J-INTEGRAL EVALUATION IN MIXED-MODE I/II

COMPACT TENSION SHEAR (CTS) SPECIMENS

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Abstract

In this paper, Finite Element (FE) simulations have been performed in order to assess the most suitable J-integral estimation method for the mixed-mode I/II CTS specimens. Several analytical formulas for the J calculation have been examined and compared to the FE results and a suitable solution has been identified. Finally, a specific plastic η factor, η_{pl}, for the above-mentioned specimen has been proposed and the mixed-mode J-R curves of a ductile steel evaluated.

Sommario

In questo articolo sono state condotte analisi ad elementi finiti per valutare il metodo di stima del integrale J più attendibile per le prove di tenacità a frattura in modo misto su campioni CTS. I risultati delle analisi EF sono stati confrontati con soluzioni analitiche riportate in letteratura, identificando una formulazione che permette di stimare J al variare del rapporto di modo misto. Infine è stato proposto alternativamente uno specifico fattore η plastico, η_{pl}, e si è valutata la curva di resistenza J-Da in modo misto di un acciaio ferritico da costruzione.

1. Introduction

For its fitness in describing the reliability and the damage evolution in flawed components, the Fracture Mechanics-based design approach has been discussed and implemented in the last decades. While the experimental determination of the mode I fracture toughness for linear elastic and elastic-plastic with small-scale yielding material behaviour is since long regulated (ASTM E399, ESIS P1-92, procedures), there is still a lack of generally accepted rules for the measurement of mixed-mode ductile fracture toughness despite its importance in many engineering situations [1].

It is known, that the mixed-mode crack resistance curve can be still expressed in terms of the J-integral fracture parameter, provided that an equation is given to calculate J from the load-displacement data. Several analytical formulas for the η_{pl} estimation, as well as FE-calculated values, can be found in literature [2-6] for different mixed-mode specimens.

In this paper, the most suitable estimation method for the mixed-mode I/II CTS specimens (Fig. 1) used in previous experiments on a DIN StE 550 steel [7] is assessed through the comparison of FE simulations to analytical estimations based on literature proposals. A formula for the calculation of η_{pl} as a function of mode-mixity is finally given.

2. J-integral in mixed-mode I/II

In the mixed-mode or mode II loading cases, the J-integral can be still evaluated like in mode I from the area under the load-displacement curve [2-4, 8-9]. According to the usual procedure [10] J is divided into an elastic part J_{el} and a plastic part J_{pl}. These two components can be written as (plane stress):

$$J_{el} = \frac{K_I^2 + K_{II}^2}{E} \qquad (2)$$

$$J_{pl} = \eta_{pl} \frac{U_{pl}}{B(W-a)} \qquad (3)$$

where U_{pl} is the plastic work done by the applied load and η_{pl} is the plastic η-factor. The elastic component can be readily determined from the stress intensity factor solutions of [11] as a function of the applied load. Like in the work of Jeon [9] (asymmetric four point bending specimen), the plastic part of J is estimated under the assumption that the mode I η_{pl}-derivation of Bucci et al. [12] is applicable also for cracks under mixed mode loading. For ideal plasticity and constant load line displacement J_{pl} can be written as:

$$J_{pl} = -\frac{1}{B}\frac{\partial U_{pl}}{\partial a} = -\frac{1}{F_{pl}}\frac{\partial F_{pl}}{B\,\partial a}U_{pl} \qquad (4)$$

where F_{pl} is the plastic limit load. Combining (3) and (4) yields:

$$\eta_{pl} = -\frac{W-a}{F_{pl}}\frac{\partial F_{pl}}{\partial a} \qquad (5)$$

$$\eta_{pl} = 1 + \frac{0.75 \cos\phi \frac{W}{b}\left(1 + \frac{f_1}{f_2}\right)}{\frac{4\sin^2\phi}{(f_1 + f_2)} + f_1 + f_2} \qquad (6)$$

With the mixed mode limit load for superimposed tension, bending and shear from [5] (Chapter 2.13.4) following expression for the η_{pl} factor is obtained:

where

$$b = (W - a)$$

$$f_1 = 0.75 \cos\phi \frac{a}{b}$$

$$f_2 = \sqrt{\left(0.75 \cos\phi \frac{a}{b}\right)^2 + \cos^2\phi} \qquad (6bis)$$

For a/W=0.5 the developed η_{pl}-function agrees with the finite element analysis (FEA) of a single edge notched specimen (SEN) under mixed mode loading in a very stiff fixture [2]. This is shown in Fig. 1, where the η_{pl}-factors are plotted as a function of the applied mixed mode ratio expressed through M_e (defined in Fig. 1). Mode I and mode II η_{pl}-values of a pin-loaded SEN-specimen [6] and a compact tension shear specimen [4], both similar to the investigated CTS configuration, are also included in the diagram.

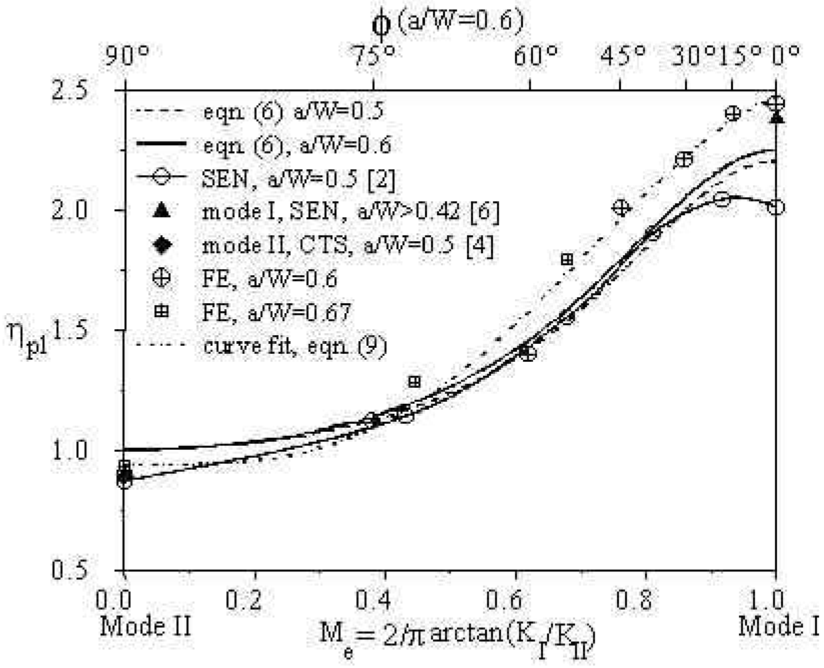

Figure 1

Dimensionless η_{pl}-factors for SEN and CTS specimens under mode I, mode II and mixed mode loading conditions.

Another technique for the experimental evaluation of the mixed mode J-Integral was presented by Thogo and Ishii [3]. They calculated $J_{pl,I+II}$ for asymmetric three and four point bending from the sum of mode I and mode II contributions:

$$J_{pl,I+II} = \frac{1}{B(W-a)}\left(\eta_{pl,I}U_{pl,I} + \eta_{pl,II}U_{pl,II}\right) \qquad (7)$$

where $\eta_{pl,I}$ and $\eta_{pl,II}$ corresponded to pure mode I and pure mode II loading respectively. Consequently $U_{pl,I}$ ($U_{pl,II}$) was calculated from the mode I (mode II) components of plastic displacement and force. Here the method of Thogo and Ishii led to:

$$J_{pl,I+II} = \frac{1}{B(W-a)}\left(238\, U_{pl,I} + 09\, U_{pl,II}\right) \qquad (8)$$

with $\eta_{pl,I}$ taken from the pin loaded SEN specimen (27) and $\eta_{pl,II}$ taken as an average of the known literature values [2, 4] of CTS-like specimens under pure mode II loading, while the elastic J-component still equalled equation (4). Finally, it is important to note, that the developed J-estimations are only valid for small and coplanar crack propagations.

3. Experiments

Fracture tests at 15°, 45°, 75° and 90° loading angles were carried out with 4-mm thick CTS specimens [11], of which a scheme is reported in Fig. 2. The material tested was a fine grained structural steel with the German designation StE 550 (yield strength plateau at 580 MPa and ultimate strength 650 MPa). Further details on the experimental procedure can be found in [7].

The J-analysis required a U_{pl}-evaluation from the plastic load line displacement versus force curve. In the CTS specimens the load line corresponds to the specimen centreline (Fig. 2) and it was therefore necessary to interpolate the load line $cod_{I,LL}$ (cod_{II} is not affected by the rotation of the two specimen halves) linearly from the clip gage readings and the δ_I-values measured optically at the fatigue crack tip (see Fig. 2). The corrected $cod_{I,LL}$ and the cod_{II} values were then projected on the load line to give the load line displacement cod_{LL}. The plastic component U_{pl} was obtained by subtracting the elastic work from the total work. Since the investigated crack propagations were relatively small, the initial linear cod_{LL}-F relationship was used to calculate the stored elastic energy at the end of the tests.

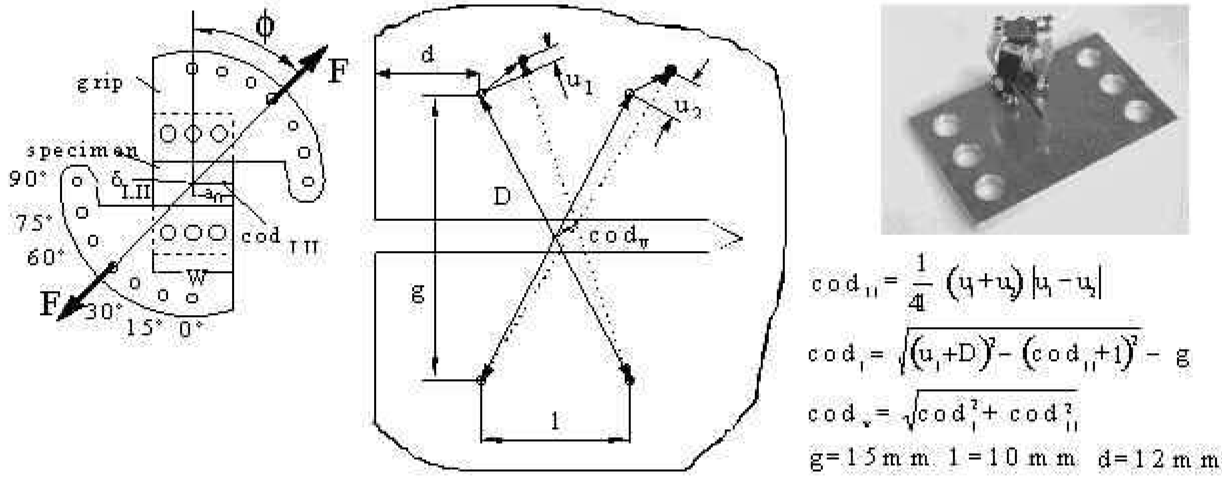

Figure 2

CTS specimen outline and measurement system for cod_I and cod_{II} [13].

4. Finite element calculations

To check the validity of the J-estimation formulas of the previous section two-dimensional, plane stress finite element (FE) analyses of CTS specimens were performed using conventional small strain theory, incremental plasticity with associated Von Mises flow rule and isotropic hardening. The analyses were conducted using the ABAQUS code on an HP 712/80 workstation. The investigated CTS specimens had crack-to-width ratios of a/W=0.6 and 0.67, that are the two extremes of the experimental range. Loading angles of ϕ=15°, 45°, 75° and 90° and ϕ=60°, 75° and 90° were considered for the two a/W ratios, respectively. Crack growth was not examined. In Fig. 3 the FE model of a CTS specimen loaded at ϕ=75° is represented. The mesh was build up with isoparametric, eight-noded elements. A circular core with quarter-point collapsed elements surrounded the crack tip. This modelling produced the 1/r-singularity appropriate for plastic crack tip fields. The high stiffness fixtures were simulated by the rigid beam frames visible in Fig. 3.

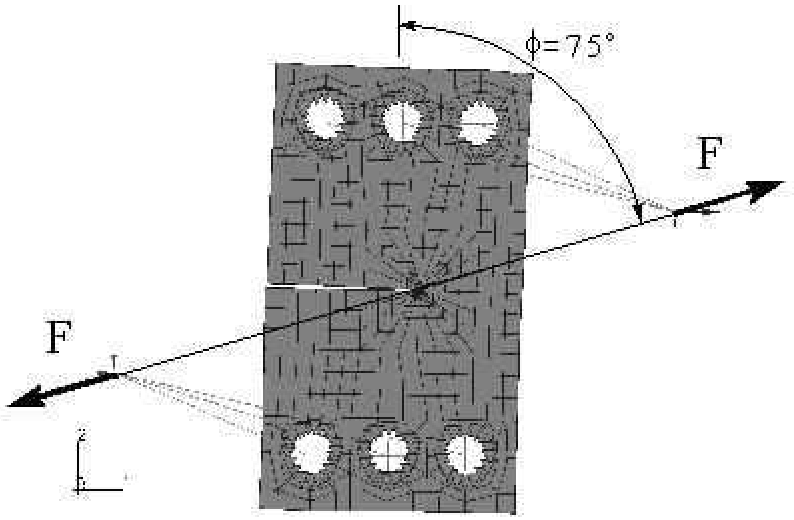

Figure 3

Finite element model of the CTS specimen with a/W=0.6 under a loading angle of 75° (deformed mesh).

The position of load introduction could be varied to generate different mixed-mode ratios. The lower frame extremity was pinned at a fixed location while the load was applied to the upper frame. During the loading procedure the load point displacement direction was constrained into the defined loading direction. The connection between the specimen and the frame was simulated with rigid cylindrical surfaces (whose contact points with the specimen are represented by the triangles in Fig. 3).

A "softened" contact pressure-clearance law was defined in order to avoid convergence problems when solving the contact conditions. The model was checked against the values given in [11] under elastic loading conditions. The difference between the J_{el} of the present FE analysis and the one of [11] was always smaller than 10% for different loading ratios. This difference was attributed to the loading modality used there, where nodal forces were applied onto the specimen holes. For the elastic-plastic calculations the engineering stress-strain curve of StE 550 steel was used as a material model. The ABAQUS output J-values were checked on several paths around the crack tip. The region where path dependency was found increased with increasing mode II loading components, as shown also in [14]. The load line opening displacement, $cod_{I,LL}$, has been linearly extrapolated from the opening displacement in two points far from the deformed crack tip zone.

5. Results and discussion

In Fig. 4 the numerically obtained J-values are plotted as a function of the load line displacement for the CTS-specimens with a/W=0.6 under different loading angles. These curves are compared to the J-values calculated from the areas under the FE load-displacement curves, just like the experiments, following the formulas (6) and (8) for J_{pl} and formula (2) for J_{el}.

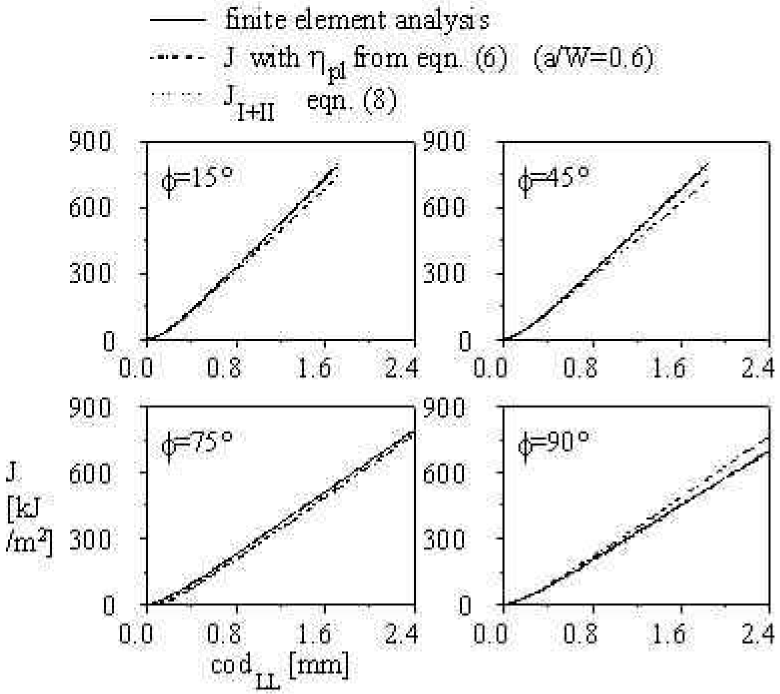

Figure 4

J-values obtained directly from the finite element code compared to the J-values calculated from the areas under the FE load versus load line displacement (cod_{LL}) curves.

Both methods agree quite well with the finite element records. In the case of 75°-loading the differences between the estimated and the finite element J are attributed to J_{el}, as stated previously. Especially for the near mode I loaded specimens ($\phi \leq 45°$) the method of Thogo and Ishii (eqn. (8)) yields more accurate results, because the analytically developed η_{pl}-formula (6) apparently underestimates the real η_{pl} in mode I.

This is also shown in Fig. 1**,** where the η_{pl}-values extracted from the FE calculations are compared to the analytical results (crossed symbols in Fig. 1). Interestingly in the small range of investigated crack lengths the a/W-effect on η_{pl} is covered by the change in mixed mode ratio M_e. This suggested following fit of the FE results:

$$\eta_{pl,FE} = 2.665 - 1.729 \exp\left(-2.204\, M_e^{3.269}\right) \qquad 0.6 \leq \frac{a}{W} \leq 0.7 \qquad (9)$$

which is valid for $0.6 \leq a/W \leq 0.7$ as stated previously.

The J-integral crack resistance curves resulted to be relatively insensible to the respective J-evaluation method: J_{I+II} in Fig. 5 and J_{FE} in Fig. 6. The R-curves showed a decrease with increasing mode II loading components, according to what was found by other authors in ductile ferritic steels with low work hardening capability or yield plateau [2, 15-16]. Therefore the proposed methods for the calculation of J are believed to give consistent results. Furthermore, it can be noticed that the use of the mode I J-R-curves of C(T)-specimens instead of the mixed-mode ones may lead to unconservative estimations near to mode II.

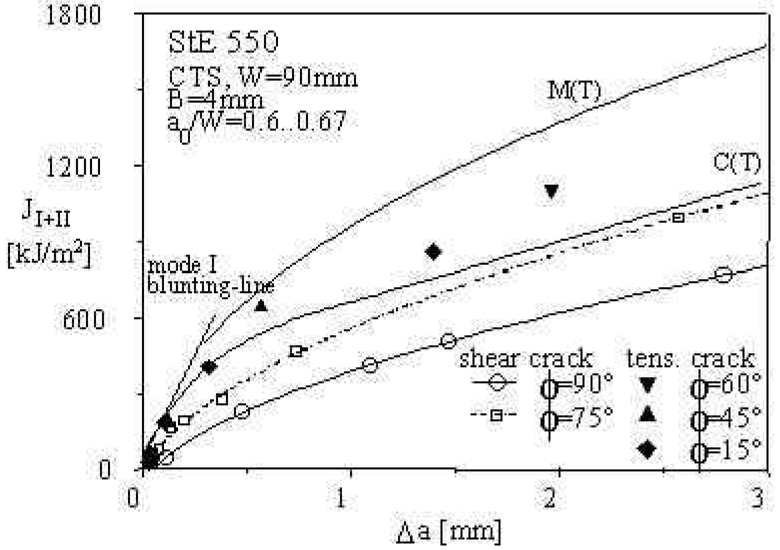

Figure 5

J integral evaluated with the approach of Thogo and Ishii (eqns. (2) and (8)) versus stable crack growth

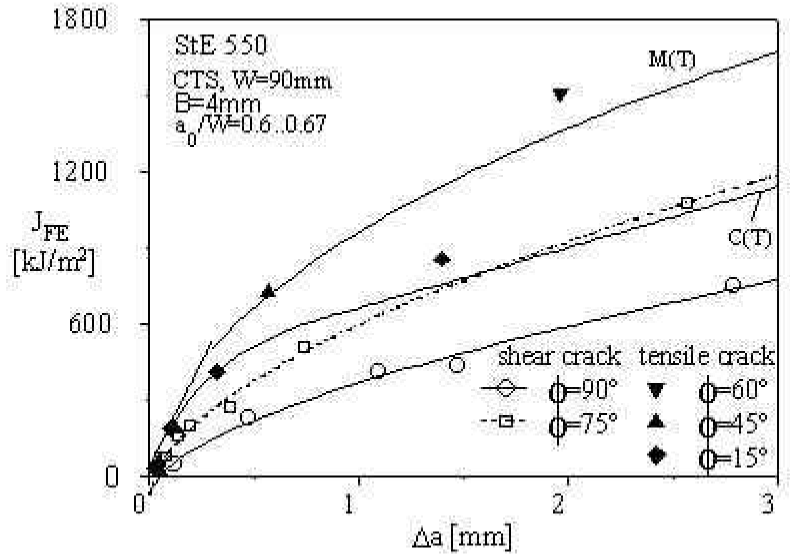

Figure 6

J integral evaluated with eqns. (2), (3) and the η_{pl}-factor extracted directly from the FE analysis (eqn. (9)) versus stable crack growth.

6. Conclusions

In this paper for the feasibility of some models for the J-integral calculation under mixed-mode I/II conditions in CTS specimens are examined and validated using a FE approach. It has been found that the model proposed in eqn. (8) for the calculation of J yielded quite accurate results on the whole range of mixities. Furthermore, a plastic η -factor has been extracted from the FE analysis as a function of the mixed-mode ratio and for a/W varying between 0.6 and 0.7. The calculation of the mixed-mode J-R curves with the proposed formulas yielded results that are consistent with the literature.

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Atti del convegno

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