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Influence of Loadings on the Fracture Toughness of Older Structural Steels

Influence des charges sur la fragilité à la rupture d'anciennes structures métalliques

Lasteinfluss auf die Bruchzähigkeit älteren Baustahls

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SUMMARY

Full scale rolled wide flange beam elements taken from dismantled railway bridges, and extracted small laboratory fracture toughness specimens have been used to study the influence of quasi-static loading rates and temperature upon fracture toughness. It is found that quasi-static loading rates affect fracture toughness of older structural steels significantly both at summer and winter temperatures.

RÉSUMÉ

Des éléments de profilés laminés à larges semelles, découpés dans des ponts-rails démantelés, et de petites éprouvettes de laboratoire ont été utilisés pour étudier l'influence du taux de charge quasi-statique et de la température sur la fragilité de la rupture d'anciennes structures métalliques. Il a été constaté que la fragilité est affectée de manière significative par ce taux de charge, aussi bien à des températures estivales qu'hivernales.

ZUSAMMENFASSUNG

An herausgeschnittenen Breitflansch-Walzträgerstücken, die von demontierten Eisenbahnbrücken stammten, und aus ihnen gewonnenen kleinen Bruchmechanikproben wurde der Einfluss quasi-statischer Belastungsraten und der Temperatur auf die Bruchzähigkeit untersucht. Es zeigte sich, dass quasi-statische Belastungen die Bruchzähigkeit älteren Baustahls sowohl bei Sommer- als auch bei Wintertemperaturen signifikant beeinflusst.

1. INTRODUCTION

Most structures in service are subjected to quasi-static loading conditions. We have found experimentally that typical loading rates in railway bridges of ordinary structural steel affect fracture toughness and structural reliability. This kind of influence has not been reported widely in quantitative terms in the literature, particularly in the elastic-plastic range. Quasi-static means in this context loading rates just above the maximum rate stipulated in current fracture toughness testing standards, e.g. ASTM E813 [1], but not high enough to involve effects of inertia.

For structures in cold climate regions with winter temperatures frequently down to -30 °C and below, it is of vital importance to understand the combined effect temperature and loading rate upon fracture toughness of structural steels. The ductile-to-brittle transition of ferritic steels with decreasing temperature under static loading conditions is a well-known phenomenon.

The concept of transferability plays an important role in evaluation schemes of existing structures. The aim of fracture toughness testing is to evaluate structural reliability with respect to fracture from data obtained with small standard laboratory specimens. In this work we present experimental results from quasi-static fracture toughness testing of fatigue precracked full scale beam elements from dismantled railway bridges and of extracted Compact tension and Three point bend specimens.

2. MATERIAL

The test material comprised three broad flange I-beams. Two beams (Beam I, DIP 55 and Beam II, DIP 42 1/2) were taken from dismantled railway bridges and one St37 Class D beam (Beam III, HEB 400) was acquired directly from the manufacturer and used as reference material. Tensile properties are shown in Table I. The chemical composition of the steels are typical for carbon steels.

Table I. Tensile properties.

Beam	R_{eL} (MPa)	R_m (MPa)	A_5/A_{10} %	Z %	T (°C)
I	224	380	30	70	+ 20
II	300	480	33		- 30
III	283 295	442 470	34 33		+ 20 - 30

3. EXPERIMENTAL

Full scale precracked 6 m long elements of Beam II and III were cooled to the testing temperature -30 °C and slowly loaded to failure in four point bending. Precracking, experimental details and the results of the static tests has been described elsewhere [2].

After static failure, one of the beam halves of each beam was precracked as above with an edge crack at its midsection and cooled to the testing temperature. The beam element was loaded to failure in three point bending at the maximum obtainable loading rate in a 10 MN servo-hydraulic closed loop testing machine. The distance between the outer supports was equal to or just above four times the beam height. During testing were recorded the load and load point displacement plus some fifteen strains, displacements and temperatures.

A series of standard Compact and Three point bend specimens were tested, except the loading rate, in accordance to ASTM E813. The laboratory specimens were machined from the flanges of the beam elements. Specimen thickness was always equal to the full flange thickness in order to obtain the best estimate of the effective toughness of the flange material. The loading rates were based on measurements on railway bridges in service, generously provided by the Swedish National Rail Administration [3].

For materials with a considerable non-linear behaviour before fracture, it is always difficult to detect the point of initiation of stable crack growth. The standard unloading compliance technique cannot be used for the present loading rates. A scanning electron microscope was used to investigate the amount of stable crack growth preceding the final fracture on the fracture surfaces.

Fracture toughness was calculated from the area under the load-displacement curves to the maximum load using the equation for the three-point bend specimen $J_c = 2A/(Bb)$, where A is the area under the load-displacement curve, B specimen thickness and b remaining ligament. J_c is considered valid if the specimen meets the ASTM thickness requirement.

4. RESULTS

Crack lengths, loading rates and fracture toughness results for static and quasi-static testing of the beam elements II and III are summarized in Table II. The results of the static testing of the full scale beam elements are discussed in [2]. The points of interest for the present work are summarized here. The J-integral for the Beam III geometry is for convenience shown in Fig 1.

Table II. Effect of Loading rate, Full scale Beam elements, Temperature -30 °C.

Beam	Load. rate	Crack length (mm)	dσ/dt (MPa/s)	dK/dt (MPa √m/s)	Jc (kN/m)	Note
II	static quasi-static	38 78	2 385	1 220	(>100) 41	Buckled Brittle
III	static quasi-static	70 60	2 510	1 254	93	Ductile Brittle

The Beam II element rather buckled than failed through fracture because the crack was shallow and the beam geometry deficient towards one of the beam ends. The Beam III element failed through unstable fracture. The fracture toughness of the beam element is close to the lower limit of the scatter band of the extracted specimens.

In the quasi-static test the Beam II element failed in a very brittle manner. The fracture was fast and unstable and the fracture surfaces show all the characteristics of a brittle fracture. They are flat and normal to the nominal bending stress, there are no shear lips and chevron markings run to the point of initiation at the tip of the fatigue crack. The beam element failed at a nominal bending stress 158 MPa or 53 percent of the yield stress. The quasi-static fracture toughness is less than half of the lower limit for static testing of the extracted specimens.

In the Beam III element the loading rate was somewhat higher than in Beam II. This beam element failed also in a very brittle manner as described above. The beam halves were however free to move just enough to hit and short-circuit a data acquisition cable. Therefore no data were registered for this experiment. We are left with the impression of the laboratory staff that this beam was much more brittle than in the static test.

The static fracture toughness results obtained with extracted specimens from beam elements II and III are given in full in [2]. The static fracture toughness is typically 120 - 300 kN/m for specimens from both beams.

The influence of the loading rate upon the fracture toughness of specimens extracted from Beams II and III is shown in Fig 2. The number of specimens from Beam III (but not from Beam II) is great enough to indicate the decreasing trend of the fracture toughness with increasing loading rate. However, at some increased loading rate, which is not necessarily the same for the Beam II and III steels, the quasi-static fracture toughness is reduced to approximately 15 - 25 percent of the static fracture toughness.

The fracture toughness as a function of loading rate obtained with three point bend specimens extracted from Beam I is shown in Fig 2. Some typical load-load point displacement plots for the fracture toughness tests at -30 °C and +20 °C are compared in Figs 3.

For the specimens tested at -30 °C, the non-linear material behaviour prior to fracture was principally observed at low loading rates. The increase in loading rate from 1 to 250 MPa√m/s, caused a decrease in fracture toughness in the order of two thirds. Further increase in loading rate up to 1588 MPa√m/s gave only a minor decrease in fracture toughness.

The effect of loading rate at +20 °C is more complex. Here stable crack growth of varying extent occurred before fracture. At low loading rates the load point displacement curves were linear up to a first critical load beyond which the load continued to increase at a lower rate. In some cases a local maximum occured at this critical load after which the load begun to increase again. Unstable crack growth was principally observed at a second critical load maximum.

5. DISCUSSION

The extracted specimens from the beam elements were always made to the full thickness of the beam flanges from which they were taken. In [4] it was shown that this is necessary to obtain the best estimate of the effective toughness for a structural element of an inhomogeneous material in which the toughness varies across the thickness. This and the condition that specimen and full scale element constraints agree reasonably have been shown in [4] to be two necessary conditions for transferability under static loading.

The major reduction of toughness occur in the loading rate 1- 250 MPa√m/s. Only a minor further reduction of toughness occur for higher loading rates up to 1588 MPa √m/s. This trend is in general accordance with observations of Krabiell and Dahl [5] for steel Fe E 510 and by Yongning and Huijiu [6] for a C-Mn steel.

The effect of loading rate at +20 °C is more complex. Here stable crack growth of varying extent occurred before fracture. At low loading rates the load versus load point displacement curves were linear up to a first critical load beyond which the load continued to increase at a lower rate. In some cases a local maximum occurred at this critical load after which the load begun to increase again. Fracture occurred at a second critical load which was always greater than the first.

The first critical load is associated with the development of a plastic hinge mechanism in the specimen ligament and probably also with the onset of stable crack growth. At high loading rates the first critical load increased somewhat but beyond this point, the load decreased with increasing displacement until fracture followed.

In real structures the loading is controlled rather than displacement. If a structural element is loaded to first critical load and slightly beyond, e.g. due to a growing fatigue crack,

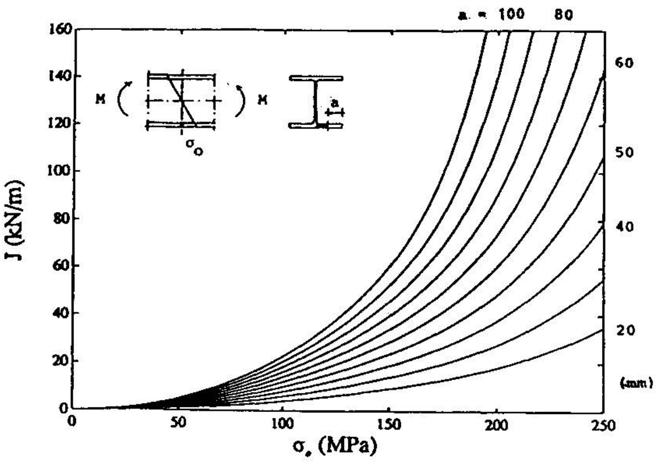

Fig. 1 Crack driving force J versus nominal stress s_o for beam HEB 400.

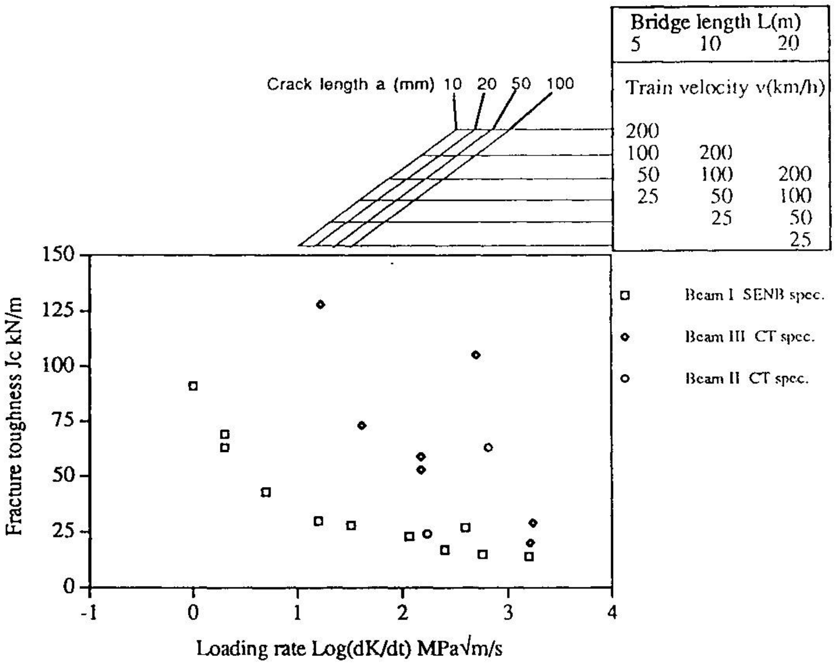

Fig.2 Comparsion of experimental results at the temperature -30 °C with loading rates in bridges.

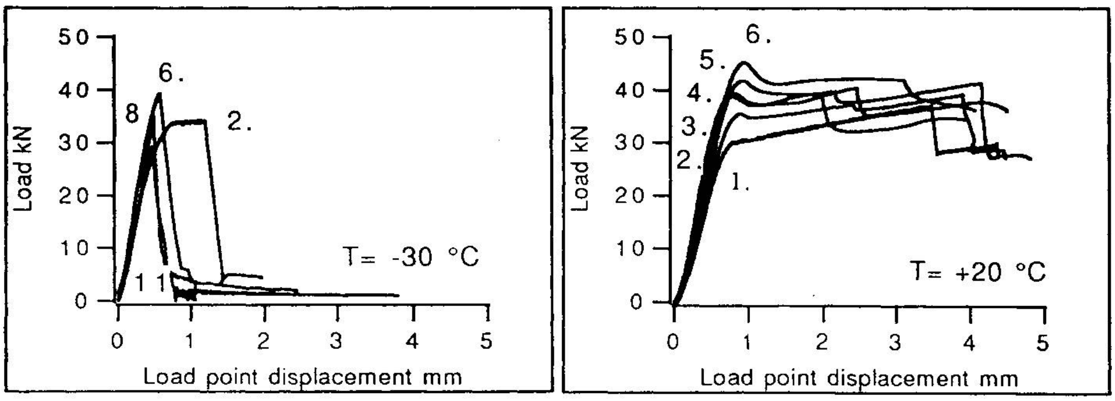

Fig.3 Load-load point displacement behaviour of fracture toughness tests at -30 and +20 °C as a function of loading rate. The loading rates at -30 °C are for **2.** 2, **6.** 33, **8.** 250 and **11.** 1588 MPa√m/s. The loading rates at +20 °C are for **1.** 2, **2.** 100, **3.** 280, **4.** 670, **5.** 1611 and **6.** 4115 MPa√m/s.

only an increased permanent deformation will occur at low loading rates. At best this will serve as the necessary warning that something unusual is going on and allow retrofit. At high loading rates, on the other hand, the situation becomes unstable at the load maximum associated with the first critical load. When this load is attained the structural element will collapse.

However, this behaviour is observed in small bend specimens while typical crack geometries in real structures are loaded in tension. The behaviour of e.g. a full scale beam element in this respect is therefore not necessarily the same. To study the transferability of this kind of behaviour is the subject of a future study.

For quasi-static loading we have in fact so far just one single data point, from Beam II, which however fit the general pattern very well. We therefore conclude that the reduction of fracture toughness due to increased loading rate in a full scale structure can be predicted from data obtained with extracted specimens. Whitout proving the contrary we assume that full thickness specimens are necessary for inhomogenous materials also in the quasi-static case.

The present results show that ordinary train speed and winter temperatures reduces fracture toughness to values that might be critical for the integrity of a structure. The results of this work also show that increased safety is obtained at low train speed not because of reduced loading but because of increased material toughness. On the other hand, increased maximum train speed means decreased safety.

Conclusions

The experimental results indicate that a) transferability in this particular case of full scale beam elements and quasi-static loading rates investigated is good enough for engineering applications and b) that the quasi-static loading rate along with temperature should be taken into account to obtain an accurate measure of fracture toughness and reliability of structures of ordinary structural steels.

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