% of cylinder strength f_{cc}. Concrete subjected to lower stresses may only fail after an extremely high number of cycles exceeding the amount a bridge deck may be subjected to during its service life. Also, the present results are considerably above the fatigue strength as suggested by present codes (Fig. 7). Recent research on plain concrete shows that fatigue failure under axial compression only occurs at a stress level above 60% of the cylinder strength f_{cc} [9]. These stresses are larger than the maximum possible stress level implied by the requirements of codes for structural safety and serviceability limit states.
- The detail category of 170 MPa for non-welded mild steel reinforcement is confirmed by the tests in the domain of high stress ranges, but appears to be conservative for stress ranges smaller than about 230 MPa (Fig. 7). There are indications that the ratio of minimum to maximum stress may influence the fatigue resistance of rebars in slab-like elements.
- In the case of concrete subjected to shear stresses, the test results suggest a high fatigue strength; e.g. no fatigue failure was observed for $\tau_{c,max}$ = 0.6 MPa and after more than 20 million load cycles. However, bridge slabs are also subjected to shear stress reversals; the fatigue strength may be significantly lower when compared to shear without stress reversals (Fig. 2b).
- Fatigue damage was only observed when the maximum fatigue load was greater than 60% of the ultimate static load F_u. The requirements for structural safety and serviceability limit states are by far not fulfilled at this high load level. For example, maximum deflection of one specimen was 1/170 of the span or about 6 times larger than the limit value of 1/1000 suggested by codes.
- Fatigue loading which results in stresses below the fatigue limit of steel and concrete affects serviceability (deflection, crack opening) but not fatigue safety.
- The tested beams have been designed and made according to principles of good fatigue design practice. If these principles are not respected, the fatigue strength may be significantly reduced. Factors affecting the fatigue strength of reinforced concrete include :
  - welded rebars including tack welding (Fig. 1)
  - strong corrosion and pitting corrosion of rebars resulting in defects and reduction in cross section.
  - deteriorating concrete (microcracking due to corroding rebars and freeze-thaw cycles)

Also, the fatigue action effect (including dynamic impact) may be amplified by higher axle loads and bad condition of the bridge deck surface.

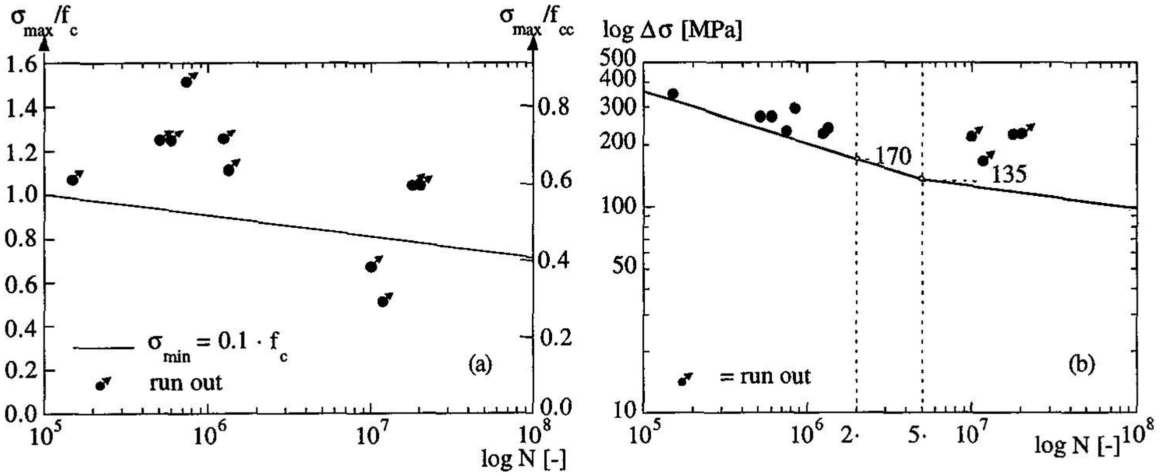

Fig. 7 Test results in comparison with fatigue strength of (a) concrete under compression and of (b) mild steel reinforcement according to [6] (f_c : nominal design compressive strength, f_{cc} : static cylinder strength).

5. Future research

To improve knowledge about concrete fatigue behaviour, additional slab-like beams will be tested. Beams with a span to depth ratio of about 8 will be subjected to eccentric 3-point-bending to enhance shear fatigue failure of concrete. In addition, the fatigue damage mechanism of plain concrete under compression is being investigated using microscopy and the effect of shear stress reversals due to moving wheel load will be studied.

Other research topics will include the fatigue behaviour of structural elements with welded reinforcement and deteriorating concrete as well as methods to determine the remaining fatigue life of deck slabs.

6. Conclusions

1. Based on current knowledge, the fatigue safety of existing reinforced concrete bridge decks may be a problem.
2. The fatigue safety of existing bridge deck slabs appears to be satisfactory if the principles of good fatigue design practice have been respected and the deck slab is in good condition.
3. Research into the fatigue behaviour of reinforced concrete slabs needs to be intensified and suitable methods to examine the remaining fatigue life must be developed.

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