Crack growth tests to assess the remaining fatigue life of old steel bridges

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Crack Growth Tests to Assess the Remaining Fatigue Life of Old Steel Bridges

Essais de propagation de fissures pour estimer la durée de vie restante d'anciens ponts en acier

Risswachstums-Versuche zur Schätzung der Restlebensdauer alter Stahlbrücken

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SUMMARY

While evaluating the remaining fatigue life of old steel bridges, a complementary test has been employed a crack growth test for standardized specimens. The findings of these tests assist the evaluation in two ways. Firstly, an estimate of fatigue strength can be made, and, secondly, the propagation of existing and postulated cracks can be predicted.

RÉSUMÉ

Pour l'évaluation de la durée de vie restante d'anciens ponts en acier, un outil complémentaire a été utilisé – des essais de propagation de fissures sur des éprouvettes standardisées. Les résultats d'essais apportent deux améliorations distinctes. D'une part, une estimation de la résistance à la fatigue peut être faite, et, d'autre part, la propagation de fissures existantes ou postulées peut être prédite.

ZUSAMMENFASSUNG

In das Verfahren zur Ermittlung der Restnutzungsdauer alter Stahlbrücken ist ein zusätzliches Hilfsmittel einbezogen worden – Rissfortschrittsversuche an Standard-Proben. Aus den Ergebnissen dieser Versuche folgen zwei Verbesserungen des Verfahrens. Zum einen kann die Ermüdungsfestigkeit des Materials geschätzt werden, und zum andern kann das Anwachsen vorhandener oder postulierter Risse vorausgesagt werden.

1. INTRODUCTION

Many old riveted steel bridges in different countries approach now their hundredth birthday - or even more - and very often, there is no reason to put them out of service. The replacement of all these bridges far exceed the available financial resources. However, even if the funds existed, in several cases replacement would be the least acceptable option because many of the bridges are of historical importance [1] [2] [3].

During the last years, repeatedly the question emerged whether or not an old bridge should be preserved for the future and should remain under (full) traffic load for some more decades.

Applying the procedure of rating old bridges as specified e. g. by Hirt [6], we decided to add a supplementary element qualified for characterizing the fatigue behaviour of highly stressed structural elements: Crack growth tests as being well known from other fields of engineering.

As we found by performing the incorporation of this additional tool, it offers more than only confirmation of the fatigue strength characteristics of structural elements.

Figure 1. Steel bridge of the Berlin Metropolitan, built in 1898, replaced 1988

2. MOTIVATION OF THE INVESTIGATION

During some years, we have been concerned with the rating of old steel bridges, the most of them in Berlin, however some of them in West Germany. It is not even a simple task to produce evidence that an "overdue" bridge may be kept in service. After having executed all the steps of the procedure of evaluating the remaining fatigue life of highly stressed structural members, we tried to identify the fatigue behaviour of the material produced more than hundred years ago. Presuming that the growing of cracks under repeated loading will be the governing physical effect of fatigue [7], we performed crack growth tests on samples of the structural members in question.
However, as a result, it was not only possible to answer the question of similarity of the steel of the turn of the century and that of today: The direct application of the crack propagation concept to structural members had the

consequence of looking to the structural details having in mind to find where the first crack could occur.

In this context, it is not only important to look at the structural details for rating a certain bridge for its further use. There is the other task to approve the procedure of rating by fatigue-loading old bridges up to the point of having large cracks. This task can only be done after putting bridges out of service and simulate traffic load, preferably in the laboratory. This kind of loading of these bridges (constant-amplitude loading, variable-amplitude loading) should be discussed to get as much information from these tests as possible (see e. g. [9]).

In the following, three main topics shall be presented and discussed.
- Crack growth tests and its results
- Application of fracture mechanics approach to bridge's structural members
- Measured stresses (strains) and the treatment of small stress cycles.

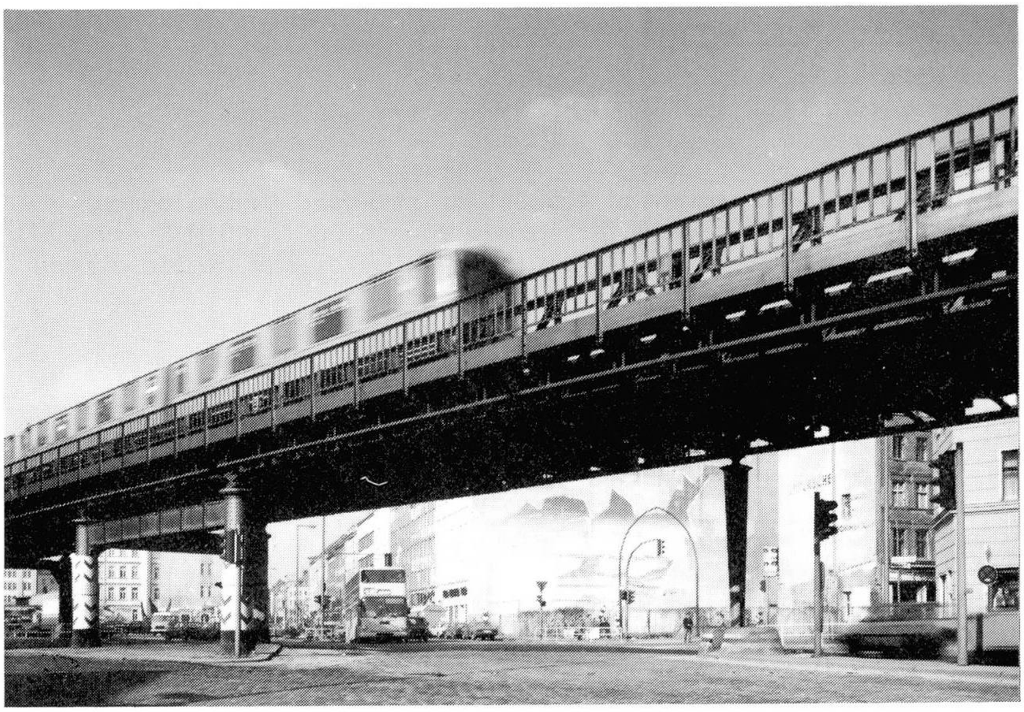

Figure 2. Truss girder bridge of the Berlin Underground, built in 1902, replaced in 1989

3. CRACK GROWTH TESTS; RESULTS

Up to now, crack growth tests have been included in the investigation of three bridges in our institute [5] [8]. The first one, a road bridge, was built in 1952 with unidentified material from the thirties. The other ones, two parallel bridges of the Berlin Metropolitan, fig. 1, were erected in 1898. The latter ones are now replaced because of widening of the streets they crossed. In all cases, we measured strains under traffic. The two bridges of the Berlin Metropolitan will be used as models of natural size to evaluate their fatigue life after hundred years of loading, maintance and corrosion.
Today, we perform cyclic loading tests on parts of the Berlin Underground Bridge shown in fig. 2, which was built in 1902.

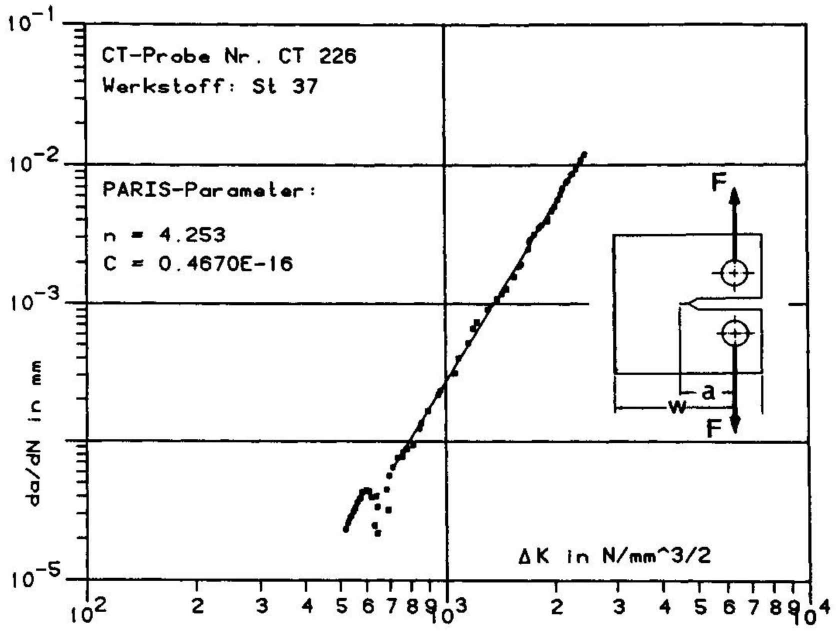

Figure 3. Result of one of the crack growth tests (ASTM E 647-83) with regression line regarding the Paris equation (1)

The crack growth tests which supplemented the set of standard technological tests (strength, chemical analysis) were performed according to ASTM E 647-83 [10]. The specimens were 12.5 mm thick. The initial value of the cyclic stress intensity factor ΔK reached 300 $N/mm^{3/2}$ to 500 $N/mm^{3/2}$.

The results of the tests, given in terms of the Paris-equation, fig. 3,

$$da/dN = C \, \Delta K^n \qquad (1)$$

a crack length
N number of loading cycles
ΔK cyclic stress intensity factor
C;n material parameters of crack groth

have proven that there is no significant difference between mild steel produced at the turn of the centuries and today.
The value of n tends to a little bit higher values than presented in textbooks for present-day steel

$$n = 2.83 \ldots 4.75.$$

However, relatively large values of n correspond to very small values of C,

$$C \approx 10^{17} \quad \text{for } n > 4.3.$$

Thus, high values of crack growth for moderate values of ΔK appear for small values of n and large values of C, e. g. n = 3 and $C = 10^{-13}$.
From our crack growth tests on specimens of steel produced about 100 years ago - up to now a rather limited number of tests - we can deduce that this steel behaves like present-day steel concerning fatigue.
For the future investigations we intend to include the evaluation of the threshold-value of ΔK for crack growth that has a certain relationship to the cut-off limits of the fatigue strength curves.

In this connection, it should be mentioned that the characteristic values of strength (yield, stress, tensile strength) of the material in question reach about 230 N/mm^2 and 360 N/mm^2, respectively; the total elongation at fracture reaches about A_5 = 30 %.

4. APPLICATION OF FRACTURE MECHANICS TO STRUCTURAL MEMBERS

The application of fracture mechanics in the evaluation of remaining fatigue life implies the modelling of cracks in structural members, which can presumably appear, fig 4. The propagation of cracks then is only governed by the stress intensity at the crack's tip as expressed by the Paris equation. On this basis, it is possible to predict how far a certain crack can grow within the period of time between two inspections.

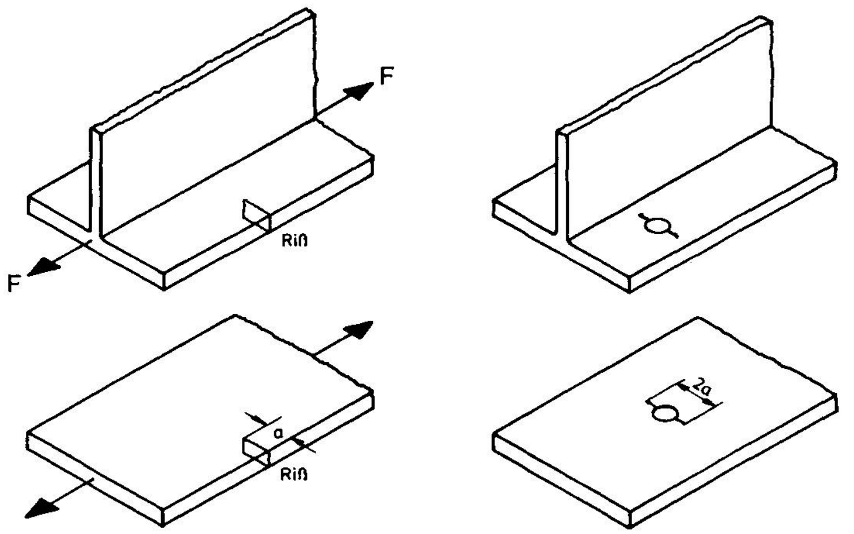

Figure 4. Crack patterns in riveted members for evaluating stress intensity factors and crack growth

It is an advantage of fracture mechanics to enable this kind of prediction and to lead to a deeper insight into the problem of survival of structural members under cyclic loading than only the application of fatigue strength curves can generate.

5. HIGH-CYCLE FATIGUE STRENGTH AND FATIGUE LIMITS

The long-life fatigue behaviour of welded structures has been subject of discussion and research quite recently [9]. However, the same problems occur for old riveted structures, too. Looking at the results of measurements at some bridges, we found that only very few of the stress cycles exceed the cut-off limits as given e. g. in the ECCS Recommendations [11], fig. 5.
Because of the fact that the allowable stresses about 100 years ago reached about 90 N/mm^2 or even 120 N/mm^2, the stresses in structural members of bridges of the Metropolitan or Underground in Berlin reach under traffic only 30 N/mm^2 or even 50 N/mm^2. Maybe, that in the past, in the course of an eventful history, overloadings could have taken place. This uncertainty of the loading in the past makes it complicated to judge the fatigue damage that bridges could have experienced during service life.
However, looking at what happens during crack growth tests, it seems that only a few cycles of high loading do not influence the crack growth significantly. This does not necessarily hold for loadings in the threshold stress range as expressed in [9] by the sentence: Stress ranges below the constant amplitude fatigue limit (CAFL) influence the fatigue life if there is at least one cycle in the variable-amplitude spectrum above the CAFL.

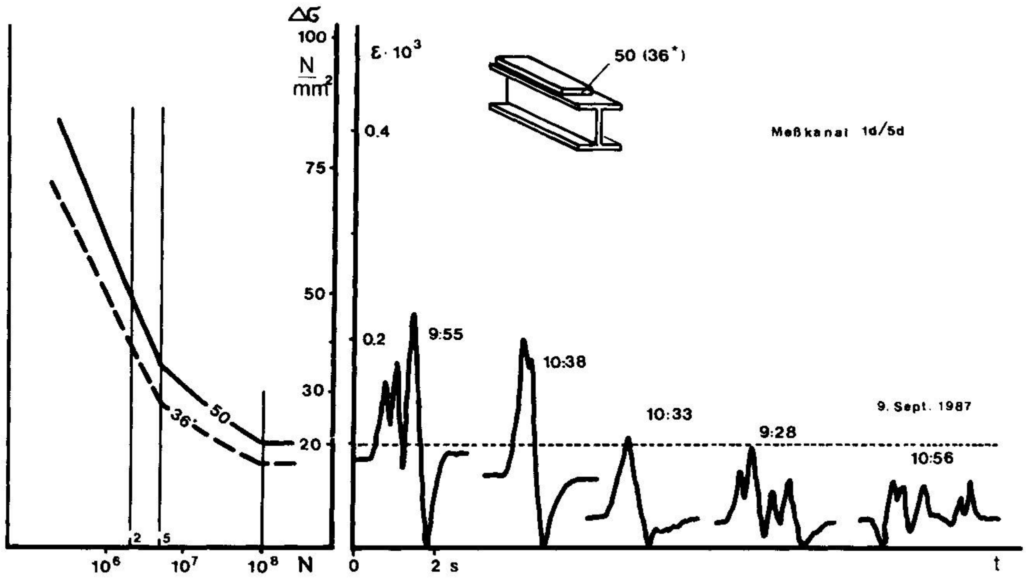

Figure 5. Measured strains/stresses during about 3 hours of observation at one measuring point.
The curves on the right hand side represent the largest measured cycles (indicated: time of vehicle passing) [5] which are compared with the cut-off limits of the ECCS-fatigue strength curve 50 (36*) [11]

6. EXPERIMENTS WITH OLD BRIDGES

In the Federal Institute for Materials Research and Testing (BAM), we started with experimental investigations the subject of which are complete small-span bridges or parts of larger ones. In some case, we could measure strains under traffic flow before they were replaced. There are many questions that should be answered. However, in a first step, we are going to apply constant-amplitude loading that generates in the structural members stresses in the range we measured before.

The most of the loadings will be in the range near the CAFL. For the future investigations, we are going to discuss in which stress range we should perform the tests.

We hope that we can contribute to improve the answers on the question for how much longer a certain bridge will carry the loading within certain limits of safety margins.

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