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Toughness Evaluation and Assessment of Old Bridge Steel

Estimation et évaluation de la ténacité de l'ancien fer puddlé

Bestimmung und Bewertung der Zähigkeit alter Brückenstähle

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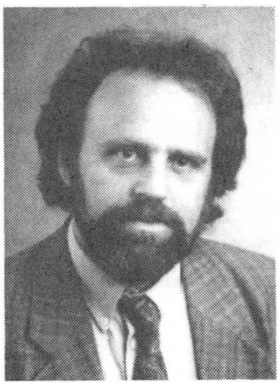

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SUMMARY

Compared with the current requirements concerning toughness, the Charpy fracture ener-gy of old bridge material, especially wrought iron, is extremely low. In order to determine sufficient safety of these bridges with respect to spontaneous fracture, a simplified failure assessment based on fracture mechanics principles is recommended. A practical metho-dology to determine and to assess fracture toughness is developed and presented in this paper, which takes the special fracture behaviour of wrought iron into account.

RÉSUMÉ

Dans le cas des aciers d'anciens ponts, particulièrement en fer puddlé, la ténacité mesu-rée par l'essai Charpy est extrêmement basse. Pour évaluer la sécurité à la rupture spon-tanée, on a recours à une analyse simple basée sur des lois en mécanique de rupture. Le présent travail propose une méthode pratique d'estimation et d'évaluation de la ténacité, laquelle tient compte du comportement à la rupture du fer puddlé.

ZUSAMMENFASSUNG

Im Vergleich mit den entsprechenden Anforderungen an die heutigen Baustähle ist die Kerbschlagarbeit von Schweisseisen, dem typischen Werkstoff alter Brücken, äusserst tief. Zum Nachweis einer genügenden Sicherheit gegen Spontanbruch wird deshalb empfohlen, eine approximative bruchmechanische Analyse durchzuführen. Es wird eine praxistaugliche Methode zur Bestimmung und Bewertung der Bruchzähigkeit vorgestellt, die das spezielle Bruchverhalten dieser Werkstoffe berücksichtigt.

1. INTRODUCTION

An important part of the integrity of steel structures is the material's toughness, which has to be high enough to exclude the possibility of spontaneous brittle fracture even under the most unfavorable loading conditions. For this reason, in most of today's design standards for steel construction toughness requirements are given, in most of them in terms of Charpy fracture energy. When the safety of old steel bridges has to be assessed, these criteria often lead to difficulties: The Charpy fracture energies of these materials, especially of materials like wrought iron, which is very common for bridges that are about 100 years old, are often not high enough to meet the requirements of these standards. Furthermore, old bridges are likely to be affected by additional unfavorable factors with respect to brittle fracture, like local corrosion, unknown fatigue damage (hidden by the rivet heads and hardly detectable by nondestructive testing methods), low temperature, aging effects due to local plastic deformation, and possibly increased loading rates. So the question of the safety of the structure and whether or not the low Charpy fracture energy of these materials can be tolerated needs to be comprehensively investigated. For this purpose its is recommended to perform - complementary to the standard stress and strain analysis - a fracture mechanics analysis, which is in line with modern standards like e.g. Eurocode 3 [1].

In a fracture mechanics analysis, the applied stress intensity factor at a hypothetical crack, K_I, is compared with the fracture toughness K_{Ic} of the material (see e.g. [2]). In [3] it is shown that the fracture toughness of wrought iron is relatively high, at least higher than what is expected from the low Charpy fracture energy, indicating that the well known correlation formulas between Charpy energy and fracture toughness give overconservative predictions of the latter for this kind of material [4, 5]. Therefore it is advisable not to rely on such correlations but to perform direct fracture toughness tests. Unfortunately, such tests are in general rather time consuming and costly, and often there is not enough testing material available to determine the fracture toghness under all the relevant loading conditions the structure is subjected to in service. For these reasons testing on small specimens, especially instrumented impact tests on precracked Charpy specimens, are advantageous. However, there are two major problems arising when doing such tests: First, there is not yet a standard or generally accepted evaluation procedure available, and second, the loading rate is in general much higher than in service, so there must be a reliable way to compensate for this effect. At EMPA, simplified procedures for these purposes have been recently developed [6, 7, 8]. Nevertheless, due to the special fracture behaviour of old bridge materials like wrought iron that will be discussed in this paper, these evaluation procedures need some modifications and adjustments when applied to these materials. Another important point that is also affected by the special fracture behaviour is the required fracture toughness. Regarding the typical inhomogenity of wrought iron and the corresponding pronounced scatter of the toughness values, it is suggested to use an additional requirement which reflects not only the initiation but also the propagation resistance of cracks.

In this paper the above mentioned topics are discussed and illustrated with some examples. Simple formulas to be used in practical applications are presented. For their mathematical derivation, reference is given to further publications of the author, where also additional references can be found.

2. FRACTURE BEHAVIOUR OF WROUGHT IRON

Compared with today's structural steel there are several differences in the fracture behaviour of wrought iron. Concerning the Charpy (CVN) test results, the most striking ones are the low magnitudes of the upper shelf CVN-energies, the relatively high temperature (40°-80°C) where the upper shelf regime begins, and the large width of the brittle-to ductile transition temperature range, which results in a relatively low slope of the transition curve. In the transition regime, the force vs.

deflection diagram exhibits some noteworthy qualitative differences as well, as schematically shown in Fig. 1: Whereas ordinary steel in the brittle-to-ductile transition range (Fig. 1, (a)) exhibit a sudden steep fall at a certain (temperature-dependent) deflection due to unstable brittle cleavage crack growth, curves of wrought iron (Fig. 1, (b)) decrease more or less continuously after the maximum force, indicating a macroscopically stable crack growth behaviour (see Fig. 5 for an example). The fracture energy consumed in the crack initiation phase (i.e. area under the load-deflection-curve up to about maximum load) is very small compared with the propagation energy (after about maximum load) in the case of wrought iron, and a sharp corner at maximum load is formed, indicating a relatively sudden and well defined transition from crack-tip-blunting to crack propagation. In the upper shelf and lower shelf range, the shape of the curves is qualitatively the same for both types of materials.

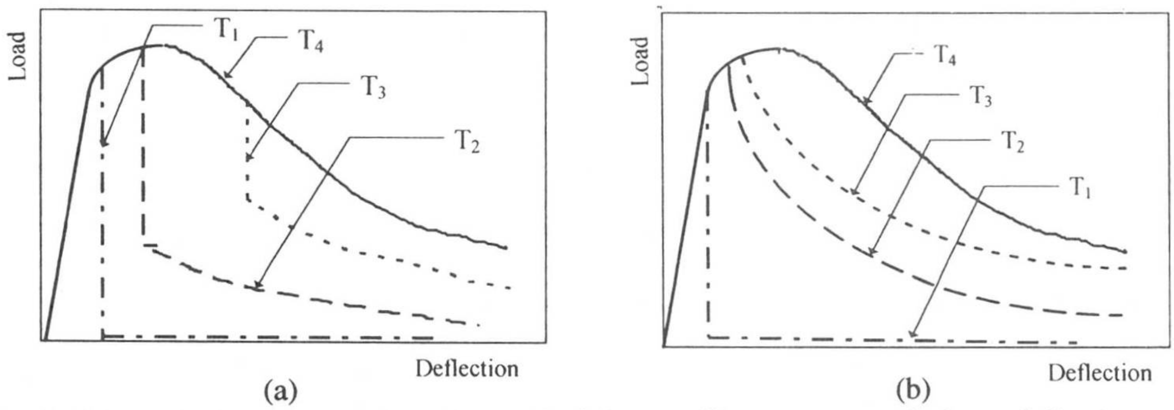

Fig. 1: Schematical representation of smoothed (i.e. oscillations removed) force-deflection curves of ferritic steel (a) and wrought iron (b) at four different temperatures $T_1<T_2<T_3<T_4$.
T_1: lower shelf; T_2: lower transition range; T_3: upper transition; T_4: upper shelf

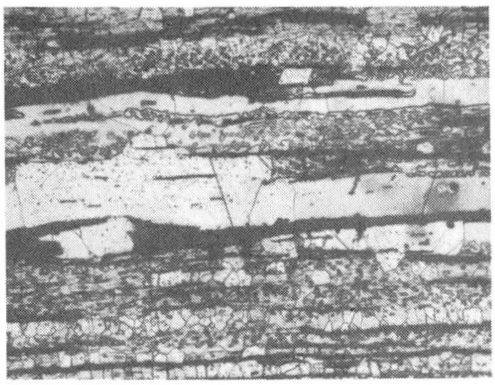

Fig. 2: Microstructure of wrought iron (L-S orientation, magn. 50x)

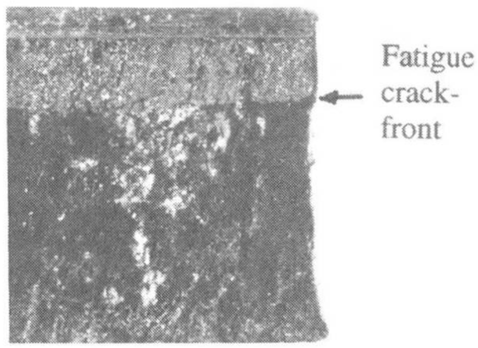

Fig. 3: Fracture surface of a precracked (L-T) Charpy specimen in the upper transition range

This fracture behaviour of wrought iron is attributed to the characteristic lamellar or fibrous microstructure of the material and its large content of nonmetallic inclusions (see Fig. 2). This leads to a fibrous, "wood-like" fracture surface in the upper shelf regime. In the transition regime, there is not a single crystalline area on the fracture surface like in the case of normal structural steel, but a number of small zones of cleavage fracture (bright spots in Fig. 3). The lower the temperature, the higher is the total area of these brittle spots, explaining the decreasing crack propagation energy with decreasing temperature as visible in Fig 1 (b). The relatively sharp corner of the load-displacement curve at maximum load is explicable by the various local cleavage events concentrated near the fatigue crack front. The macroscopic stability of the subsequent crack growth can be explained by the ability of the microstructure to arrest the local unstable cleavage cracks, which is possible by delamination and crack branching, and the corresponding reduction of local constraints as the crack propagates. Thus, the effect of the characteristic lamellar and inhomogenious microstructure with its statistically distributed local brittle zones is twofold: On one hand it is responsible for the relatively low and scattering initiation toughness K_{Ic} (depending on whether or not a local brittle zone is present near the original crack-tip), on the other, it prevents a macroscopically unstable cleavage fracture from being triggered by the local cleavage events. So there is sort of a balance between beneficial and unbeneficial effects that should be appropriately accounted for in a failure assessment analysis.

3. EVALUATION OF FRACTURE TOUGHNESS BY INSTRUMENTED PRECRACKED CHARPY-TYPE TESTING

Instrumented impact testing on precracked Charpy specimens is very advantageous in terms of material needs and testing time consumption, especially for tests at different temperatures. Their drawback is that there is no "exact" or generally accepted procedure to determine fracture toughness from these tests. In [7] and [8] a simplified single specimen evaluation procedure is suggested. The following formula allows the approximate determination of K_{Ic} throughout the complete transition range including upper and lower shelf:

$$K_{Ic} \cong \left[\frac{0.85 \cdot F_m^2 \cdot l^2}{B^2 \cdot (W-a)^3} + \frac{4 \cdot E}{B \cdot (W-a)^{3/2}} \sqrt{U_{mp} \cdot U_t \cdot 0.2mm} \right]^{1/2} \tag{1}$$

F_m denotes the maximum force measured by the instrumented tup, U_{mp} the plastic (non-recoverable) part of the fracture energy at F_m, U_t the total fracture energy, E Young's modulus, B and W the specimen thickness and height, respectively (both =10 mm for standard Charpy geometry), and a (>0.3W required) the initial fatigue crack length (Fig. 4). In the case of wrought iron, the plastic part of the absorbed energy at maximum load is often much smaller than the elastic part, so it can hardly be determined accurately from the test diagram. For this reason, we suggest to modify eq. (1) by replacing U_{mp} by the total energy U_m at maximum load. The latter includes, as one can show, the first term of eq. (1), which represent the elastic component of the measured K_{Ic}, so this term can be omitted. Physically, this modification is justified by a virtual rounding-off of the load vs. deflection curve in the region of maximum load, as indicated by the dotted line in Fig. 5. One obtains:

$$K_{Ic} = \left(\frac{4 \cdot E}{B \cdot (W-a)^{3/2}} \cdot \sqrt{U_m \cdot U_t \cdot 0.2mm} \right)^{1/2} \tag{2}$$

The apparent advantage of this approximate evaluation formula (2) is its simplicity and unambiguity. The only parameters that have to be determined from the force-displacement diagram are the two well defined energy values U_m and U_t (see Fig. 5). Thus, (2) is well suited for automatic evaluation by means of a computer program. Note that in case of very small U_m, the kinetic energy of the specimen, which can be easily estimated, should be subtracted from U_m.

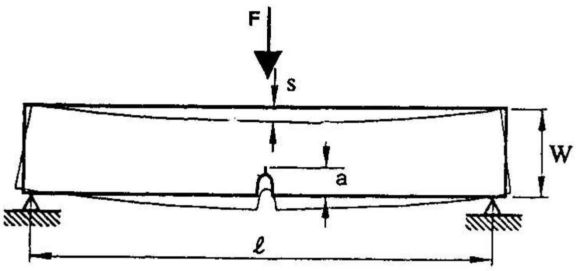

Fig. 4: Mechanical system of an impact bending test on precracked CVN- specimen

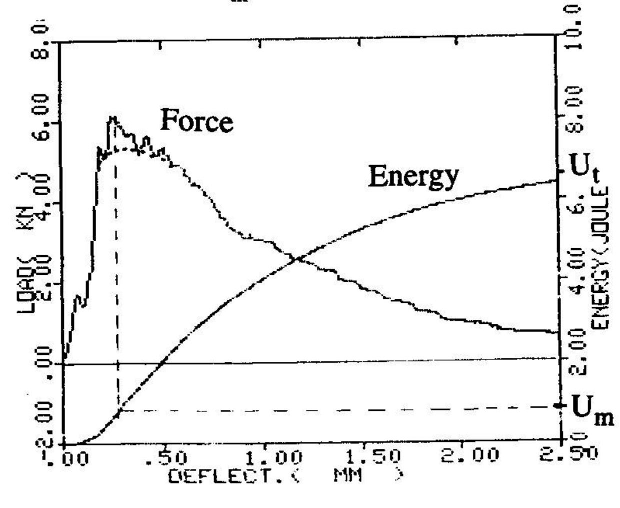

Fig. 5: Example of force (smoothed) and energy as a function of deflection, and definition of test data U_m and U_t used in eq. (2)

4. TEMPERATURE SHIFT DUE TO LOADING RATE

The crack-tip loading rate expressed in $\dot{K}_I$ is usually much higher at impact testing than in the relevant parts of the real bridge. Therefore the effect of the lower loading rate should be accounted for when transferring the toughness data from the test specimen to the real structure. Lowering the loading rate causes a shift of the K_{Ic}-vs.-temperature curve towards lower temperatures [6]. The relation between the brittle-to-ductile transition temperature, T_t, (defined as the temperature at which the fracture toughness equals a certain value K_t, usually K_t=100MPam$^{1/2}$), and the loading rate in terms of $\dot{K}_I$ is derived in [6]. Rearranging equation (2) of ref. [6] leads to the much simpler form

$$\log\frac{\dot{K}_I}{\dot{K}_{test}} = A_1 - \frac{A_2}{T_t(\dot{K}_I)} \tag{3}$$

A_1 and A_2 are material dependent constants that can be derived by performing impact tests at two different impact speeds $\dot{K}_{test}$. The latter can be roughly determined from the impact speed $\dot{s}$ by the formula

$$\dot{K}_{test} = \frac{2\cdot E\cdot R_p\cdot b_0\cdot \dot{s}}{K_t\cdot \ell} \tag{4}$$

The actual loading rate in service, $\dot{K}_I$, has to be estimated from the expected strain rate and a conservative assumption of a crack size. In cases where only tests at one impact velocities are performed, the temperature shift $\Delta T=T_t(\dot{K}_I)-T_t(\dot{K}_{test})$ can be estimated by the simplified relation

$$\Delta T = \left(22 - 0.016\cdot R_p\right)\cdot \log\frac{\dot{K}_I}{\dot{K}_{test}}\ (^\circ C) \qquad (R_p\text{: yield stress in N/mm}^2) \tag{5}$$

which follows as a first approximation of (3) and using the experimental results reported in [9]. Shifting the measured transition curve by the amount given by (5) or (3) to the left on the temperature axis delivers an approximation of the actual toughness-vs.-temperature curve, which can be used as the material data in a failure assessment procedure.

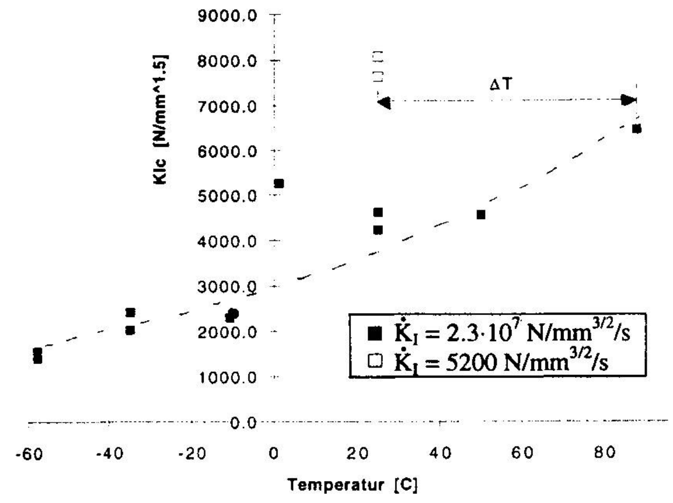

Fig. 6: Fracture toughness of wrought iron under two different impact velocities

In order to check the validity of (5) applied to wrought iron, impact bending tests on the material from a tensile rod of an old railway bridge were performed under impact speeds of 2.25 m/s and 0.5 mm/s, which correspond to crack loading rates $\dot{K}_I$ of 2.3·10^7 N/mm$^{3/2}$/s and 5200 N/mm$^{3/2}$/s, respectively. The yield stress was 273 N/mm^2, so eq. (5) predicts a temperature shift of ΔT=64°C. Fig 6 shows the K_{Ic} values as obtained using eq. (2). The temperature shift between the two loading rate can be estimated to be about 65°C, confirming eq. (5) Note the relatively large scatter of K_{Ic}.

5. ON THE REQUIRED TOUGHNESS

By the assumed condition that general yielding shall occur before onset of crack growth for any pre-existing crack, and using the so-called R6 failure assessment procedure [10] for the corresponding crack stability analysis, the following required toughness values K_{req} are obtained [11]:

- for plate-shaped components: $K_{req} = 1.38 \cdot R_p \cdot t^{1/2}$ (t: thickness) (6)
- for round rods under tensile loading $K_{req} = 2.08 \cdot R_p \cdot D^{1/2}$ (D: diameter) (7)

These values applied to the K_{Ic}-vs. temperature curve shifted by ΔT according to the previous chapter enables the lowest service temperature to be determined. Eq. (6) and (7) are applicable to any elastic-plastic materials, to modern structural steels as well as to wrought iron. In order to account for the relatively large scatter of K_{Ic} in the case of the latter, we recommend to use an additional criterion to make sure that there is enough crack growth resistance to stabilize crack growth in the case of unexpected initiation of local cleavage. In [12] a criterion to predict stability of tearing crack growth is derived. The key parameter therein is the crack tip opening angle (CTOA), which is related to (U_t-U_m) as shown in [4]. Using these relations and assuming the largest half-width of a hypothetical surface crack to be 4t results in the following criterion for stable tearing:

$$U_t - U_m \geq \frac{3 \cdot \pi \cdot B \cdot (W-a)^2 \cdot R_p^2}{E \cdot (1 - \sigma / R_p)} \tag{8}$$

In (8), σ denotes the maximum applied primary stress of the considered component in service.

6. CONCLUSIONS

- Wrought iron often exhibits Charpy fracture energies that are far below today's requirements. Nevertheless, thanks to its special microstructure, the fracture toughness and especially the crack growth resistance can be sufficiently high to guarantee safety with respect to brittle fracture.
- In order to assess the integrity of old bridges, it is recommended to perform a fracture mechanics analysis complementaryly to the standard stress analysis. For the testing part within such an analysis, instrumented impact tests on precracked specimens have proven to be very useful.
- The test evaluation procedure as well as the assessment methods developed for normal structural steel need some appropriate modification to account for the special fracture behaviour of wrought iron. The simple procedures presented in this paper allow for a simple as well as a reliable assessment of the materials toughness.
- The temperature shift due to loading rate is about the same as for normal steels.

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