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Toughness and Fracture Behaviour of Obsolete Wrought Bridge Steel

Résistance et comportement à la rupture d'anciens ponts en fer puddlé

Bruchzähigkeit und Bruchverhalten von Material alter Schweisseisen-Brücken

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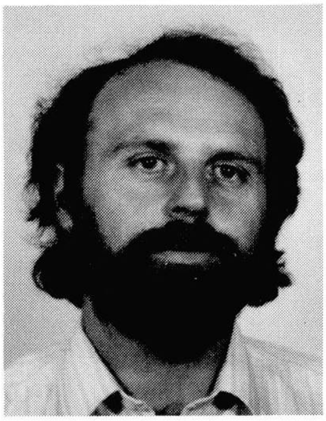

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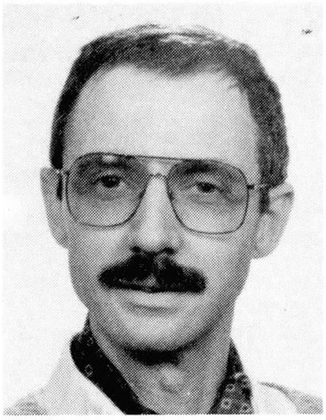

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SUMMARY
In old bridges the presence of fatigue cracks or sharp notches can hardly be excluded. Thus the question arises as to how the material behaves in presence of such defects. In the present paper, it is shown, using a case of a bridge made of wrought iron, how fracture mechanics enables some quantitative predictions concerning crack-sensitivity to be carried out.

RÉSUMÉ
Dans les vieux ponts en acier, on ne peut pas exclure complètement l'existence de défauts tels que des fissures de fatigue et des entailles. Il se pose alors la question de la sensibilité du matériau à de tels défauts. Dans cet article, on démontre pour le cas d'un pont en fer puddlé que la mécanique de la rupture fournit des indications quantitatives sur le comportement des zones fissurées.

ZUSAMMENFASSUNG
In alten Brücken kann das Vorhandensein von Ermüdungsrissen oder scharfkantigen Kerben selten ausgeschlossen werden. Es stellt sich deshalb die Frage nach der Fehlerempfindlichkeit des Materials. Im vorliegenden Bericht wird am Beispiel einer Brücke aus Schweisseisen gezeigt, wie sich mit Hilfe der Bruchmechanik einige quantitative Angaben zur Rissempfindlichkeit machen lassen.

1. INTRODUCTION

In Switzerland there is a fairly large number of approximately 100 year old bridges which are still in service. Most of them are riveted framework structures made of wrought steel. In order to be able to deal with problems like safety, reliability or remaining life of such structures it is important to know as much as possible about the actual mechanical and toughness properties of these materials.

Traditional elastic design of structural elements is based on classic stress analysis ("elastic" design) or on calculation of the plastic collapse load ("plastic" design). In the latter case the material is supposed to be able to deform plastically. In [1] a flow chart a systematic demonstration of the safety of a structure is presented. Based on ideas given in [2] it is suggested to proceed in three steps: classical design, failure analysis and failure assessment under extreme conditions at the end of the service life. Within such a safety analysis for obsolete steels material testing on the basis of fracture mechanics or related tests are of great importance for the designer.

In general there is not only the global strength and stability of the structure to be investigated, but also local problems like fatigue crack growth and residual strength of cracked components. Since there is only little known about fatigue crack growth, one can hardly exclude the possibility of cracks in critical components, typically e.g. a crack emanating from a rivet hole hidden by the head of the rivet. From the relatively poor properties related to ductility and toughness, like Charpy fracture energy and reduction in area, one must conclude a relatively low toughness [3, 4]. Thus there is a strong need to know as much as possible about the crack–sensitivity of the material, i.e. the behaviour of the material in presence of cracks or crack–like defects.

The adequate means for treating these kind of problems is the theory of fracture mechanics. Concerning wrought iron there is an apparent lack of knowledge in this field. It is the topic of the present investigation to get more insight in the fracture behaviour and fracture mechanisms of wrought iron in the presence of a sharp crack. First it is shown, how the fracture toughness of wrought iron was determined and by which parameters it is influenced, and how the material properties can be used to predict the fracture behaviour of structural elements.

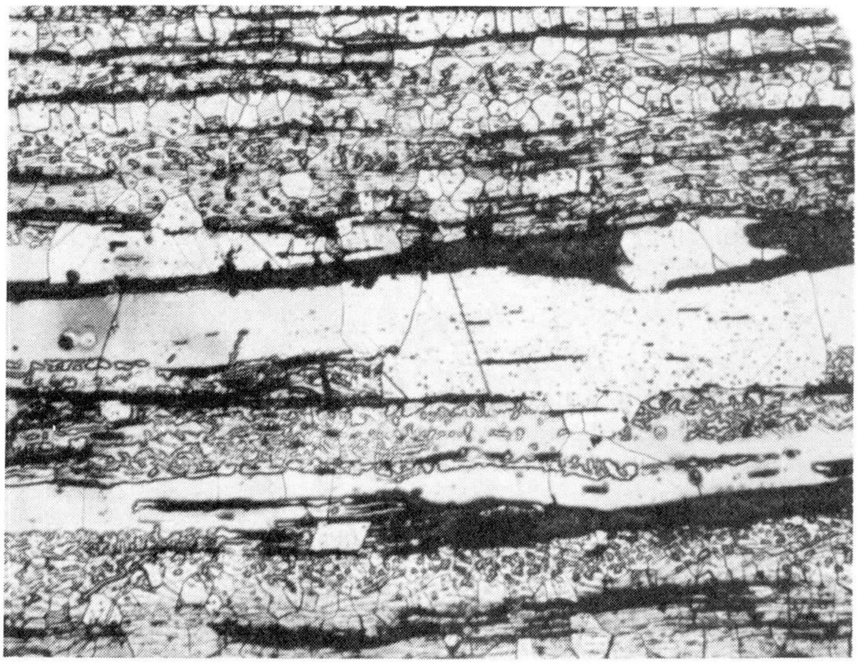

Fig. 1: Microstructure of wrought iron (magn. 50x)

2. MATERIAL

The characteristics of wrought iron is its layered structure, which is a result from the manufacturing process. It consists of sheet shaped layers of recristallized ferrite and of nonmetallic inclusions (Fig.1). Because of the anisotropy of the material several loading directions and crack orientations have to be differentiated in material testing. The present investigation is restricted to loading in axial direction and crack-extension in-plane (with respect to the material layers) and out-of-plane (crack type A resp. B, see Fig. 2). This structure can be clearly seen on the fracture surfaces of broken specimens, which exhibit a "wood-like" topography.

The mechanical properties in axial direction of the material used in the present investigation are given in Tab. 1. Concerning the yield stress and the ultimate tensile strength the material is comparable to an ordinary structural steel. The properties related to ductility and toughness, like elongation, uniform strain and reduction in area at fracture, are apparently lower than in the case of ordinary steel. The charpy impact energy is extremely low. Unlike ordinary structural steel there is only a minor increase of impact energy within the transition region. The fracture energy remains at relatively low values even for full ductile fracture. Thus the material appears to be considerably more brittle than common structural steel of today.

The relatively low uniform strain should be taken into account especially in cases of additional loads, short-term overloads, erection procedures, etc. Any modification which causes or requires plastic redistribution of stresses or plastic settlements should be avoided.

In other loading directions the ductility-related properties are even worse. This has to be accounted for e.g. in the case of repair. Any heat effect due to preheating, welding or oxy-arc cutting may transform the metallurgic structure such that the (favorable) anisotropy is destroyed. Since the content of sulfur, phosphorus and other impurities is relatively high, new brittle alloys may be formed by remelting. Therefore repair by welding should be omitted.

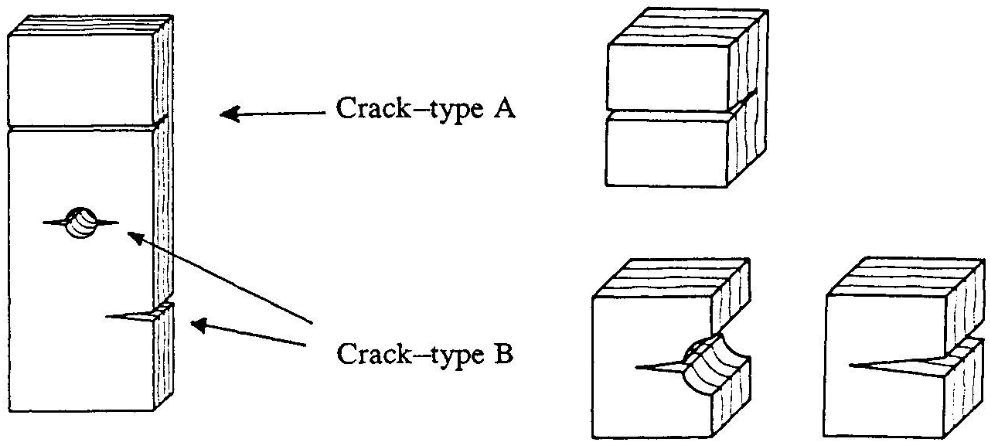

Fig. 2: Definition of crack-type A resp. B.

Yield stress [MPa]	Ultimate strength [MPa]	Elongation at fracture [%]	Uniform strain [%]	Red. in area [%]	Charpy impact energy (cr.typeA) [J]	
					RT	100°C
241	371	21	0 - 16	31	10 - 18	44

Tab. 1: Material properties of the investigated wrought iron

3.1. MATERIAL TESTING ON THE BASIS OF FRACTURE MECHANICS

3.1. General

In order to quantify the crack–sensitivity of the material and to predict the fracture behaviour of a structural component in presence of a crack or similar stress–raisers the theory of fracture mechanics is the adequate means. For an introduction in this field we refer to [5]. There are several parameters to characterize toughness in the sense of fracture mechanics, the most widely used being the critical stress intensity factor K_{1c}, the so–called plane strain fracture toughness, a factor which characterizes the resistance of the material against crack–growth. Although it looses its physical significance in the case of cracks in mild steel like wrought iron and of relatively thin–walled structural components like the typical structural members considered in the present investigation, it still is useful as a material property and also in order to perform a failure assessment analysis (e.g by applying the so–called R6–Method, see later in this article).

3.2. Determination of K_{Ic}

One of the difficulties in applying fracture mechanics to mild steels is the experimental determination of K_{1c}. Since large plastic straining occurs prior to forced crack growth, the underlying assumptions according to the theory of linear elastic fracture mechanics are no longer fulfilled. This problem can be circumvented by using the J–Integral concept. The J–Integral is a global parameter which relates the global loading of a component to the the magnitude of local plastic strain in the vicinity of the crack–tip, thus being capable to characterize the state of load of a crack. The critical value of J, denoted by J_{1c}, characterizes the state of onset of crack–growth.

The most straightforward way of determining J_{1c} is the one according to [6], which is similar to ASTM E813 [7]. These standards are based on the simple relations between energy–consumption and J in the case of a deeply cracked specimen in bending and tension, which were found by Rice et al [8].

In the present investigation CT– specimens of different sizes were used (Fig. 3). The crack extension was measured by the method of partial unloading [6, 7]. The crack–mouth–opening v is measured by a clip gage. An example of v in function of the load F is shown in Fig. 4. From these curve it is possible to calculate the so–called J–resistance–curve (J–R–curve) of the material. The J–R–curves resulting from the CT – tests are shown in Fig. 5. From a J–R–curve one obtains the critical J–Integral J_{1c} as indicated in Fig.5. Its values are given in Table 2. By the equation

$$K_{1c} = \sqrt{[E\, J_{1c}/(1-\upsilon^2)]}, \qquad (1)$$

the fracture toughness can be calculated (E denotes Youngs modulus and υ Poisson's number). The corresponding K_{Ic} are given in Tab.2.

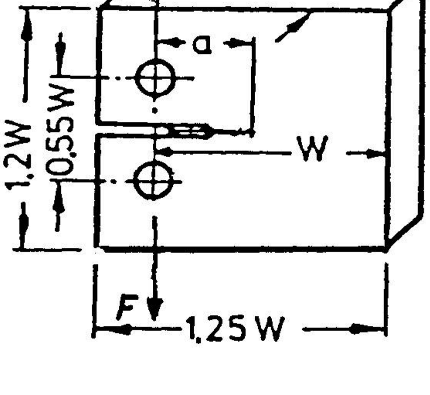

Fig. 3: Geometry of compact tension (CT–) specimen used. For dimensions see Tab. 2.

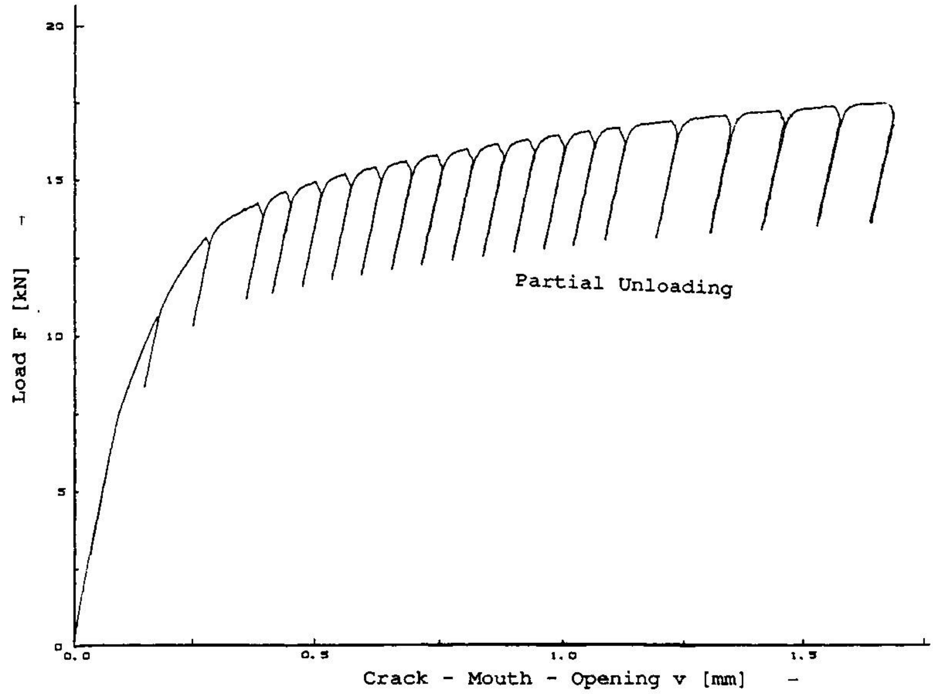

Fig. 4: Example of load vs. crack–mouth opening at load–line as measured on specimen W4

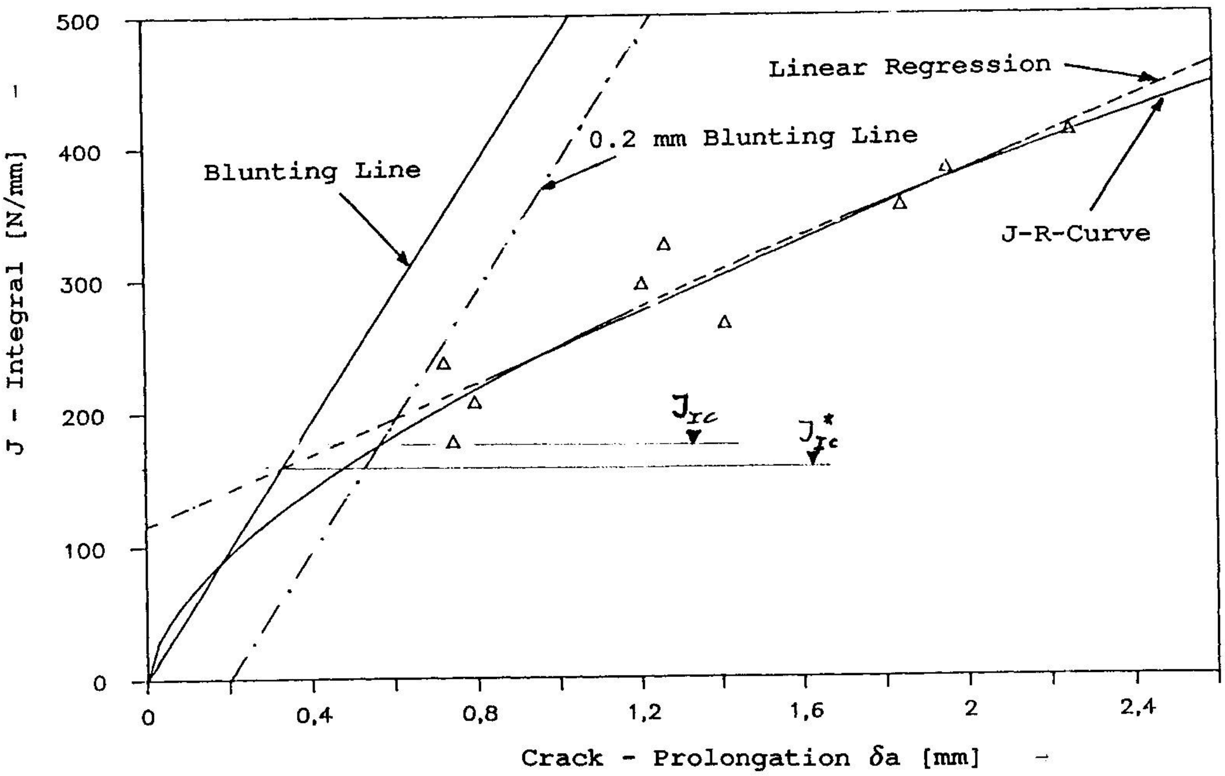

Fig. 5: Example of J–Integral vs. crack–prolongation δa (J–resistance–curve) calculated from load–displacement–curve (Fig. 4) and definition of J_{1c}. For comparision J_{1c} according to ASTM E813–81 (issue 1981 of [7]), denoted by J_{1c}^*, is also shown.

Specimen	W † [mm]	B † [mm]	J_{1c} [N/mm]	K_{1c} [$N/mm^{3/2}$]
W1	25	12	146	5517
W2	25	12	143	5454
W3	50	12	139	5371
W4	50	12	176	6057
† see Fig. 3 for definition				

Tab. 2: Fracture toughness obtained from four tested specimens

3.3. Dynamic fracture toughness

For lower temperature and increased loading rate and different crack–orientation the testing according to paragraph 3.2 becomes much more complicated and costly. Thus these kind of tests were performed on precracked Charpy specimens, loaded by the instrumented Charpy pendulum. The pendulum mass was chosen to be 20 kg, and the impact speed reduced to 1.74 m/s.

A computer program calculated the load–deflection–curve and from this the consumed energy in function of time or deflection for each test. An example is shown in Fig. 6. By means of the following relation, which is based on the results in [8], one obtains the J–Integral from these diagrams:

$$J = K_1^2(a)\,(1 - \upsilon^2)/E \; + 2\,U_p/t(h-a) \qquad (2)$$

In eq (2) $K_1(a)$ denotes the elastic stress intensity factor for a three–point–bend–specimen with crack–length a (and can be found in the hand–books, e.g. [9]), t the thickness of the specimen, h its width and U_p the plastic part of the consumed energy, i.e

$$U_p = \int_0^{u_p} F\,du_p \qquad (3)$$

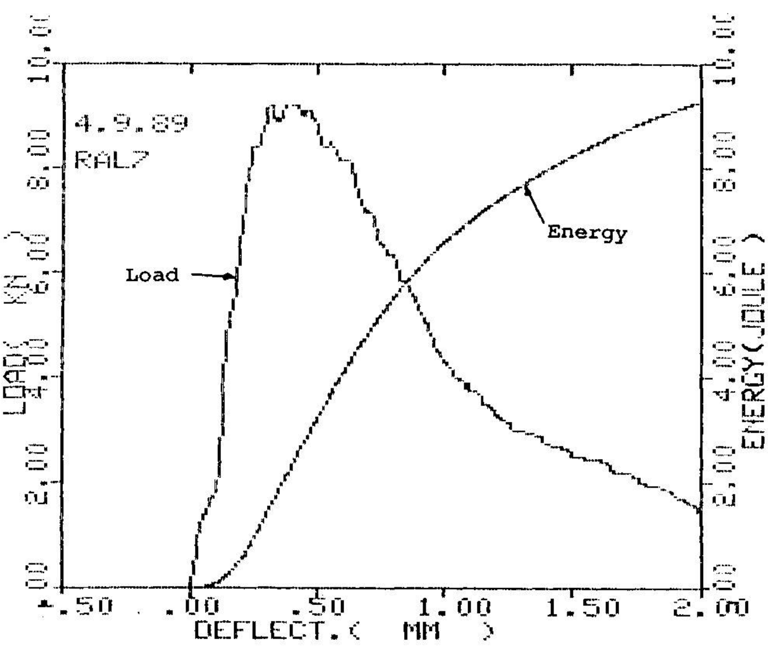

Fig. 6: Example of a load vs. deflection curve and transmitted energy vs. deflection curve of a 3–point–bend impact test with precracked Charpy–specimen. This curve is calculated from the load vs. time curve.

where u_p denotes the plastic part of the beam deflection. If eq.(2) is evaluated at the instant of initiation of crack extension, the resulting J corresponds to a dynamic equivalent of J_{1c} and can be used to calculate the dynamic fracture toughness K_{1d} analogously to K_{1c} by using eq.(1). However, detection of the instant of initial crack–extension on curves like Fig. 5 sometimes is quite difficult and the main source of errors of this procedure. In the present case there are reasons to assume, that crack extension started soon after the maximum load (disregarding the superimposed oscillations) was achieved (a discussion on this topic will be published, [10]). The dynamic fracture toughness obtained by this procedure is shown in Fig. 7.

3.4. Discussion

The J–R–curves (Fig. 5) have two remarkable characteristics mainly: First the initiation toughness, characterized by J_{1c} (resp. K_{1c}), is relatively high, nearly as high as typical values of ordinary structural steel. From the low Charpy impact energy values much lower values were to be expected. Secondly, the gradient of the J–R–curves above J_{1c} is much smaller than in the case of an ordinary structural steel. That means, that the increase of resistance against crack–growth caused by the crack extension is relatively small. This probably explains, why the charpy impact energy is much lower than one would expect from the K_{1c} value.

Whereas the Charpy test exhibited no clear transition behaviour the dynamic fracture toughness measured on precracked Charpy–specimens show a remarkable increase in the temperature range between approximately 0 and 40°C. According to [11] the shift in the transition temperature between static loading and impact loading is about 90°C (for steel with yield–stress of 240 N/mm²). Thus one can conclude, that fracture toughness is at the upper shelf (i.e. approximately 5000 N/mm$^{3/2}$) for all in–service conditions.

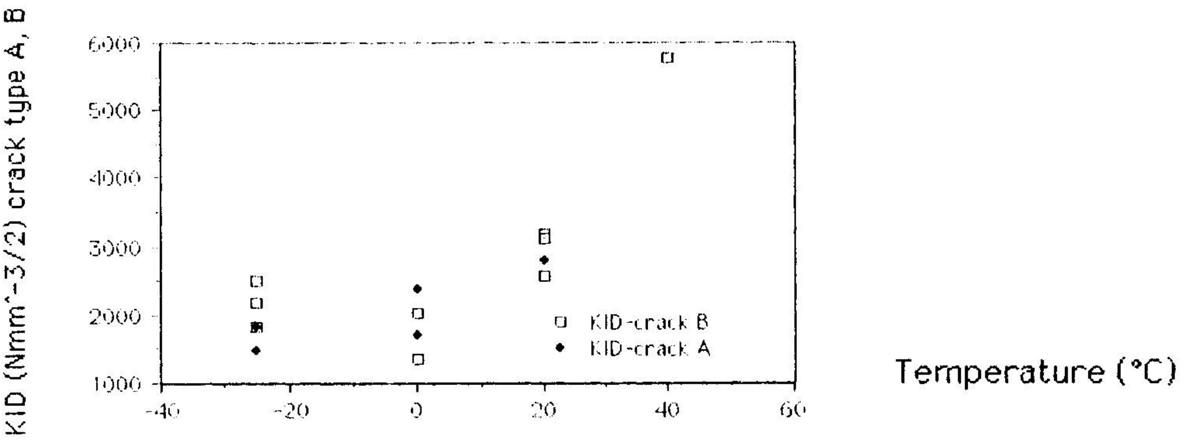

Fig. 7: Dynamic fracture toughness vs. temperature

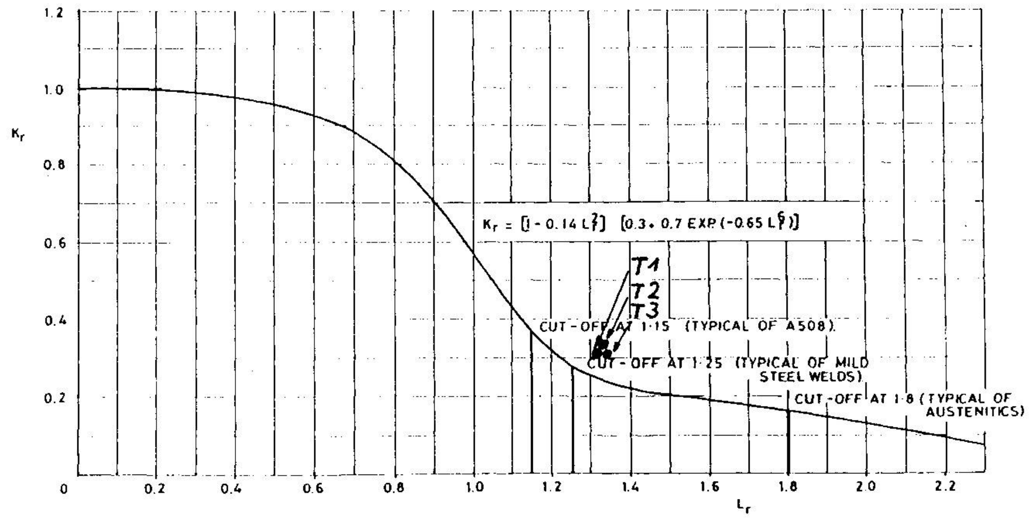

Fig. 8: Failure assessment diagram according to [12]. The points T1, T2 and T3 correspond to fracture tests on precracked component–like specimens

4. FAILURE ASSESSMENT AND CONCLUSIONS

In applying the concept of fracture mechanics to failure assessment of a real structure some difficulties arise: Since the plastic zone ahead of the crack is too large, the theory of linear–elastic fracture mechanics does not apply. On the other hand, performing an analysis of elastic–plastic fracture mechanics is a hard and complex piece of work. For these reasons some relatively simple and easy to–handle methods were developed in recent time. The best known and general accepted methods are the Feddersen–scheme [12], the R6 – Method [13] and the so–called EPRI–"engineering approach" [14]. These methods enable a relatively quick and reliable assessment of the structural safety and integrity on the basis of fracture mechanics.

In the following the application of the R6– method is shortly demonstrated. The central figure of the method is the so–called failure assessment diagram shown in Fig. 8. This diagram reflects the interaction of plastic collapse and crack–instability of a cracked structural component. The horizontal axis contains the quotient of the load L of the considered component divided by the plastic collapse load L_o the vertical axis the stress intensity factor divided by the fracture toughness. The considered component should be safe, as long as the point corresponding to a given crack–geometry and a given load stays beneath respectively on the left hand side of the failure curve shown in Fig. 8.

If the stresses in a component are not known exactly, it is appropriate to base the failure assessment on conservative assumptions. Given (or assumed, resp.) the stress, the maximum (critical) crack –length can be calculated. In Tab. 3 some critical crack–length corresponding to some typical crack–configurations (see Fig. 9) and conservatively assumed stress–states are given. These results base on the conservative assumtion of K_{1c} to be minimum 4000 $N/mm^{3/2}$.

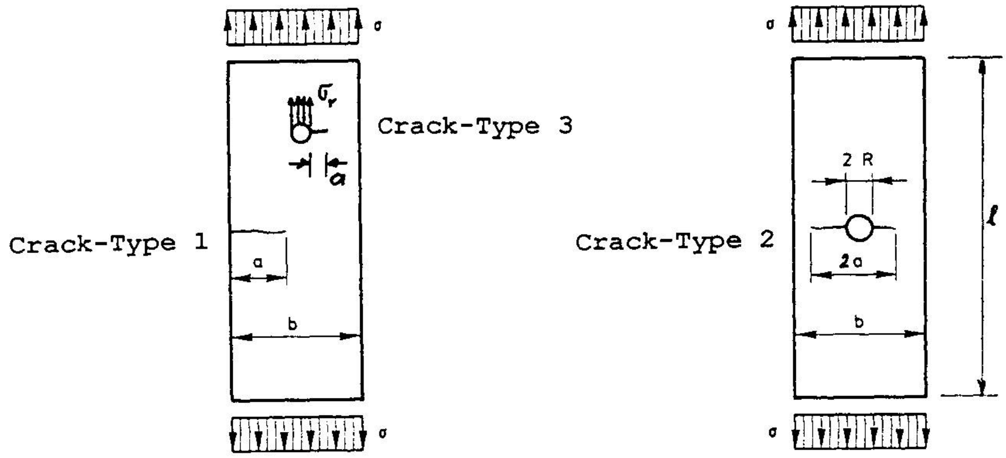

Fig. 9: Definition of crack–types 1, 2 and 3 considered in Tab.3.

In order to verify this failure assessment procedure three tensile tests on precracked component–like specimens were carried out. As test–specimens flat plates of width b = 70 mm, length l = 800 mm and thickness t = 12.5 mm, containing a fatigue crack of a = 18 mm, emanating from a drilled hole of R = 8 mm, were used (see Fig. 9, right hand side). The plates represented a part of a L–shaped profile of the bridge. Since the points corresponding to the maximum measured correspond to unsafe stress–states they are expected to lay slightly outside the safe region of the failure assessment diagram. As shown in Fig. 9 they actually did (Points T1, T2, T3), verifying the R6–method.

The main conclusions from these results are the following: The crack sensitivity of wrought iron is not as high as expected, but comparable with ordinary structural steel. Small cracks which might be missed by visible inspection, e.g. cracks hidden by rivet heads, are hardly able to trigger spontaneous fracture. Structural components which are not weakened by corrosion or visible cracks are supposed to have their original strength.

Crack-type†	loading of component			critical crack size a† [mm]
	axial stress	resid. stress [N/mm²]	rivet stress	
Type 1	240	-	-	22
Type 1	160	90	-	49
Type 2	240	-	-	28
Type 3	240	-	240	10
† see Fig. 9 for definition				

Tab.3: Critical crack sizes for some typical stress-states of a strip- or plate-shaped component made of the investigated wrought iron.

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