Fatigue Safety of Existing Steel Bridges

Sécurité à la fatigue de ponts métalliques

Ermüdungssicherheit von Stahlbrücken

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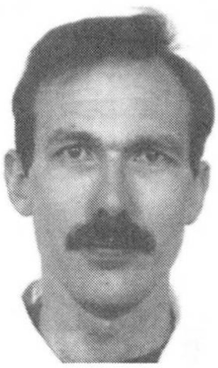

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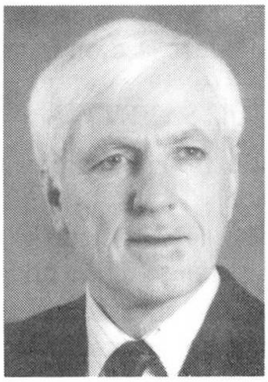

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SUMMARY

Today, mainly two types of steel bridges are fatigue critical, railway bridges from the beginning of the 20th century and highway bridges built in the 1950s and 1960s. In this paper a practical method is presented to calculate the remaining fatigue life of existing struc-tures that is closer to the real behaviour than previous methods. The method helps to make better decisions regarding maintenance, replacement and rehabilitation. The use of the proposed method is illustrated by an example.

RÉSUMÉ

Aujourd'hui, deux types de ponts métalliques sont critiques vis-à-vis de la fatigue: les ponts-rails construits au début du 20e siècle et les ponts-routes datant des années 50 et 60. Cet article présente une approche pratique et simple permettant aux ingénieurs de calculer la durée de vie restante de structures existantes, ceci d'une manière plus proche de la réalité qu'il n'était possible auparavant. De plus cette méthode aide à prendre des décisions concernant la maintenance, les remplacements et les réparations. Un exemple permet d'illustrer l'utilisation de la méthode proposée.

ZUSAMMENFASSUNG

Heute sind vielfach zwei Arten von Stahlbrücken hinsichtlich Ermüdung gefährdet: die zu Beginn des 20. Jahrhunderts erbauten Bahnbrücken und die in den 50er und 60er Jahren errichteten Strassenbrücken. Im vorliegenden Beitrag wird ein praxisnahes Verfahren vorgestellt, welches dem Ingenieur erlaubt, die Restlebensdauer bestehender Konstruktionen zuverlässiger abzuschätzen als dies bis anhin möglich war. Zusätzlich können mit diesem Verfahren auch bessere Entscheidungsgrundlagen für Unterhalt, Ersatz und Wiederinstandsetzung zur Verfügung gestellt werden. Der Nutzen des vorgeschlagenen Verfahrens wird anhand eines Modellbeispiels veranschaulicht.

INTRODUCTION

Today, there are mainly two types of bridges the remaining fatigue life is often questioned - railway bridges from the beginning of this century and highway bridges built in the 1950's and 1960's. The following discussion will be focused on the first type of bridges. Often, the structural capacity of these bridges is still satisfactory due to a very conservative design at this time, but fatigue becomes often very critical. Therefore it is important to estimate reasonably the remaining fatigue life of these structures. On the same time engineers must evaluate alternatives by making assumptions about the traffic in the future and they must be enable to make proposals for reinforcements and rehabilitations or traffic restrictions.

The objectives of this paper are to give some indications how fatigue safety can be assessed and the remaining fatigue life can be estimated. Therefore the procedure for the assessment will be discussed and a damage accumulation model based on fracture mechanics will be introduced.

ASSESSMENT OF FATIGUE SAFETY

For design and assessment of existing structures the following three main factors must be considered in order to verify fatigue safety:

- **Applied stress ranges:** The applied stress ranges are a function of the service loads, including impact, and the structural response of the bridge to those loads.
- **Geometry of the detail:** The stress concentration caused by the geometry of the detail, the manufacturing procedure, and the crack shape due to a given stress direction all influence the fatigue life. These will be considered by assigning a detail to a predefined category.
- **Number of stress cycles:** The number of stress cycles applied in the past directly influences the remaining fatigue life of a structure.

An assessment of fatigue safety may be required as a result of observations (e.g., increasing in displacements of vibrations characteristics or the occurrence of corrosion or cracks) or because of changes in service conditions (e.g., increase of axle loads or number of vehicles) or for a legal reason when a assumed service life is reached. In the assessment of fatigue safety the following three stages can be distinguished:

- **Stage 1 - Identification of fatigue critical details:** It is recommended that a thorough study of the available documents be made and a detailed inspection of the bridge be carried out. A list of priorities of fatigue critical details can be established on the basis of a calculation that uses the current design rules.
- **Stage 2 - Calculation of remaining fatigue life:** In addition to inspection and maintenance, a reliable estimation of the remaining fatigue life based on an appropriate calculation is needed.
- **Stage 3 - Monitoring of fatigue critical details:** For structures subjected to fatigue, regular inspections can be essential.

CALCULATION OF REMAINING FATIGUE LIFE

For existing structures a sophisticated procedure must be recommended where the damage increase of each stress range can be taken into account. This is important because the traffic conditions have normally changed since construction. The axle loads have gotten heavier and the number of vehicles, i.e., the traffic frequency, has increased significantly. Therefore the traffic has become more fatigue aggressive.

For the verification of the fatigue safety normally fatigue strength curves are used. Depending on the geometry and the manufacturing process the corespondent fatigue category for the investigated detail can be identified. The damage increase d_i per stress $\Delta\sigma_i$ is defined as the inverse of the number of stress ranges N_i which could be applied for a constant amplitude $\Delta\sigma_i$. Failure would be assumed when the accumulated damage $D = \Sigma d_i$ is 1.0.

This calculation gives good results as long as all stress ranges are above the constant amplitude fatigue limit $\Delta\sigma_D$. When some stress ranges are below $\Delta\sigma_D$, as illustrated in Fig. 1, there are several alternative approaches that can be used:

a) **Constant slope:** The approach used in North America is to calculate the equivalent stress range, using the root mean cube, and compare this to the allowed stress range for a given number of stress cycles.

b) **European approach:** Below the constant amplitude fatigue limit $\Delta\sigma_D$ a different slope $m' = 2m-1$ is taken into account, considering that the stress ranges below $\Delta\sigma_D$ do not contribute to the damage increase in the same way as the stress ranges above $\Delta\sigma_D$ do [1].

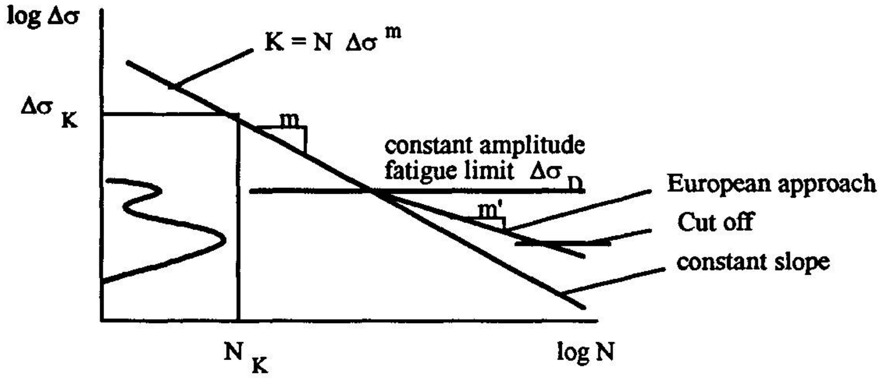

Figure 1 : Stress range spectrum with different fatigue strength curves

Both methods will give conservative results. However, for a reliable and economic assessment of the fatigue safety of existing structures it is important to have a better understanding of the way the stress ranges below the constant amplitude fatigue limit contribute to the damage increase. Therefore a damage accumulation, called FM-model, based on fracture mechanics has been developed.

In fracture mechanics it can be observe that with an increasing crack the crack rate per stress cycle increases. On the same time smaller and smaller stress ranges contribute to the crack propagation. The stress range below no further damage occurs is called the damage limit $\Delta\sigma_{th}$. It decreases with the increase of the damage D, for more information see [2].

$$\Delta\sigma_{th} = \Delta\sigma_D \cdot (1 - D) \tag{1}$$

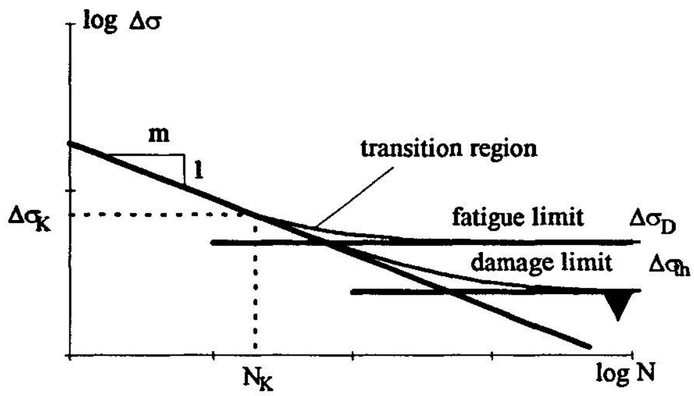

Figure 2 : Decreasing of the damage limit including the rounding of the transition region

The decreasing of the damage limit $\Delta\sigma_{th}$ is illustrated in Fig. 2. Between the constant slope region above the constant amplitude fatigue limit $\Delta\sigma_D$ a transition region can be observed. A similar observation can be made in fracture mechanics and therefore the damage increase per stress cycle can be quantified.

The prediction of the decreasing of the fatigue limit can be compared with fracture mechanics and it will be seen that with the FM-Model the fatigue life is underestimated by 5 to 8 % referred to the fracture mechanics calculation. The range depends on the assumed detail and the applied stress range spectrum [2].

APPLICATION

In order to illustrate the application possibilities the basic information from a railway bridge built in 1900 will be used. In an other situation the results can be completely different.

The main assumptions of the railway bridge are:

- year of construction: 1900
- year of reference: 1995
- actual traffic volume: 60 trains per day
- traffic mixture: 50 % freight trains; 50 % passenger trains
- fatigue strength: category 67, i.e. fatigue strength at 2 million cycles: 67 MPa constant amplitude fatigue limit at 7 million cycles [3]
- static system: simple span beam with the influence line of the moment in the middle of the span
- section modulus: 25×10^6 mm^3

In the following figures the damage evolution of different damage accumulation models is shown. The FM-Model will be compared with the traditional approaches, the Constant Slope and the European model (Fig. 1). In Fig. 3 a constant traffic model is assumed. The traditional damage accumulation models show a constant increase of the damage, in the way it will be expected for design, the FM-Approach has a acceleration in the damage increase, because with increasing damage more and smaller stress ranges contribute to the damage increase. The differences between the three models is obvious because the majority of the stress ranges of the applied spectrum is below the constant amplitude limit. Based on the damage accumulation model used, the fatigue life will be estimated in a range of almost 100 years. If all stress ranges are above the constant amplitude fatigue limit and above the influence of the transition region the three curves are identical.

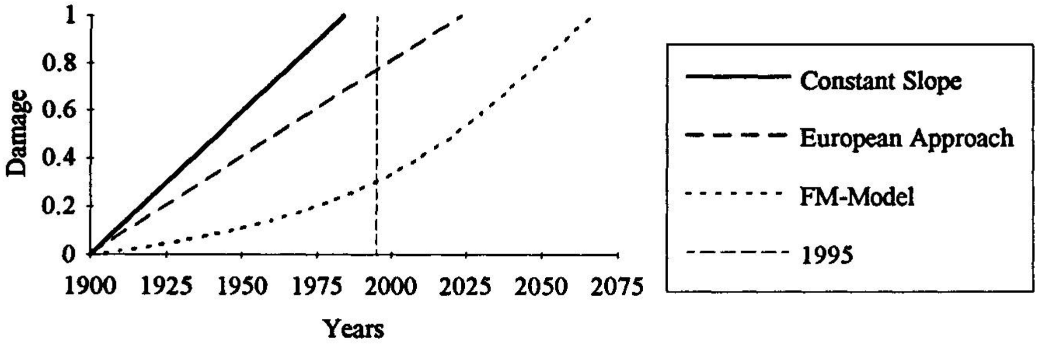

Figure 3 : Damage evolution for a constant traffic model

For the traffic in the past it is normally appropriate to consider a traffic evolution, where the increase of axle loads and the increase of the number of passages will be taken into account. For railway bridges the UIC (Union Internationale des Chemins de fer) proposes a traffic evolution like shown in Fig. 4. For each time period an other number of trains per day and other trains must be considered. The corespondent damage evolution is shown in Fig. 5. Due to the traffic evolution even the traditional methods change now the slope. Nevertheless, for each defined traffic model the damage increase is constant. However, the FM-model shows a continuous increase of the damage.

In Fig. 6 the influence of the percentage of freight trains is shown. The total number of trains is unchanged. The value at the left, 0 %, corresponds to exclusively passenger trains and 100 % to exclusively freight trains. The remaining fatigue life is given in years, where 0 corresponds to the reference year 1995 and 100 corresponds to 2095. Freight trains have heavier axle loads and are unfavorable with respect to the remaining fatigue life, this parameter can influence the remaining fatigue life significantly. Accurate information about the traffic is very important in order to calculate a reliable estimations of the remaining fatigue life.

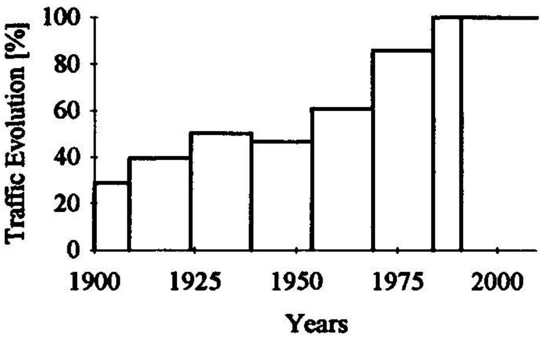

Figure 4 : Traffic evolution corresponding to UIC

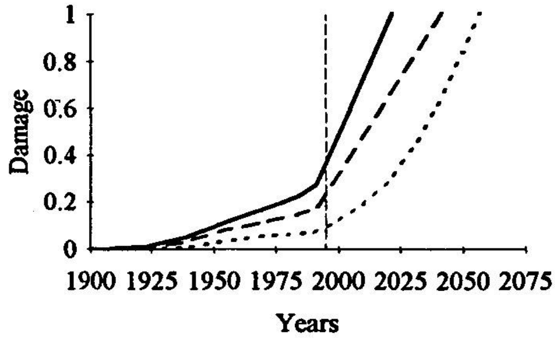

Figure 5 : Damage increase for a given traffic evolution (legend see Fig. 3)

Fig. 7 shows the influence of the traffic volume, expressed by the number of trains per day. Even when the number of trains must be estimated and an uncertainty of ± 10 % must be assumed, the calculated remaining fatigue life will not change significantly.

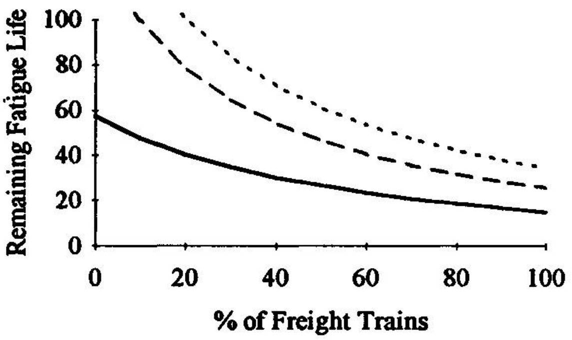

Figure 6 : Influence of the percentage of freight trains (legend see Fig. 3)

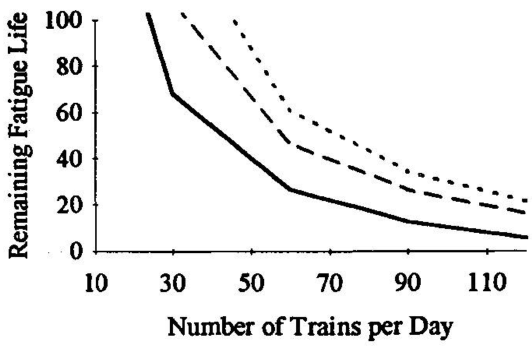

Figure 7 : Influence of the traffic volume (legend see Fig. 3)

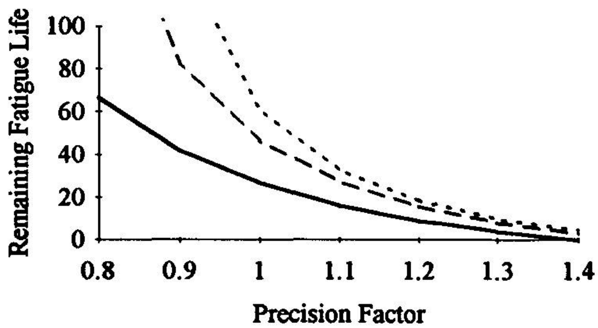

Figure 8 : Influence of the precision factor (legend see Fig. 3)

One of the most important parameters needed for the calculation is the influence line. There can be significant differences between calculated and measured values. In Fig. 8 the influence of the assumed influence line is shown by applying a precision factor.

The calculated remaining fatigue life is very sensitive to this parameter and it is highly desirable to carry out field measurements in order to create as accurate a picture of the influence line as possible.

In Fig. 9 the influence of a second track is shown. In all cases the total number of trains will be assumed to be the same. The first assumption correspond to a bridge where the total traffic in both directions is on the same track. This is compared to a second assumption that corresponds to a bridge with two tracks where on each track 50 % of the original traffic will be assumed. The influence of the stress ranges on the investigated detail of the second track is due to the lateral distribution 80 % of the influence of the first track; train crossings are excluded. In a third assumption different train crossings are assumed.

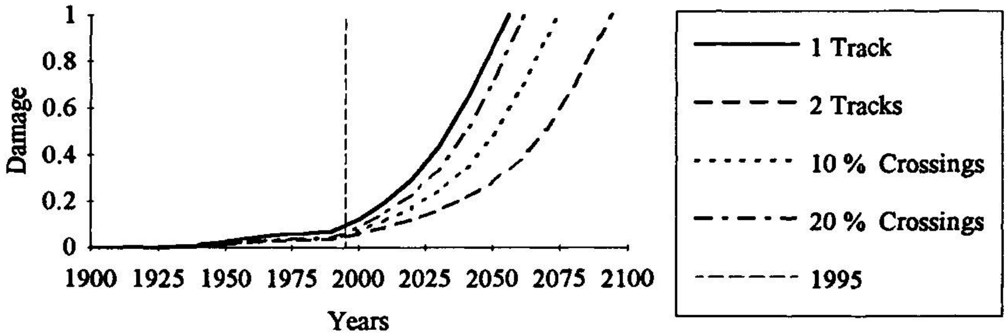

Figure 9 : Influence of parallel tracks and train crossings

CONCLUSIONS

The main foundings of the presented study can be summarized as follows:

1. For a reliable and effective assessment of the remaining fatigue life, three steps must be distinguished: Identification of Fatigue Critical Details - Calculation of the Remaining Fatigue Life - Monitoring of Fatigue Critical Details
2. For the calculations of the remaining fatigue life, a reliable and precise approach, based on fracture mechanics, called FM-Model, is presented. The prediction of remaining fatigue life with the FM-Model is much closer to the real behavior than with traditionally used approaches as the root mean cube method or the European S-N curves.
3. The applied stress ranges have a predominant effect on the remaining fatigue life. The stresses will normally overestimated with traditional static analysis. In order to elaborate a more realistic static model it is useful to carry out field measurements.

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