THE PREDICTION OF FAILURE OF COMPLEX LOADED COMPONENTS IN THE ELASTIC-PLASTIC REGIME

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ABSTRACT

The J-Integral has been created as a criterion for fracture in the elastic-plastic regime, especially for large scale yielding (Rice, 1967). Its role as a fracture criterion for elastic plastic materials becomes comprehensive by its function as an intensity parameter of the HRR-field (Hutchinson, 1968a, 1968b; Rice and Rosengren, 1968). By this way it should determine stresses and strains in the HRR-field and therefore fracture, too. For this reason it should be applied to ductile fracture as well as to quasi-cleavage or cleavage fracture. Very little information is available on the usefulness of J for prediction of failure of complex loaded real structures. Because of the increasing significance of this problem for the assessment of safety margins, J_{fc} of a quenched and tempered steel has been measured in dependence on temperature in the cleavage fracture range including large scale yielding conditions using CT-specimens. On the basis of the results of these tests and a FEM-analysis the failure load of biaxial bent plates with a semi-elliptical surface crack has been predicted. The actual failure load of those plates was significant lower than the predicted one.

KEYWORDS

Complex loaded components; biaxial loaded plates; prediction of failure; cleavage fracture, 3D elastic-plastic FE-analysis; experiments; J-Integral; influence of constraint.

INTRODUCTION

The J-Integral has been created as a criterion for fracture in the elastic-plastic regime, especially for large scale yielding (Rice, 1967). Its role as a fracture criterion for elastic plastic materials becomes comprehensive by its function as an intensity parameter of the HRR-field (Hutchinson, 1968a, 1968b; Rice and Rosengren, 1968). By this way it should determine stresses and strains in the HRR-field and therefore fracture, too. For this reason it should be applied to ductile fracture as well as to quasi-cleavage or cleavage fracture. Under small scale yielding conditions J is identical to G.

The capability of J as a fracture criterion has been tested very intensively at specimens of a large variety of types (CT, CCP, SECB) and sizes (Dawes, 1979; Kaiser and Hagedorn, 1982; Landes and Begley, 1972; McMeeking and Parks, 1979; Milne and Curry, 1980; Shih and co-workers, 1979). Differences in J_R-curves of different specimen types are interpreted as a result of different demands in size depending on the specimen type. Very little information is available on the usefulness of J for prediction of failure of complex loaded components.

Zahoor and Paris (1979) have analysed the failure of two vessels of the HSST-programme. But the comparison of the calculated results with the experimental results is only very approximative in the sense of conservative estimation. Milne (1981) has reanalysed the results of the tests of the HSST-vessels V5 and V9 with nozzle corner cracks. But this analysis could only be an estimation, too.

Regarding biaxial loading as a simple case of complex loading one may find in the literature results of considerable efforts to correlate fracture under biaxial and uniaxial loading (Adams, 1973; Alpa and co-workers, 1979; Aurich and co-workers, 1977, 1979; Dietmann and Kussmaul, 1978; Eftis and co-workers, 1977a, 1977b; Erbe and Puffer, 1979, 1981; Garrett and co-workers, 1980; Hilton, 1973; Kibler and Roberts, 1970; Lee and Liebowitz, 1977; Leevers and co-workers, 1976; Miller and Kfouri, 1974, 1979; Radon and co-workers, 1977; Schmidt and co-workers, 1980; Ueda and co-workers, 1977). The influence of biaxial loading on fracture has been investigated on the applied side as well as on the material side. But in no case the failure of a biaxially loaded specimen has been predicted for plane strain conditions on the basis of results of uniaxial loaded specimens, e.g. CT-specimens. Because of the increasing significance of this problem for the quantification of safety margins a research programme has been carried out.

EXPERIMENTAL

For the investigations a quenched and tempered steel with the German designation 20 MnMoNi 5 5 was used, which is very similar to the US steel A 533 grade B. The cast ingots have been forged into plates of the dimensions of about 4000 mm by 1000 mm by 150 mm. The specified and the actual analyses are shown in Table 1. Tensile specimens (length and transverse direction), Charpy-V-notch specimens (L-S, T-L), CT 50-specimens (L-S, L-T) and CT 100-specimens (L-T) have been cut from plates and machined in accordance with the appropriate test standards. The mechanical properties are listed in Table 2. The results of the Charpy-tests are plotted in Fig. 1.

The CT-specimens have been tested in accordance with ASTM E 399-81. Valid K_{Ic}-values could only be obtained below 173 K from the CT 50-specimens and below 193 K from the CT 100-specimens. For all temperatures J_{fc} has been evaluated by the method of Merkle and Corten (1974). J_{fc} is defined as J at cleavage instability.

TABLE 1 Chemical Composition of the investigated Material

	C	Si	Mn	Mo	Ni	P	S
Check	0,19	0,22	1,42	0,47	0,54	0,009	0,009
KWU-specification re-WS 1.1	0,17- 0,25	0,15- 0,30	1,15- 1,50	0,45- 0,60	0,40- 0,80	0,012	0,015

	Al	Cr	Cu	V	Co	Ta
Check	0,002	0,14	0,07	0,01	0,008	0,01
KWU-Specification re-WS 1.1	0,050	0,20	0,10	0,03	0,03	0,03

TABLE 2 Mechanical Properties of the investigated Material

Direction	Yield Strength N/mm²	Tensile Strength N/mm²	Elongation in 5 D %	Reduction of Area %	Charpy shelf energy J
Longitudinal	487	633	26	68	128
Transverse	474	618	25	63	54

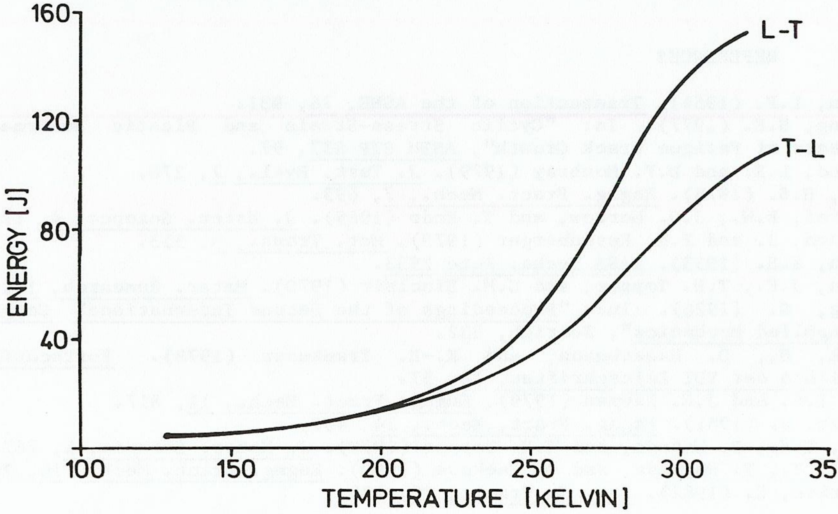

Fig. 1. Charpy energy vs. temperature of the investigated material.

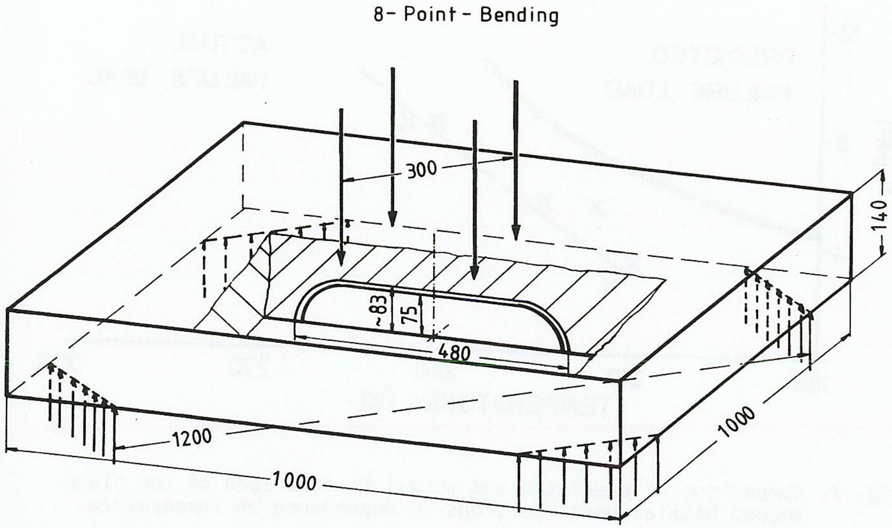

Fig. 2. Dimensions of the plate shaped specimens and loading points for biaxial bending

As an example of a complex loaded component plates of 1000 mm by 1000 mm by 140 mm were cut from the forged plates, provided with a semi-elliptical surface crack and loaded by biaxial bending. The geometry of the test plate and the crack is shown in Fig. 2. A crack starter of 430 mm length and 75 mm depth was machined and extended up to 480 mm and 83 mm respectively by fatigue in accordance with ASTM E 399-81. The plate-shaped specimens were in eight point bending in an 20 MN-testing machine. Biaxial bending could be attained by an appropriate distribution of the support and loading points (see Fig. 2.). The loading fixture is shown in Fig. 3. The plates have been instrumented by 5 clip gauges for COD-measurement, an extensometer for measuring the bending displacement and strain gages to registrate the symmetry of deformation. The test data were plotted by X-Y-recorders. Valid K_{Ic}-data from the plates could be obtained below 213 K.

RESULTS AND DISCUSSION

Fig. 4 shows the results of the CT-specimen tests from 153 K up to 233 K in terms of J_{fc}. If J_I governs the crack opening stress σ_{yy} in the J-dominated zone and this stress is responsible for cleavage fracture and if the constraint, given in terms of ε_{zz}, in the specimen is larger than in the structure, J_{fc} obtained from specimens ought to be suitable to predict failure of a complex loaded structure. J of the plates has been calculated by 3D elastic-plastic finite element method (FEM) (Olschewski and coworkers, 1983). In Fig. 5 J is plotted versus the angle φ with the load as parameter. The unstable crack propagation in the plates started from nuclei

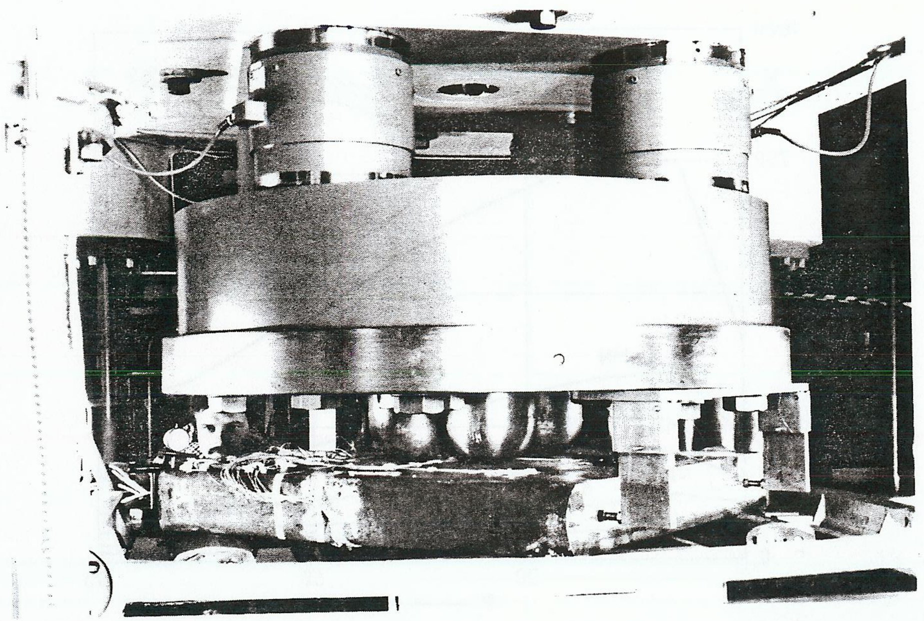

Fig. 3. Loading device for biaxial bending of the plate shaped specimens.

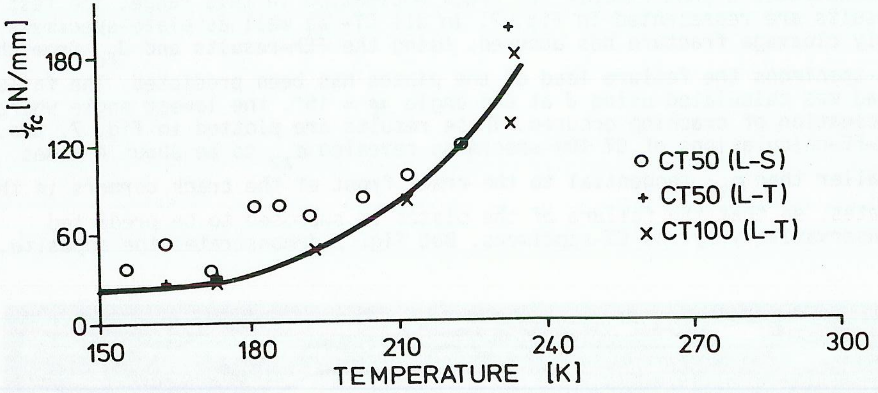

Fig. 4. Results of CT-specimen tests in terms of J_{fc} in dependence on temperature.

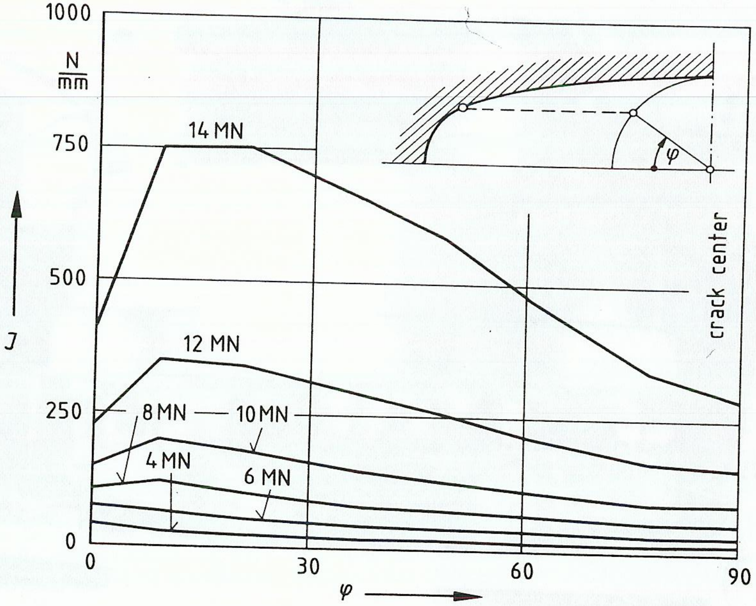

Fig. 5. J-Integral around the semi-elliptical surface crack of the plate.

ahead of the preexisting cracks at angles φ between 15° and 45°. Fig. 6 demonstrates a good example for crack nucleation in this range. The test results are represented in Fig. 7. In all CT- as well as plate-specimens only cleavage fracture has occured. Using the FEM-results and J_{fc} from the CT-specimens the failure load of the plates has been predicted. The failure load was calculated using J at the angle φ = 15°, the lowest angle where nucleation of cracking occured. These results are plotted in Fig. 7, too. 3D-FE-calculations of CT 100-specimens revealed ε_{zz} to be about 4 times smaller than ε_{tt} tangential to the crack front at the crack corners in the plates, so that the failure of the plates is supposed to be predicted conservatively by the CT-sepcimens. But Fig. 7 demonstrates the opposite.

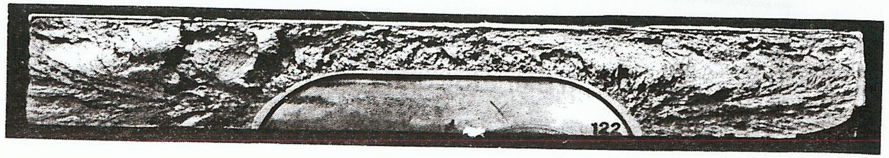

Fig. 6. Fracture surface of a plate shaped specimen, test temperature 270 K, cleavage fracture.

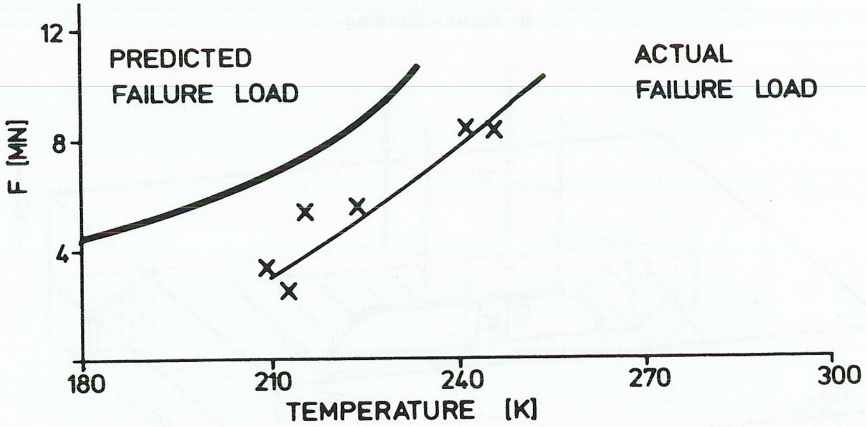

Fig. 7. Comparison of predicted and actual failure load of the plate shaped biaxial bent specimens in dependence on temperature.

The reason for this difference was not completely understood till now. Possibly the stress field ahead of a crack in an elastic-plastic material is governed by two parameters as suspected already.

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