Material identification and verification method for the residual safety of old steel bridges

Material Identification and Verification Method for the Residual Safety of Old Steel Bridges

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Summary

This paper presents a method to determine the residual safety and service life of old steel bridges on the basis of a fracture mechanics based toughness verification. The reliability of this method has been improved on the basis of statistical evaluations of material properties of old steel bridges that have been used to derive safety elements for the model uncertainty according Eurocode 3, Part 1.1 - Annex Z [10].

1. Introduction

A great part of existing steel bridges for roads and rails are riveted structures that were built in the last century. Many of these old bridges have undergone several phases of repair or strengthening after damages in the world wars or due to changes of service requirements. For these bridges the question of the actual safety for modern traffic loads and the remaining service life is put forward.

A procedure to determine the residual safety and service life of old steel bridges on the basis of fracture mechanics based toughness verifications has been developed in close co-operation between the Institute of Ferrous Metallurgy and the Institute of Steel

Construction of RWTH Aachen. The results may be used for economic decisions for either the further strengthening of an old bridge or the replacement by a new bridge [1], [2], [3], [4], [5] The method has been applied to many steel bridges in particular in Eastern Germany [6], [7], [8] and also to other structures susceptible to fatigue, e.g. guyed masts, antennae, structural machinery parts etc.

During the last years intensive research works [9] have been carried out to improve the reliability of the method on the basis of statistical evaluations of material properties of old steel bridges and to derive safety elements for the model uncertainty according Eurocode 3, Part 1.1 - Annex Z [10]. This improved method will be presented in the following.

2. The basis of the toughness verification

2.1 Brittleness and ductility

A structural member to be assessed for its residual safety may, due to its prior damages and undetected cracks, react to tension loads by different failure modes which influence the model for calculating the action effects. These failure modes may be best distinguished by the example of a plate in tension with a central crack (Figure 1) that models a member with a hole with cracks on both sides:

- unfavourable failure is exhibited, when fracture occurs before net section yielding with only local yielding at the crack tips. In this case all actual stresses in the net section comprising residual stresses, stress concentrations and stresses due to other restraints have to be taken into account. This failure mode is commonly called "brittle" failure;
- if failure occurs by failure after net section yielding, only the nominal stresses due to external loads in the net section are relevant and notch effects, residual stresses and stresses due to other restraints may be neglected. This mode is called "ductile" failure.

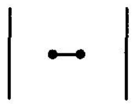
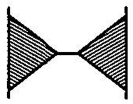
yielding pattern	failure mode	design values
	brittle fracture before net-section yielding	applied stress distribution in the net section + residual stresses + restraints
	ductile fracture after net section yielding	aplied nominal stress distribution in the net-section

Fig. 1 *Definition of failure modes and the applied design values of stresses dependent on the ductility*

The failure mode is mainly influenced by material, temperature, loading rate and shape of the structural member. For old steel bridges both failure modes 1 and 2 are relevant, as the assessment has to be carried out for design situations with low temperatures, where the toughness values are low.

2.2 Determination of vital elements

The toughness-related safety checks are restricted to risk areas with high failure consequences. Therefore, failure scenarios have to be established, where the consequences of failure of different bridge elements for different design situations are investigated (Figure 2). Vital elements are those bridge elements, the failure of which would cause an immediate overall collapse. Vital elements loaded in tension have to be checked in view of toughness-controlled failure unless their cross-sections are sufficiently redundant (Figure 3) so that they do not produce risks. Sufficient redundancy is supposed to be available when crack affected parts of the cross-section may fail without the yield strength being exceeded in the residual cross-sectional parts.

The check shall be based on several loading cases with combinations of self weight, traffic loads including dynamic impact and temperature, which can be based on probabilistic approaches, and with and without residual stresses and restraints depending on the expected failure mode.

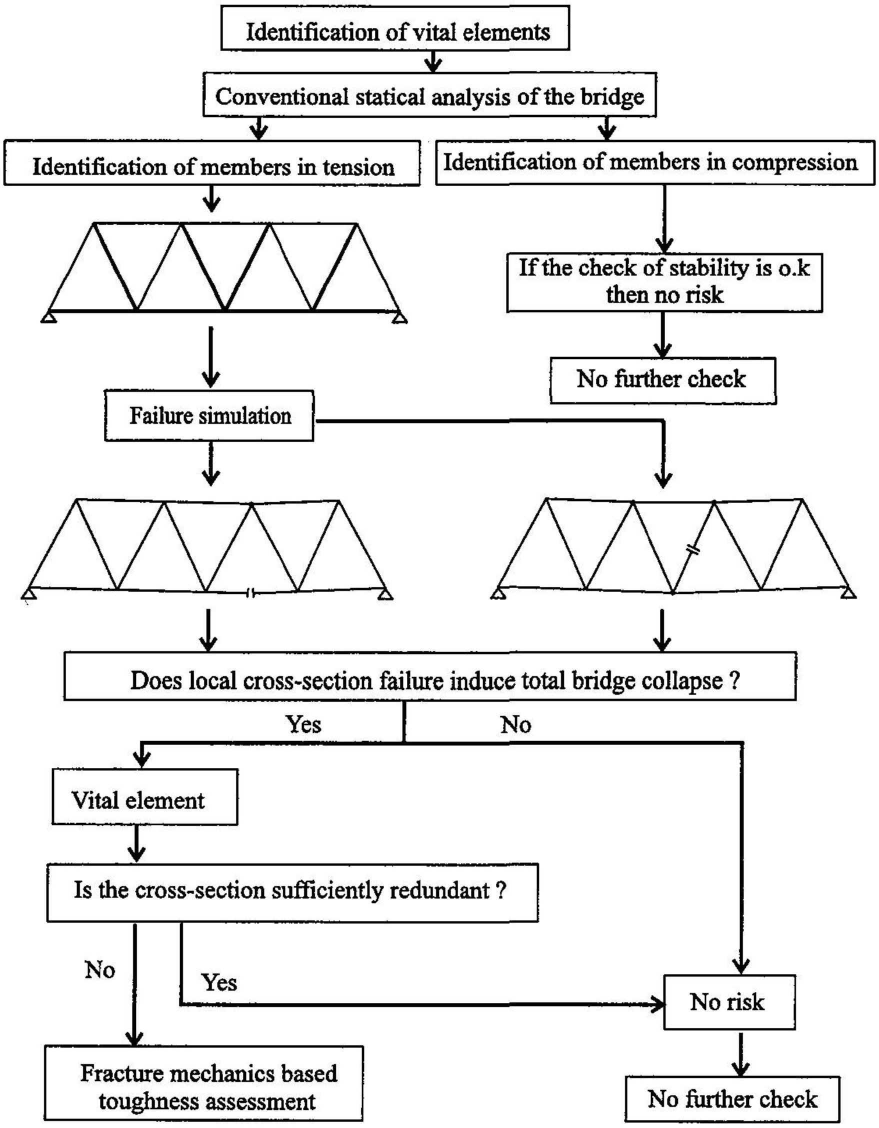


Fig. 2 Procedure for the identification of vital elements

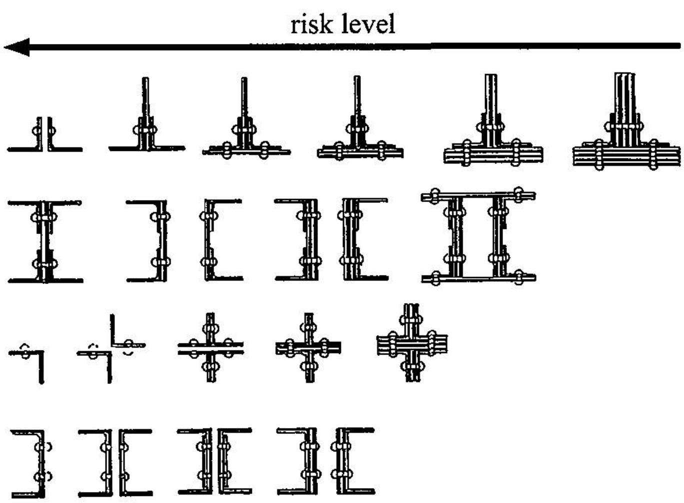


Fig. 3 Typical cross-section of old riveted steel bridges

2.3 Assumption of initial cracks

The toughness assessment requires assumptions on the prior damage of the structure, expressed in terms of initial cracks. From fatigue tests with parts taken from old steel bridges it is known that cracks in old riveted bridges most probably initiate under the rivet heads propagating through the plate thickness and the widths of the outer plates [11]. Hence, it is assumed that on both sides of a rivet hole initial cracks may have formed that have just reached a sufficient size to be detectable. This limit is considered to be 5 mm coming out of the rivet head (Figure 4 a). It has been proved by comparative studies that such a crack configuration may be modelled by a single crack with the initial size $a_0 = D + 2{\cdot}5$ mm only. In case cracks are assumed to initiate in plates covered by angles (Figure 4 b), the initial crack size is considered such, that a detectable crack size of 5 mm comes out of the flanges of the angle.

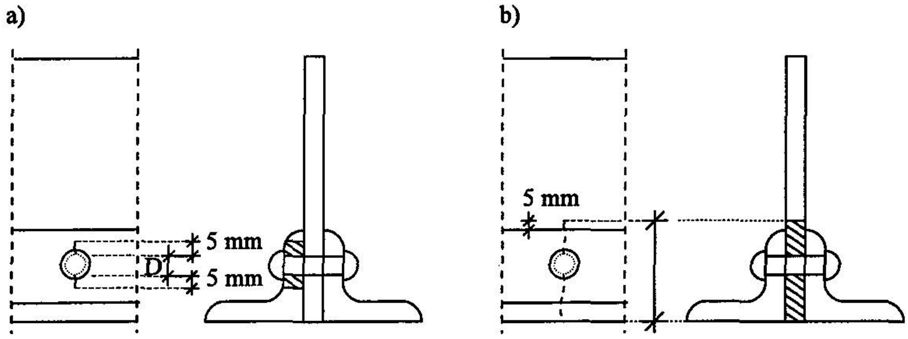


Fig. 4 Assumption for the initial crack size a_0 for a) angles, b) plates covered by angles

2.4 Basic verification principles

For a given loading case, true-stress true-strain curve and crack situation e.g. for the initial crack size a_0 in a vital element, a fracture mechanic action effect in terms of the crack driving energy J_{appl} may be calculated, see 2.5 (Figure 5). The curve J_{appl} - σ_{appl} allows to determine whether the applied stresses lead to net section yielding ($J_{appl} > J_{yield}$) or not ($J_{appl} < J_{yield}$).

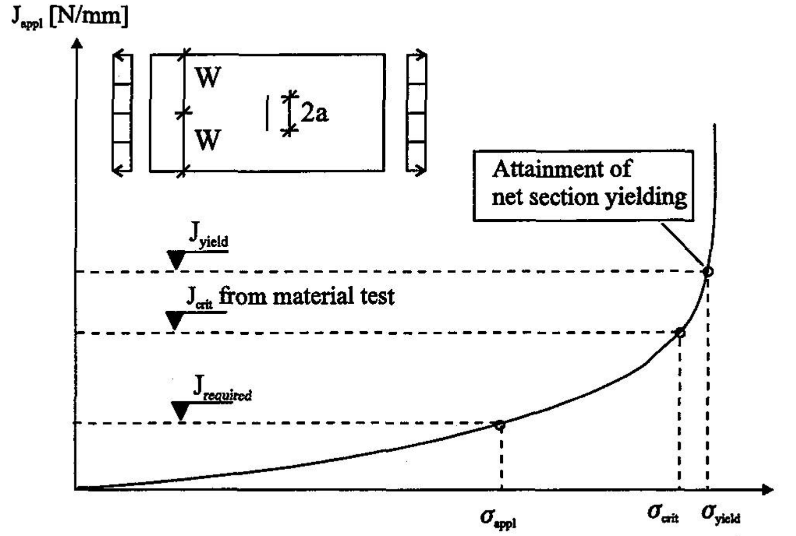


Fig. 5 Typical J_{appl} - σ_{appl} diagram for a given plate model with a crack size a

Either from prior knowledge (see 2.6) or from the miniaturised plate samples (Figure 6) 1/2 CT-10 samples the crack extension resistance J_{crit} may be determined for a given temperature. This value may be compared with J_{appl} in the toughness safety verification (see Figure 5):

$$J_{appl} \leq J_{crit} \tag{1}$$

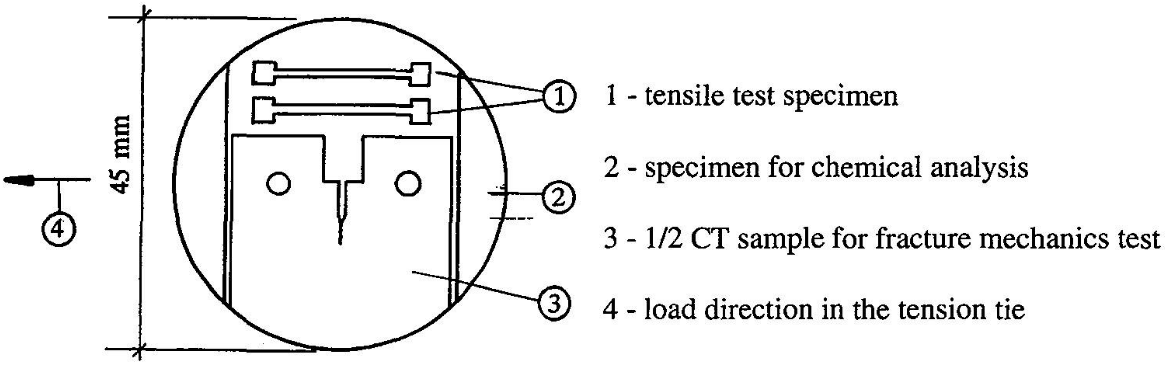


Fig. 6 Miniaturised plate sample

In case J_{appl} has been calculated for an initial crack size a_0 and J_{appl} is smaller than J_{crit} it can be concluded that cracks with detectable sizes are acceptable for the bridge without catastrophic consequences and a collapse without warning will not occur if the bridge has been sufficiently inspected. If this check is not positive, the member has to be strengthened with tough material or to be replaced before the next cold season (loss of toughness at low temperatures).

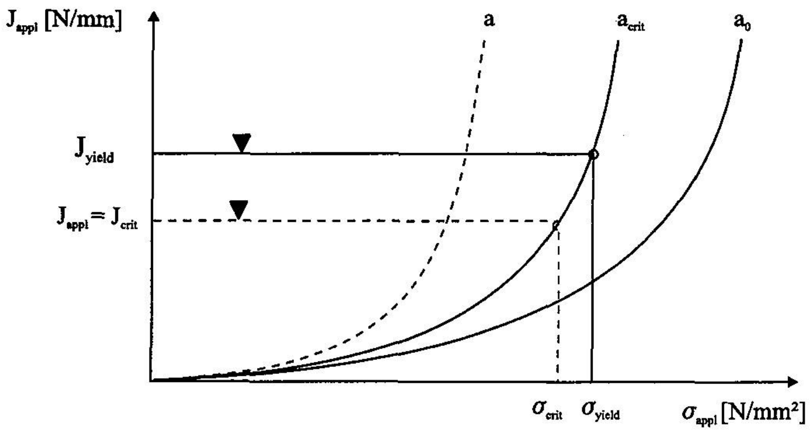


Fig. 7 Determination of a_{crit} *by iterative variation of* a*-values*

The critical crack size a_{crit} may be determined by iterative variation of the crack size. It fulfils

$$J_{appl} = J_{crit} \qquad (2)$$

(Figure 7) and by definition leads to failure. From the position of J_{yield} in this diagram it can be found out whether failure will occur before or after net section yielding and the consequences for the design values for the action side can hence be taken (Figure 5).

The difference $\Delta a = a_{crit} - a_0$ is a measure for the minimum service time from the detection of cracks until failure. It should at least cover the time interval $t_{insp + 1.5\,years}$ between two inspections where 1.5 years is an additive safety element. To verify that this minimum service time is sufficient, the crack propagation time t_p is calculated by using information on the magnitude and intensity of the traffic and the Paris equation as the calculation model (Figure 8). If

$$t_{Insp + 1.5\,years} \leq t_p \qquad (3)$$

no further actions are necessary. Otherwise either the inspection intervals must be shortened or the member must be strengthened to increase t_p. If the check $t_{Insp + 1.5\,years} \leq t_p$ is positive, the inspections at safe intervals at the critical locations of the vital elements will allow the following conclusions that may be considered as the answers to the questions put above:

> As long as no cracks are observed, the structure is sufficiently safe and fit for at least the service period up to the next inspection. This statement can be repeated after each inspection up to the point when first cracks are found. In case they are found there is sufficient time to react by replacing the members or the total bridge.

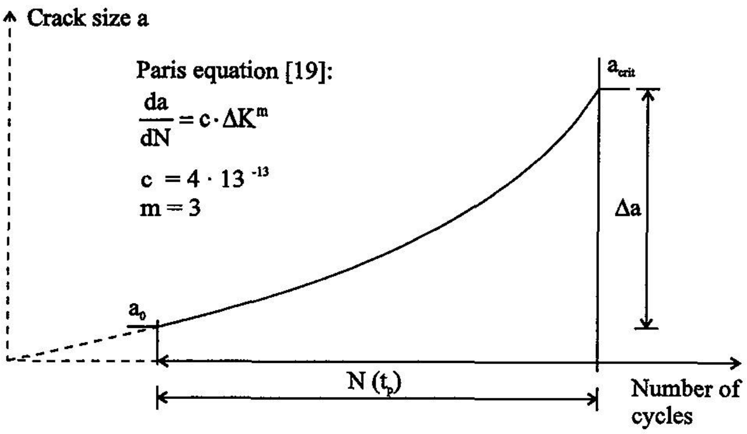
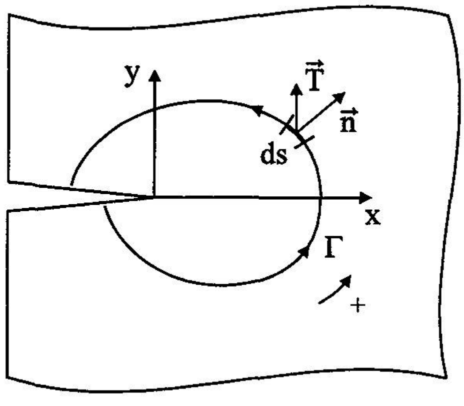


Fig. 8 Principle for the determination of minimum service time $N(t_p)$

2.5 The use of the J-integral

The J-integral as description of the material toughness is defined by [13], [14] (Figure 9). It allows a numerical quantification of the toughness related safety and can be taken from handbooks or calculated by FEM with special grids of collapsed iso-parametric elements (Figure 10). The J_{crit}-values may be determined in experienced laboratories.



$$J = \int_{\Gamma} \left(W \cdot dy - T \cdot \frac{\Delta u}{\Delta x} \cdot ds \right)$$

Γ - integration path around the crack tip
W - energy density
T - stress vector
ds - element of the integration path
u - displacement vector

Fig. 9 Definition of the J-Integral

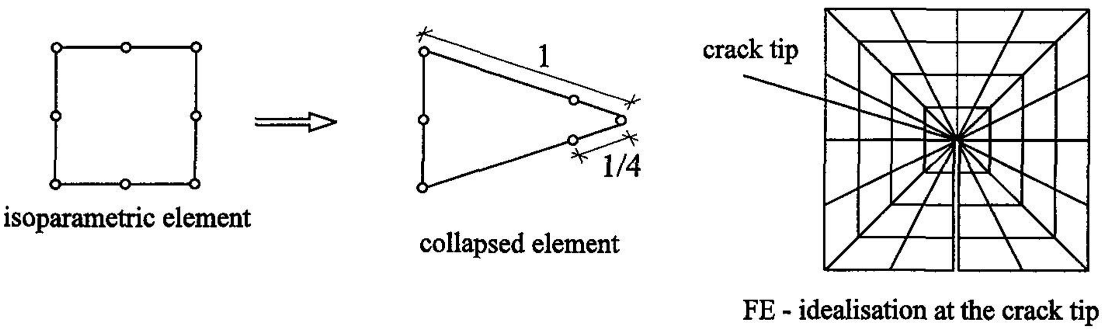


Fig. 10 Finite element and FE-grid for calculating J_{appl}

2.6 Material identification and properties

In old riveted bridges wrought iron as well as puddle iron has been used. Wrought iron has similar properties in chemical composition and microstructure to low strength-low alloy steels of today and is applicable to the fracture mechanics safety assessment. Puddle iron has an totally different microstructure, which can be characterised as laminar type, build up from ferrite and slag. To distinguish specimens taken from riveted bridges after their original production method by means of chemical and/or metallographical analysis a schema has been developed [15] which is presented in Figure 11.

Based on a statistical evaluation of the chemical and the microstructure properties of 407 specimen from riveted bridges, it was also concluded, that the obtained data for the strength and toughness of wrought iron could be treated as a statistical homogenous population.

The statistical distribution of the material strength has been derived from an amount of 205 tests at 0°C and 283 tests at -30°C. Table 1 shows the results in terms of mean values, standard deviations and fractiles. The Lognormal distribution fitted best for the statistical description of the characteristic strength.

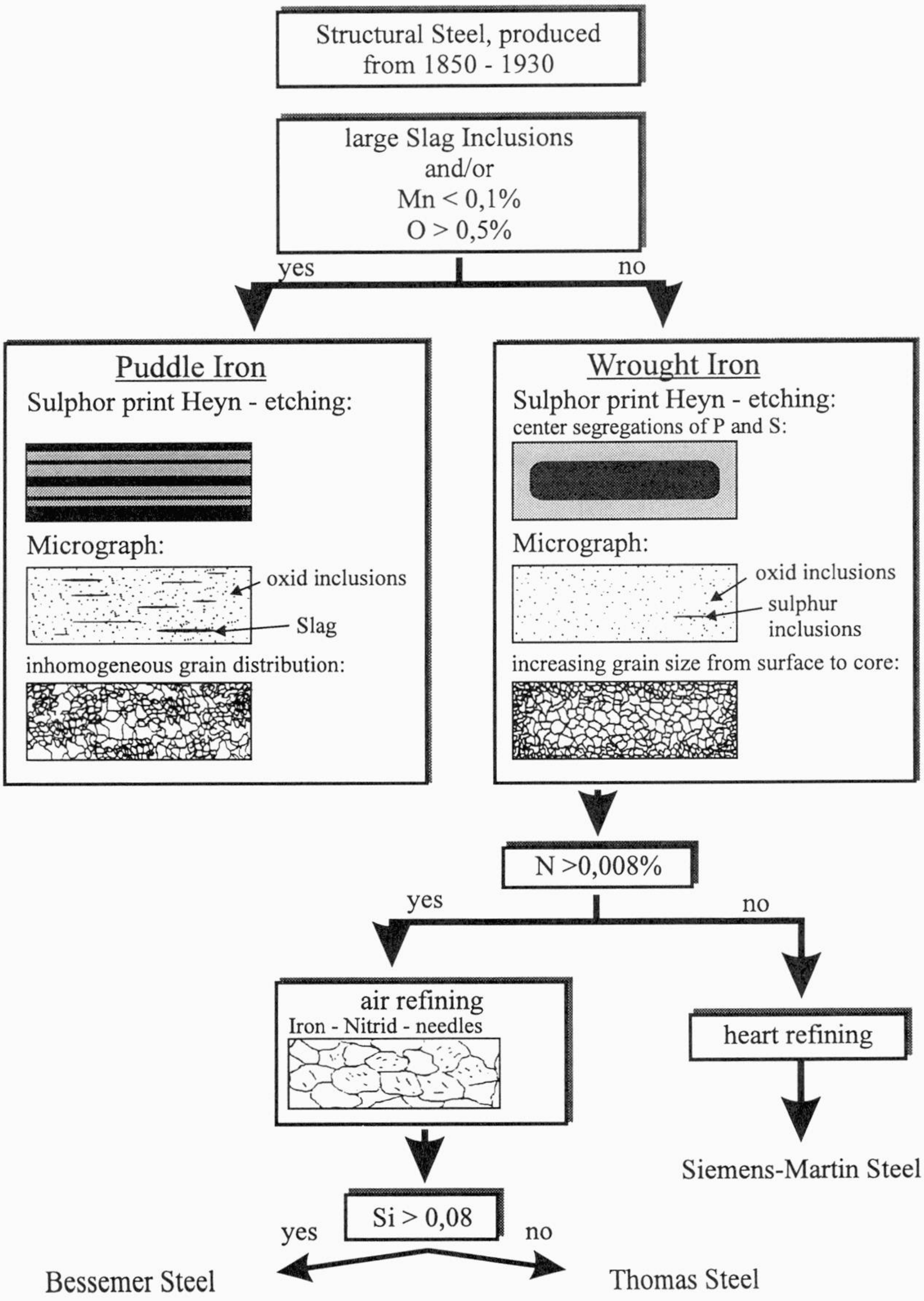


***Fig. 11** Identification scheme for old steels*

	R_{eL}	R_m	R_{eL}	R_m	A	Z	J_{crit}	J_{crit}
T [°C]	-30	-30	0	0	0	0	-30	0
Typ	Log.	Log.	Log.	Log.	NV	NV	Weib.	Weib.
$x_{0,05}$	257	385	248	374	26	57	17	30
$x_{0,50}$	310	446	293	423	34	66	62	91
$x_{0,95}$	375	516	345	479	41	75		

Log. = Log-normal distributed, NV = normal distributed,
Weib. = Weibull distributed (3-parameter), R_{el} = Yield Strength, R_m = Yield Stress,
A = Fracture Elongation, Z = Reduction of Area, J_{crit} = Fracture Toughness acc. [16]

Table 1 *Characteristic values of strength, fracture strain and fracture toughness distributions for wrought iron from 412 tests*

If material tests from the bridge shall be avoided, a conservative safety assessment may be carried out with the combination of 5% fractiles for -30 °C:

$$R_{eL} = 257\ \text{N/mm}^2 \text{ and } J_{crit} = 17\ \text{N/mm}$$

3. A new practical verification procedure

3.1 General

The iterative process needed to calculate a_{crit} with the J-integral concept as indicated above is rather time-consuming, expensive and appears to be restricted to fracture-mechanic experts only. Therefore, a more simplified presentation of the method was looked for to make the toughness verification as easy as a conventional strength verification.

3.2 Determination of a_{crit}

This simplified method has been developed in [17] by using three basic plate models with initial crack configurations (Figure 12) which may be considered as representative for any structural detail of riveted steel members. For these three models the values a_{crit} may be easily determined depending on the stress level $d = \sigma_{appl}/R_{eL}$, the plate width W and the value of J_{crit}.

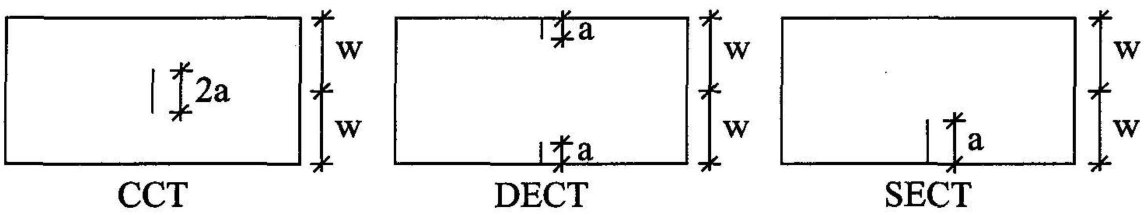


Fig. 12 *Basic plate models and crack configurations for fracture mechanic assessment CCT: plate with centre crack -, DECT: plate with double edge crack, SECT: plate with single edge crack in tension*

The basis of the determination of a_{crit} is the safety check where J_{appl} may be calculated for $\sigma_{appl} \leq \sigma_{gy}$ where σ_{gy} is the applied stress to achieve general yield in the net section. σ_{appl} is the applied stress for the relevant load combination. The values σ_{gy} may be taken as follows [17], [18]:

- plate with centre crack or single edge crack:

$$\sigma_{gy} = R_{eL} \cdot (1 - a/W) \tag{4}$$

- plate with double edge crack

$$\sigma_{gy} = R_{eL} \cdot (1 - a/W) \cdot (1 + 0.25 \cdot a/W). \tag{5}$$

The value for J_{appl} may the be determined from:

$$J_{appl} = J_{gy} \cdot \left[1 - \left(1 - \left(\frac{\sigma_{appl}}{\sigma_{gy}} \right)^2 \right)^d \right] \tag{6}$$

where

$$J_{gy} = \frac{2W \cdot R_{eL}^2 \cdot k_1 \cdot a/W \cdot (1 - a/W^{k_2}) \cdot k_3}{210000 \cdot (a/W + k_4)} \tag{7}$$

is the J-value for general yield in the net section and k_1, k_2, k_3, k_4 are fitting variables.

The accuracy of the approach from equations 6 and 7 may be taken from a comparison with FEM calculations as shown in Figure 13 for a plate with a centre crack.

An example for a graph that gives a_{ccrit}-values in dependency of $d = \sigma_{appl}/R_{eL}$ for various J-values for a plate with a centre crack is given in Figure 14.

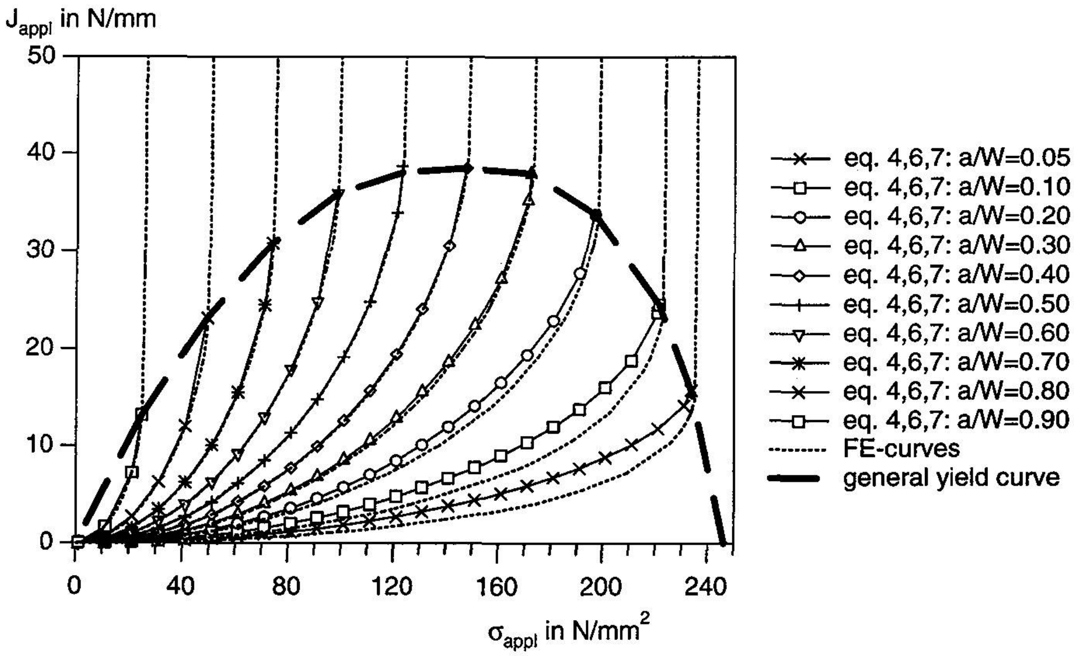
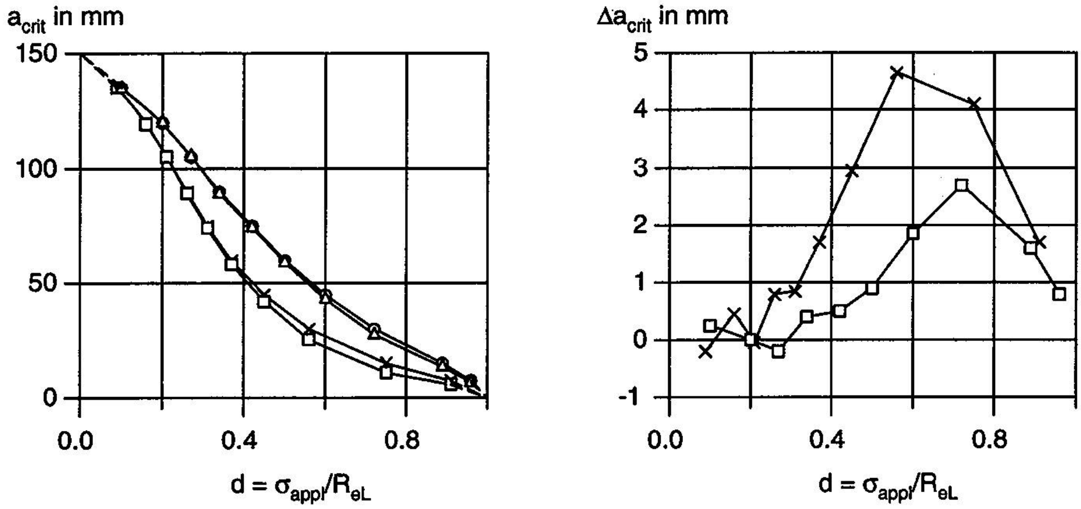


Fig. 13 Comparison of σ_{appl} - J_{appl} curves from FEM and results with Equations (4), (6) and (7), plate with centre crack, 2W=300 mm, d=0.63, k_1=0.64, k_2=k_3=1.0, k_4=0.125



a_{crit} - FE : × : J = 10 N/mm ; o : J = 20 N/mm
a_{crit} - calc : □ : J = 10 N/mm ; Δ : J = 20 N/mm

Δa_{crit} : J = 10 N/mm × : a_{FE}-a_{calc}
Δa_{crit} : J = 20 N/mm □ : a_{FE}-a_{calc}

Fig. 14 *Comparison of critical crack sizes ; FE-Analysis to Equations (4), (6) and (7), CCT, 2W=300 mm*

3.3 Model uncertainty

The model uncertainty for the determination of failure loads F_{Rk} was checked in [17] by comparison with 82 wide plate tests with the method given in Eurocode 3, Part 1.1 - Annex Z [6]. The check was carried out both with measured material strength and fracture toughness data for modern steels and wrought iron and with 5% fractile data for wrought iron as given in Table 1.

The failure load from equation 6 reads

$$F_{Rk,model} = \frac{\sigma_{gy} \cdot t \cdot B}{1000} \cdot \left(1 - \left(1 - \frac{J_{crit}}{J_{gy}}\right)^{1/d}\right)^{0.5} \quad [kN] \tag{8}$$

where $J_{crit} \leq J_{gy}$

From these statistical evaluations the safety factors γ_M* for the prediction model were determined as γ_M* = 1,14 - 1,23 when using measured material data and γ_M* = 1,07 - 1,09 when using 5% fractile data of the material toughness J_{crit} and strength R_{eL} for wrought iron as given in table 1. Considering that the material toughness values are all determined for plane strain conditions instead of plane stress conditions which are the relevant toughness values for the structural behaviour of tension members with through thickness cracks up to plate thickness t = 100 mm [20] the following γ-Factors are proposed for Equation 7:

1. in case of using measured strength and toughness data

$$F_{Rd} = 1/\gamma_M^* \cdot F_{Rk} \text{ with } \gamma_M^* = 1{,}10$$

2. in case of using 5% fractile values for the material strength and toughness for wrought iron from Table 1

$$F_{Rd} = 1/\gamma_M^* \cdot F_{Rk} \text{ with } \gamma_M^* = 1{,}00.$$

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