16^{th} International Research/Expert Conference
"Trends in the Development of Machinery and Associated Technology"
TMT 2012, Dubai, UAE, 10-12 September 2012

EXPERIENCES WITH STANDARDISED ELASTO-PLASTIC FRACTURE MECHANICS PARAMETERS TESTING AND CALCULATION

Ismar Hajro, Damir Hodžić,
Faculty of Mechanical Engineering, University of Sarajevo
Vilsonovo šetalište 9, 71000, Sarajevo
Bosnia and Herzegovina

ABSTRACT

A standardized evaluation of elasto-plastic fracture mechanics (EPFM) parameters, such as J-integral [kJ/mm2] or crack-tip opening displacement (CTOD [mm]) resistance curves, may be performed only on appropriate and specialized testing equipment. Furthermore, calculation of corresponding resistance curves, as defined in respective testing standard, e.g. ASTM E1820, present relatively challenging and complicated task. Therefore this paper present basic aspect of experimental testing and further calculation procedure of EPFM resistance curves. Particular attention is focused on elastic compliance, C [mm/kN], which is considered as key and critical parameter for reliable results. Finally, as result of demonstrative procedure, a typical EPFM resistance curves for selected high-strength structural steel are provided..

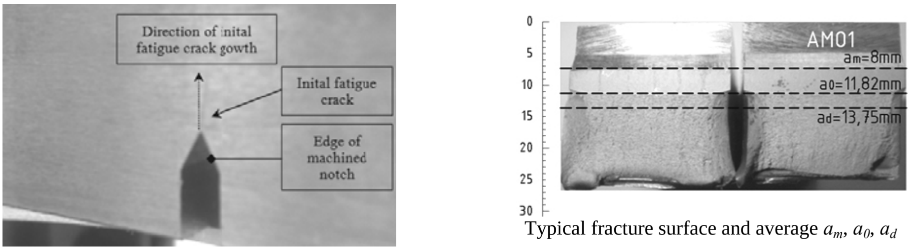
Keywords: elasto-plastic fracture mechanics, EPFM, J-integral, crack-tip opening displacement, CTOD, resistance curve calculation

1. PREFACE

An assessment of structural integrity requires good knowing of materials resistance properties. Among many such as strength and impact toughness, the most important are fracture mechanics parameters. In addition, while considering general structural materials as rather ductile ones, the corresponding resistance curves become more significant and appropriate for application, instead of critical parameters. Therefore, corresponding fracture mechanics (FM) crack growth resistance curves are required, such as J-Δa or $CTOD$-Δa, where J [kJ/m^2] is J-integral, $CTOD$ [mm] is Crack Tip Opening Displacement and Δa [mm] is crack growth. All acquired variables may be general called a quasi-static toughness, or fracture toughness, even the later term is particularly reserved for critical parameter, K_c [MPam^{0,5}] [1]. Of course, there are two ways to acquire crack growth resistance curves: (a) As prediction, using one of the available analytical methods (e.g. as provided in FITNET procedure [2,7]); and (b) Exact determination, using standard testing in accordance to relevant EN / EN ISO, ASTM or BS specification [1,2,6]. Without neglecting of all advantages and disadvantages of the first - predictive method, the purpose of this paper are standardised experimental and further calculation procedures, as specified in ASTM E1820 and BS 7448 (series). Of course, any further users should be aware of constant standard changes and development, not only of ASTM and BS ones, but also new introduced, such as ISO 12737, ISO 15653 or ISO 27306 and its field of application (e.g. either for base or weld metals) [3,4,6].

2. STANDARD EXPERIMENTAL PROCEDURE

To evaluate corresponding resistance curve, the procedure specified in ASTM E1820 [5] utilizes an elastic unloading procedure from a single specimen. Crack length is measured from compliance in this procedure and verified by post-test optical crack length measurements (Fig. 1b). Also, the asses is possible using recommended specimens: single-edge bend (SE(B)), compact, (C(T)), and shaped compact, (DC(T)). All specimens contain notches that are sharpened with fatigue cracks 1a). Specimen dimensions requirements vary according to the fracture toughness analysis a (consideration of material toughness, material flow strength, and the individual qualifi requirements). A fatigue initial crack are about to be made on high-frequency pulsating machine parameters set in accordance to specimen size and material properties [1,6]. Here, particular att should be focused on control of initial fatigue crack growth and dimension (size or length) (Fig. 1 1b). Once the specimen has initial fatigue crack which determine initial crack length, a_0 [mm] 1b), a specimen is ready for quasi-static testing. In a case of SE(B) specimen, such testing i controlled loading/unloading bending sequence. Typical arrangement of specimen during test shown on Fig. 2b. The selected material was structural steel S690QL (EN 10025-6).

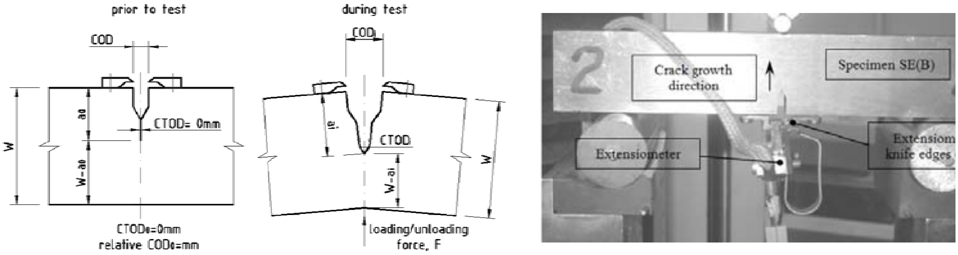


Typical fracture surface and average a_m, a_0, a_d

a) Detail of initial fatigue crack formation b) Specimen with: $B=W=25mm$, $a_m=8mm$

Figure 1. Details of SE(B) specimen notch with initial fatigue crack and fracture surface [1]

During testing, a continuous measurement of force, F [kN] and crack opening displacement, [mm] are necessary (Fig. 2a). This measurement provides direct results of testing, e.g. F- diagram (Fig. 3a). According to standard requirement the maximum crack growth, Δa [mm], c exceed 25% of remaining ligament, $b=W-a$ [mm], where W [mm] is width of specimen. Aft controlled crack growth by using loading/unloading sequence, the intentional specimen fr follows. Further, fractured specimen surface (Fig.1b) is about to be inspected and corresponding lengths, a_m, a_0, a_d, have to be measured. Particularly a_0 and a_d have to be measured on m location-lines due to parabolic crack front shape. Of course, for further consideration an av values have to be used.



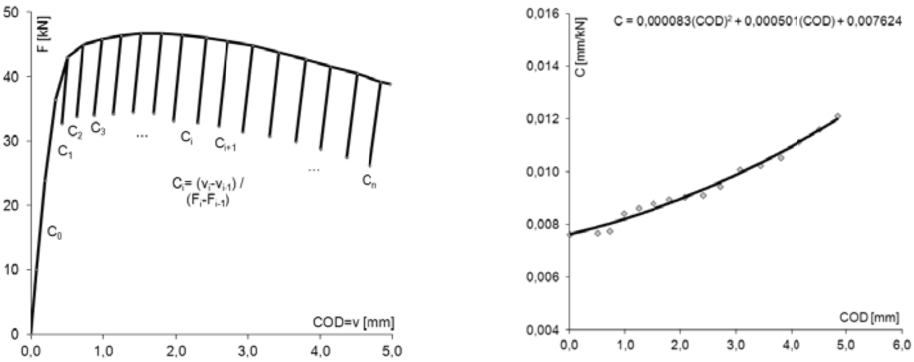
a) Definition of *COD* and *CTOD* b) Details of *COD* and Extensometer

Figure 2. Definition of CTOD and COD and typical test arrangement of SE(B) specimen [1]

3. STANDARD CALCULATION PROCEDURE

The general calculation procedure consisting of [1], while considering terms (Tab. 1, per [5]):

- Calculation of elastic compliance, C_i [mm/kN];
- Calculation of crack length (growth) for every point of loading/unloading sequence, a_i [



a) Typical *F-COD* curve b) Typical *C-COD* regression curve

Figure 3. Typical COD-F diagram and regression analysis of C-COD [1]

Elastic compliance calculation, where $v_i=COD_i$ [mm] and F_i [kN] is calculated in acc. to term (1 Tab. 1 for relevant calculation terms). Here, during specimen testing, with crack growth, a_i c elastic-compliance, C_i, increase.

Table 1. Selected terms for calculation of resistance curves [1,5]

$$C_i=\frac{v_i-v_{i-1}}{F_i-F_{i-1}}\ \ldots(1)\qquad u=\frac{1}{\left[\frac{B_e\cdot W\cdot E\cdot C_i}{S/4}\right]^{1/2}+1}\ \ldots(3)\qquad a_i=\frac{a_i/W}{W}\ \ldots(4)\qquad \Delta a_i=a_i-a_0\ \ldots(5)\qquad K_{(i)}=\left[\frac{P_i\cdot S}{B\cdot W^{3/2}}\right]\cdot f(a_i/W)$$

$$a_i/W=\left[0{,}999748-3{,}9504\cdot u+2{,}9821\cdot u^2-3{,}21408\cdot u^3+51{,}51564\cdot u^4-113{,}031\cdot u^5\right]\ (2)$$

$$CTOD_i=\delta_i=\frac{K^2{}_{(i)}(1-\upsilon^2)}{2\cdot\sigma_{YS}\cdot E}+\frac{\left[r_p(W-a_{(i)})+\Delta a\right]\cdot v_{pl(i)}}{\left[r_p(W-a_{(i)})+a_{(i)}+z\right]}\ \ldots(6)\qquad J_{(i)}=\frac{(K_{(i)})^2\cdot(1-\upsilon^2)}{E}+J_{pl(i)}\ \ldots(8)\qquad v_{pl(i)}=v_i-(P_i\cdot C_i)\ \ldots(11$$

$$f(a_i/W)=\frac{3(a_i/W)^{1/2}\cdot\left[1{,}99-(a_i/W)\cdot(1-a_i/W)\cdot(2{,}15-3{,}93(a_i/W)+2{,}7(a_i/W)^2)\right]}{2(1+2a_i/W)\cdot(1-a_i/W)^{3/2}}\ \ldots(9)\qquad J_{\max}=\min\left(b\cdot\sigma_Y/20;B\cdot\sigma_Y/20\right)$$

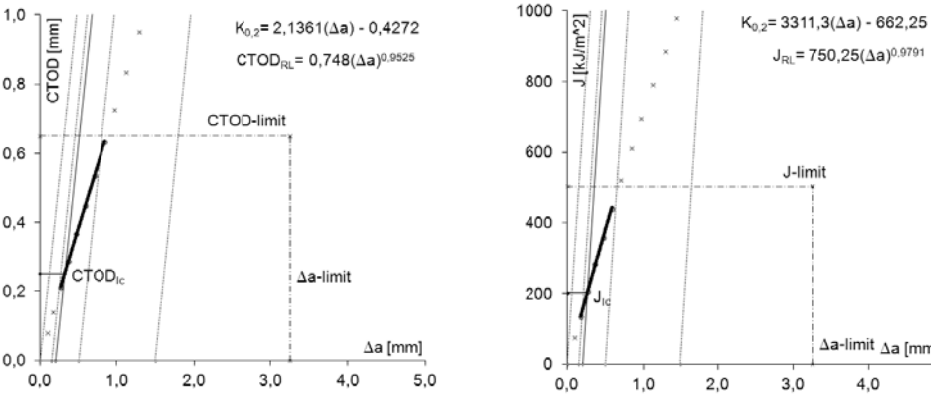
$$J_{pl(i)}=\left[J_{pl(i-1)}+\left(\frac{2}{b_{(i-1)}}\right)\left(\frac{A_{pl(i)}-A_{pl(i-1)}}{B_N}\right)\right]\cdot\left[1-\frac{a_{(i)}-a_{(i-1)}}{b_{(i-1)}}\right]\ \ldots(10)\qquad CTOD_{\max}=\frac{b_0}{20}\ \ldots(12)\qquad \Delta a_{\max}=0{,}25\cdot b_0\ \ldots(13)$$

Variables description and units: $v=COD$ [mm] crack tip opening displacement; $F=P$ [kN] force during loading/unloadi sequence; B_e [mm] effective thickness of specimen; W [mm] specimen width; E [GPa] Young modulus (used, $E=210$ for steel); S [mm] specimen span; A_{pl} [Nm] "energy" as surface below *F-COD* curve for each sequence per ASTM E18 [MPa] effective yield stress.

Correct determination of C_i present critical and key part of calculation procedure, due to the fac minor error may lead to unrealistic results of crack growth. So physically, it is not possible to $C_i<C_{i-1}$, because it could lead to conclusion that crack length, a_i, is decreased. In accordance to E1820, for C_i calculation, it necessary to have high-resolution measurement of F_i (1/4000) and (1/32000), and accuracy of at least 1%. For once obtained *F-COD* curves (Fig. 3a), the thorough of C_i results should be performed. Further, and the regression curve of *C-COD* should be acc (Fig. 3b). Once the reliable C_i results are determined, a relative crack length, a_i/W, is calculated i to term (2), with factor, u, in acc. to term (3). Further, a preliminary crack lengths, a_i, and growth, Δa_i, are calculated in acc. to (4) and (5), respectively. It should be noted that, accordi literature survey [1], it is a common practice to use a bit fitted, v, value in comparison to, *COL* $v=1{,}125(COD)$ for SE(B) specimens. Finally, calculation of $CTOD_i$ in acc. to term (6) and J_i in a (8) follows. As can be seen both variables poses elastic and plastic component; e.g. with v_{pl} for in term (11), and J_{pl} for J in term (10)). Of course, further calculation procedure requires anothe

4. COMMENTS AND REMARKS

Even numerous research use results of fracture mechanics testing, users are usually not awa resistance curves calculation background. Actually most modern fracture mechanics laboratorie available commercial, or own developed software application [6]. Therefore users mostly obtair "final" results (resistance curves or critical values). Also, validity and field of application of pro results may be matter of misleading use or misunderstanding. Thus, user should be aware of t and calculation procedure [1,6]. Finally, this is the partial purpose of this paper. In addition, au own calculation experience; based on MS Excel (with at least) 50x50 cell spreadsheet, about ter control diagrams (including results *J-Δa*, *CTOD-Δa*), and several control loops; have show num challenges with calculation performance [1]. Also, correct determination of C_i present critical an part of calculation procedure, and it should be performed with particular caution.



a) Typical CTOD-Δa curve - steel S690QL b) Typical J-Δa curve - steel S690QL

Figure 4. Typical fracture mechanics resistance curves ($CTOD_{RL}$ and J_{RL} as regression lines)[1]

Once results of fracture mechanics resistance curves are obtained, or available, the user must pe basic check and comparison of provided results with those available in similar researches. Hov depending on subject of investigation at least the following influential parameters must be consic material chemical composition and thickness (both base metal and specimen), notch (initial c position and arrangement and testing temperature. Also, brief comparison with predicted resis curves (e.g. analytically estimated), in accordance to available procedures [2,7], may be helpful, considering its conservatism.

5. REFERENCES

[1] I. Hajro, PhD dissertation, Research of ductile tearing and fracture resistance of quenched and ten high-strength steel's welded joints, Faculty of Mechanical Engineering Sarajevo, University of Sar 2010.
[2] M. Kocak, S. Webster, J.J. Janosh, R.A. Ainsworth, R. Koers, FITNET Fitness-for-Service Proce Final Draft MK7, Prepared by European Fitness-for-Service Thematic Network - FITNET, 2006.
[3] List of new published ISO standards; Secretariat TC164/SC4 - Toughness testing - Fracture (F), Pen (P), Tear (T); ISO - International Organization for Standardization, Geneva, Switze http://www.iso.org/iso/iso_catalogue/catalogue_tc/catalogue_tc_browse.htm?commid=53560; 2012.
[4] List of fatigue standards and fracture standards developed by ASTM, ASTM Interna http://www.astm.org/Standards/fatigue-and-fracture-standards.html; 2012.
[5] ASTM E1820-01, Standard Test Method for Measurement of Fracture Toughness, ASTM Committe on Fatigue and Fracture, Annual Book of ASTM Standards, Vol 03.01, 2001.
[6] Z. Burzic, S. Sedmak, M. Manjgo, Experimental evaluation of weldment fracture mechanics paran