3D FEM STUDY ON AN AUSTENITIC STAINLESS STEEL FOR VERIFICATION THE ENGINEERING TREATMENT MODEL (ETM)

A. Cornecc, G. Lin, K.-H. Schwalbe *)

3D constraint effects of finite thick specimens on the CTOD-δ5 driving force are studied by FEM on stationary cracks. The deviation margins between 3D and 2D conditions will be presented. For most cases, i.e. where the ligament is 2 times larger or more than the thickness, the difference between inside and outside is weakly exhibited that δ5 can be approximated to be constant versus the thickness. A promising idea of simplification the analytical δ5 driving force determination for 3D with the ETM construction will be presented. An example of the ETM demonstrates that the characteristics of the δ5 driving force curves can be properly described by the current ETM construction based on 2D plane stress condition.

INTRODUCTION

The Engineering Treatment Model (ETM) is part of an assessment flaw procedure in order to estimate or predict analytically the load-deformation behaviour of cracked components. A first version of ETM (ETM/1-91) is given in (1). The current extended version (ETM/2-93) is still under preparation but has been verified on some examples (2)-(4). The ETM consists of different independent parts of analytical or numerical solutions, which will be condensed together to a whole construction. The constraint influence in finite thicknesses during the elastic-plastic loading interacts with several geometry and hardening parameters and cannot be considered accurately at time. The main interest with the ETM is directed to the crack opening displacement δ5 which can be measured directly and can be used as a promising fracture parameter (5). Since the 3D effects are not yet systematically understood, more information is necessary to improve the current existing estimation procedures. In this study the 3D constraint effects at stationary cracks has been investigated numerically by FEM on typical standard geometries (CT and CCT) with two distinct limiting thicknesses: relative thin (B = 5 mm) and relative thick (B = 25 mm). With this parameters the 3Dconstraint influence especially on δ5 can be enclosed and some quantitative results can be drawn for the margins of deviations from the ETM estimation based on 2D plane stress conditions.

*) GKSS Research Centre Geesthacht, Max Planck Straße, D-21502 Geesthacht

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ETM TREATMENT OF THE MATERIAL CURVE

An austenitic steel (X6CrNi1811 or AISI 316 respectively) has been considered in the study, and is a typical material class with a wide spread area of applications. Fig. 1 shows the true stress-strain curve. For the ETM application (version ETM/2-93) a specific treatment is necessary to fit the arbitrary material curve by power laws.

The procedure is given briefly as follows: The first and the second hardening part of the material curve was determined by a regression program, where 1 is fixed through point P and n2 through point G*. The experience shows that in most cases the first hardening part has an effective hardening exponent, n4, which is smaller than n1. The average 4 = (n1 + n2)/2 is an good approximation, where n3 is like an upper bound for the first hardening part of the d5 driving force and can be determined easily by the fix-points P and G*. The intersection point of the power law with the initial elastic compliance gives the reference yield stress 04, which is necessary to fix the power laws in the ETM construction. The following values has been determined, which all are at last fixed by the two points P and G*.

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<th>Rp0.2 (MPa)</th>
<th>Rm (MPa)</th>
<th>Rm* (MPa)</th>
<th>e0.2*</th>
<th>em*</th>
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<table>
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<tr>
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<td>197.436</td>
<td>15.7088</td>
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3D SITUATION

The 3D FEM results are restricted here only on the d5 driving force, which is measured at 2.5 mm distance rectangular and versus the crack front quite analog to the experimental technique. Additionally the 2D limiting cases plane strain (upper bound on the load scale) and plane stress (lower bound) are also considered.

For CT specimens Fig. 2a shows d5 at z′ = z/(B/2) = 0 (inside) compared to z′ = 1 (outside) during the loading up to the fully plastic regime. The difference of this relation increases with thickness. Besides the absolute thickness, B, it seems better to introduce the ligament slenderness, B/L, as a controlling constraint parameter. The value B/L = 1 means a square area, which exhibits a higher constraint influence on d5 than small B/L values. In Fig. 2a for B = 25 mm (or B/L = 1) significant difference occurs between inside and outside, which increases during the increasing load, much more than for thin specimens. With this, the following statement should be noted, that for equal B/L values the same constraint situation should be expected, which is contrary to an absolute thickness correlation. This statement will be proved otherwise for B/L = 1 with different thicknesses.

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Using an average value for $\delta_s$ versus the thickness, Fig. 2b, the constraint dependence is then highly reduced below a 10% margin. That means with other words, the $\delta_s$ versus the thickness is for the most part near by the inside situation. The $\delta_s$ dependence for $B = 25$ mm has a parabolic type from inside to outside. Much smaller thickness dependence can be observe on the CCT specimens, Fig. 3, where no significant differences occur between inside and outside for the whole $B/L$ range ($0 \leq B/L \leq 1$).

Thus for austenitic steels the thickness 3D constraint situation with respective to $\delta_s$ is only weakly effected by different thicknesses. For CT specimens with square ligaments ($B/L = 1$) the crack initiation, starting at inside, but measured experimentally by $\delta_s_{outside}$ can occur below compared to respective CCT specimens. From the existing experimental results, however, such behaviour has not yet observed as significant beyond the typical scatter band. Probably, as the experimentally fatigued crack front is normally continuous curved, typically in a thumbnail form, where the difference inside/outside can be smaller than for a straight crack front.

The characteristics of the $\delta_s$ driving force can be seen at the best in a normalized ETM diagram (log-log scale). Fig. 4 for CCT and Fig. 5 for CT show the normalized $\delta_s$ curves together with the 2D limiting cases. It is interested to see, that all $\delta_s$ curves are congruent and differ over the whole loading range by a constant logarithmic shift. This leads to the idea, to determine the individual 3D $\delta_s$ values only at the limit load (or near by), because the following part of the plastic curve is the same as for the plane stress reference case. For the large strain theory (LST) especially for the 2D plane stress case, a significant deviation in the $\delta_s$ driving force curves compared to the small strain theory (SST) can be observed in the second hardening part at high load levels, Fig. 4, 5. For 3D cases this effect takes place much later, so that the SST can be used further in the interested region of application. This is an important statement, because the ETM is based on the SST.

Fig. 6 shows the ETM construction (version ETM/2-93) for CT specimens as an verification example. The ETM details are too extensive to describe them all. Information can be found in (2)-(5). A good coincidence with the 3D cases as a lower bound estimation can be stated. This is mainly due to the use of fully plastic solutions in ETM/2-93, which guarantee a good approximation in the plastic loading regime.

**CONCLUSIONS**

The following conclusions and statements of 3D constraint effects especially on the $\delta_s$ driving force specified for austenitic materials can be drawn:

- For CCT specimens the 3D effects between inside/outside can be neglected.
- For CT specimens the 3D effects between inside/outside appear only about $B/L = 1$ (square ligaments). For values $B/L \leq 0.5$ the 3D effects can be ignored.
- The 3D $\delta_S$ driving force curves are all congruent together and can be shifted in the 2D plane stress solution only by the individual 3D $\delta_S$ value at the net section yield load. This can be a key for a better considering 3D situations on $\delta_S$.
- With the new ETM as a general valid construction $\delta_S$ can due to the small 3D effects be properly described by the 2D plane stress case with high accuracy.

**SYMBOLS USED**

- CTOD = crack tip opening displacement
- CT = Compact Tension specimen, standard fracture test specimen
- CCT = Centre Cracked Tension Panel
- $a_{\text{eff}}$ = effective crack length including the plastic zone size
- $n$ = hardening exponent
- $B$ = thickness
- $B/L$ = ligament slenderness
- $L$ = ligament length
- $F$ = load
- $F_{\text{Y0.2-D}}$ = yield load at net section
- $\delta$ = crack driving force; ±2.5 mm rectangular from the crack tip
- $\delta_{\text{YSY}}$ = $\delta_S$ corresponding to $F_{\text{Y0.2:D}}$
- $\delta_{\text{Sinside}}$ = $\delta_S$ at inside, $z = 0$
- $\delta_{\text{Soutside}}$ = $\delta_S$ at outside (surface), $z = B/2$
- $\delta_{\text{SSY}}$ = analytical formula for estiamte $\delta_S$ at the net section yield load
- $\sigma_0$ = reference yield stress

**REFERENCES**


(4) Cornece, A., Verifizierungsbeispiel zum erweiterten Engineering Treatment Model (ETM/2.93) am Beispiel einer Mittenrilscheibe aus dem Werkstoff StE 460. Technical Note GKSS/WAW/93/12, 1993, GKSS Research Center Geesthacht

(5) GKSS Displacement Gauge Systems for Applications in Fracture Mechanics. GKSS Research Centre, 1992
Fig. 1: Tensile stress-strain material curve

Fig. 2: Behaviour of $\delta_5$ in a 3D CT specimen during loading
Fig. 3: Behaviour of $\delta_{5}$ in a 3D CCT specimen during loading.

Fig. 4: Comparison of 3D and 2D $\delta_{5}$ driving force behaviour for CCT specimens.
Fig. 5: Comparison of 3D and 2D $\delta_5$ driving force behaviour for CT specimens

Fig. 6: Application of the ETM/2-93 version to the 3D CT specimens describing analytically the $\delta_5$ driving force