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Assessment of Condition and Future Service Life of a Railway Bridge

Appréciation de l'état et de la durée de vie résiduelle d'un pont de chemin de fer

Beurteilung von Zustand un Restnutzungsdauer einer Eisenbahnbrücke

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SUMMARY
The condition of an old steel railway bridge is investigated. The work comprises material testing, strain recordings, condition assessment with respect to fatigue and fracture, and a proposed inspection plan for extended service life.

RÉSUMÉ
L'état d'un ancien pont-rail en acier est examiné. Le travail comprend des essais de matériaux, des mesures de déformations relatives, l'appréciation de l'état de fatigue et de rupture. L'auteur propose un plan d'inspection pour une utilisation prolongée de l'ouvrage.

ZUSAMMENFASSUNG
Der Zustand einer alten Eisenbahnbrücke wurde untersucht. Die Arbeit umfasst Materialprüfung, Dehnungsmessungen, Schätzung des Zustandes hinsichtlich Ermüdung und Bruch, und ein Inspektionsplan zur Verlängerung der Restnutzungsdauer.

1. INTRODUCTION

This paper describes part of an investigation performed by the author under a contract with the Norwegian State Railways.

The structure is a riveted steel bridge built in the year 1900. The bridge was slightly modified in 1934. This modification involved welding, and these details attracted particular interest in the condition assessment, which is limited to fatigue and fracture considerations. In this paper only the most fatigue-prone detail will be treated, while the investigation encompassed various selected details.

2. MATERIAL DATA

Material for testing purposes was provided by replacement of a diagonal member in the horizontal stiffening truss. This was made of Siemens-Martin "fluss-iron". Results from the chemical analysis are given in Table 1. The metallographic investigation showed that the steel microstructure consists of ferrite and pearlite (7%), evenly distributed. The ferrite grain size was 25μm. Tensile testing gave the following result:

σ_y (R_{eH}) = 269 MPa, σ_u (R_m) = 410 MPa, Elongation (A) = 32.4%

Results from Charpy testing are given in Fig. 1. The fractured sections showed that brittle fracture dominated at all test temperatures, although at +20^{0}C some ductile fracture was present. The minimum temperature in the bridge is likely to be in the range -20 - -25^{0}C. At these temperatures the notch toughness is 6-7 J, which is lower than requirements to ensure a ductile failure mode [1]. CTOD-values were found by 3-point bending tests at -25^{0}C. Results are given in Table 2. All tests gave brittle fracture, although with some degree of ductility. The results are seen to demonstrate considerable scatter which is also common in modern steel [2, 3]. Crack growth testing yielded a slope of 2.39 and an intercept equal to -7.807.

3. LOADEFFECT

Strains were recorded at selected points in the structure, in order to establish the distribution of stress ranges. At these points the paint was removed by grinding, and strain gauges were glued on. The strain gauges were connected to data recording and processing units, which perform "rainflow" cycle counting and store the results in histogram form. The recordings were done continuously, with periodic inspection and "dumping" of stored data on a printer. In this way it was possible to decide whether statistical parameters and distributions had stabilized. Stabilization was used as an indication that sampled data represented the train-traffic of today.

4. NDI

Nondestructive inspection was carried out in a part of the structure. For the welded and riveted joints magnetic particle and ultrasonics were used respectively. No cracks were detected.

5. ASSESSMENT OF CONDITION AND REMAINING LIFE

The assessment pertains to the most fatigue prone type of detail, i.e. stringers with welded-on brackets (Fig. 2).

5.1 Stress analyses

Two finite element stress analyses were done. A 3D plate/shell-model yielded the stress concentrating effect at the bracket end, while a 2D plane strain model provided the stress concentration at the weld toe, and the stress distribution through the thickness of the stringer flange.

The weld was modelled with a throat size equal to the nominal size. The local geometry at the weld toe was described by an angle $\theta = 68^0$ and a radius $\rho = 1.8$ mm (Fig. 3). This local geometry was based on recordings of weld geometry. The geometry modelled is the "worst case" of those recorded.

The crack was assumed to initiate at the weld toe (A), and propagate through the flange. For simplicity the crack path was assumed to grow in mode I. Thus, stresses normal to the crack plane (A-A') was employed. This is thought to be a reasonable approximation [4].

5.2 Fracture mechanics analysis

Computations were based on LEFM. The crack propagation life was computed according to the expression:

$$N_p = \frac{1}{C\Delta\sigma_{eq}^m} \int_{a_i}^{a_f} \frac{da}{G(a)(\sqrt{\pi a}\cdot F(a))^m} \qquad (1)$$

where: m = crack growth exponent (Paris eqn.)
C = crack growth coefficient (Paris eqn.)
$\Delta\sigma_{eq}$ = equivalent CA stress range, based on the stress range histogram
$G(\cdot)$ = threshold factor [5]
$F(\cdot) = F_E F_S F_T F_G$ [6]

The crack growth parameters were obtained from the test results. A conservative value of C was obtained by adding 2 standard deviations (log) to the mean value from the regression analysis. Thus, $m = 2.39$ and $C = 2.84\cdot 10^{-11}$ (MPa, m, m/cycle).

A semielliptic surface crack at the toe of the weld at the bracket end was considered. The crack shape, a/2c varies during crack growth. This was taken care of by employing the empirical relation [7]:

$$2c = \begin{cases} 9.29a & ;\ a < 1 \text{ mm} \\ 6.71+2.58a; & a > 1 \text{ mm} \end{cases} \qquad (2)$$

The initial crack depth was taken to be $a_i = 0.25$ mm. This is ten times the material grain size, which is a suggested lower limit for the applicability of LEFM to describe crack growth [8].

The critical crack size was estimated at -25^0C. Welding residual stresses equal to σ_y were included, and no account was taken of stress gradients. A calculation based on the CTOD-criterion in PD 6493 [9] yielded a max allowable crack depth, $a_{max} \approx 12$ mm. The minimum value of 5 test values was used for δ_c.

5.3 Condition and remaining life

The fatigue life given by SN-curves is approximately equivalent with the number of cycles required to initiate a crack and propagate it until penetration.

The ECCS recommendations [10] classify the actual detail as category 50. The actual stress range histogram then gives a fatigue life, $T_{SN} = 67$ yrs.

Fracture mechanics computations with $\Delta K_{th} = 3.0 \text{ MNm}^{-3/2}$ and $a_f = 20$ mm (=flange thickness) yielded $T_p' = 41$ yrs. Hence, the initiation period was estimated to be

$$T_I = T_{SN} - T_p' = 67-41 = 26 \text{ yrs}$$

The propagation period for the actual case, with $a_f = 12$ mm was found to be $T_p = 34$ yrs. The fatigue life is then given as:

$$T_f = T_I + T_p = 26 + 34 = 60 \text{ yrs}$$

The structural detail under consideration was made in 1934. Thus, in 1987 it has been in service for 53 yrs, i.e. the residual life being 7 yrs.

6. INSPECTION PLAN FOR EXTENDED SERVICE LIFE

6.1 Safety requirements

A safety index $\beta = 3.5$ is recommended if general failure may be triggered by a local failure [10]. This yields the following approximate failure probability:

$$P_f \approx \Phi\,(-\beta) = 1 - \Phi(3.5) = 2.3 \cdot 10^{-4} \qquad (3)$$

where $\Phi(\cdot)$ is the standard normal distribution.

6.2 Probability of failure

In order to satisfy safety requirements an expression for the failure probability must be established which accounts for inspection, e.g. [11]:

$$P_f = 1-[1- \prod_{j=1}^{k} (1-P_D(l_j)\cdot P(I))]^m \qquad (4)$$

where:
- P_f = probability of failure
- $P(I)$ = probability of inspection
- $P_D(l_j)$ = probability of detecting a crack with length l_j
- l_j = crack length at j'th inspection
- k = number of inspections
- m = number of cracks

This formula expresses the probability of (during k inspections) not detecting all cracks in the structure before they reach critical size. This pertains to cracks that grow from a tolerable to a critical size during the service period.

6.3 NDI plan

Stringers with welded-on brackets should be inspected with magnetic particle. The detection probability curve given in Fig. 4 is a lower bound to data in [12]. All details of the actual type should be inspected, i.e. P(I) = 1.0. The 1st inspection should be performed no later than 1994.

Details with crack detection should be repaired/strengthened by e.g. HSFG bolts and tension flange splicing plates [13].

At each detail with no crack detection at 1st inspection, one crack with surface length 6 mm is assumed present. This yields a crack growth period of about 28 yrs until fracture, Fig. 5. Thus, after the 1st inspection the bridge can remain in service for about 28 yrs without compromising safety, if the proposed inspection plan is adopted.

The number of inspections during the extended service life period was determined from Eq. (4), which for the actual case yields

$$P_f = 1 - [1 - \prod_{j=1}^{k} (1-0.99\cdot 1.0)]^{40} = 1 - [1-(0.01)^k]^{40}$$

as the number of details is 40, i.e. m = 40. To satisfy the requirement $P_f < 2.3\cdot 10^{-4}$ three inspections are necessary. The crack growth period T_p ($\approx$ 28 yrs) is divided into intervals in such a way that the crack growth increment in the depth direction is the same in all intervals. In this way inspection intervals are determined, Fig. 6.

7. SUMMARY

Data on material, local geometry and load effect for an existing bridge have been obtained and used in a fatigue and fracture condition assessment. In this assessment the traditional SN-Miner approach was combined with the LEFM approach. Simple probabilistic concepts have been employed in order to control reliability during an extension of service life.

8. ACKNOWLEDGEMENTS

Chief engineer P. Hektoen at the Bridge Division of the Norwegian State Railways is gratefully acknowledged for the permission to publish this paper.

% C	0.10	% Al	0.001
" Si	0.01	" Cu	0.17
" Mn	0.53	" Mo	0.01
" P	0.044	" Nb	0.001
" S	0.072	" V	0.01
" N	0.009	" Ti	0.001
" Cr	0.01	" Sn	0.015
" Ni	0.03		

Table 1 Chemical analysis

Specimen no.	CTOD (mm)
1	0.56
2	0.19
3	0.74
4	0.25
5	0.39

Table 2 CTOD test results at -25^{0}C

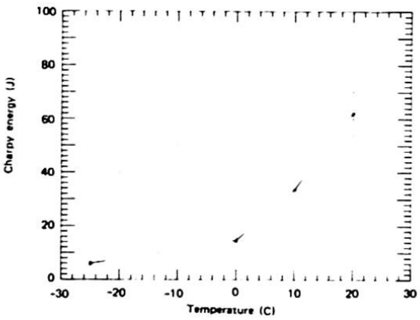

Fig 1 Charpy energy vs temperature

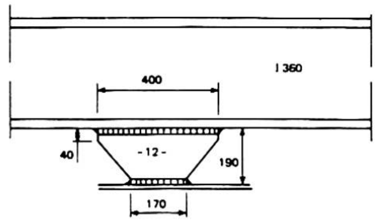

Fig 2 Stringer with welded on bracket

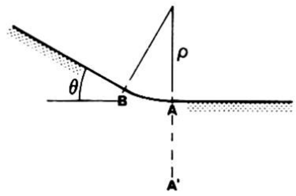

Fig 3 Weld toe geometry

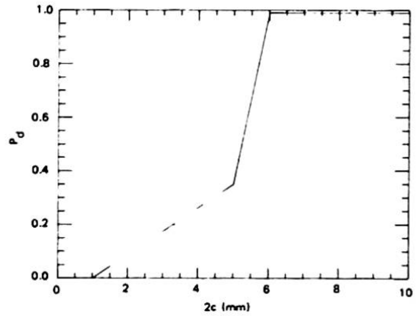

Fig 4 Detection probability (Magnetic particle)

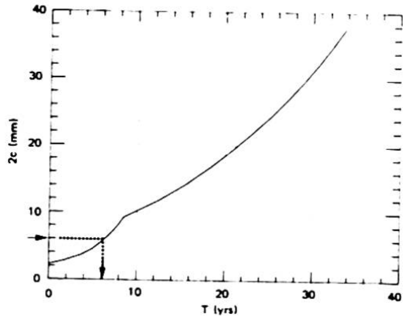

Fig 5 Crack length vs time

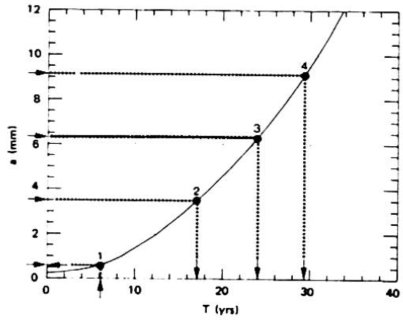

Fig 6 Crack depth vs time

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