Crack tip field in circumferentially-cracked round bar (CCRB) in tension affected by loss of axial symmetry

J. Toribio, B. González, J.C. Matos
Fracture and Structural Integrity Research Group (FSIRG), University of Salamanca (USAL)
E.P.S., Campus Viriato, Avda. Requejo 33, 49022 Zamora, Spain
toribio@usal.es, bgonzalez@usal.es, jcmatos@usal.es

ABSTRACT. In this paper, the stress intensity factor (SIF) is computed in a circumferentially-cracked round bar (CCRB) subjected to tensile loading, considering that the resistant ligament is circular and exhibits certain eccentricity in relation to the cylinder axis. The computation was performed by means of the finite element method (FEM) using a three dimensional (3D) model and the *J*-integral, the analyzed variable being the eccentricity of the circular ligament. Results show that the SIF is higher at the deepest point of the crack and that an increase of eccentricity (in relation to the bar axis) raises the difference between the SIF values along the crack front. From a certain value of the misalignment a bending effect appears, so that the crack remains closed in the area near the point of lower depth.

KEYWORDS. Stress intensity factor; Finite element method; *J*-integral; Circumferentially-cracked round bar; Eccentricity of circular ligament.

OPEN ACCESS

Citation: Toribio, J., González, B., Matos, J.C., Crack tip field in circumferentially-cracked round bar (CCRB) in tension affected by loss of axial symmetry, Frattura ed Integrità Strutturale, 41 (2017) 139-142.

Received: 28.02.2017
Accepted: 15.04.2017
Published: 01.07.2017

INTRODUCTION

Cylindrical samples with annular cracks exhibit numerous advantages when compared to the standard specimens recommended by the ASTM E399 Standard [1]: (i) they are easy to machine and thus cheaper; (ii) they need less amount of material to guarantee the plane strain condition because their circular geometry increases the constraint, thereby assuring a plane strain state with independence of their size; (iii); the annular crack does not end in a plane stress region. These specimens also exhibit some disadvantages such as the frequent appearance of non-symmetric crack advance [2], thus producing eccentricity of the circular ligament in relation to the bar axis. This phenomenon may be caused by slight non-symmetries regarding the sample, the grips or the testing machine, as well as non-uniform material properties [3], residual stress effects, etc.
Diverse SIF solutions were published in the matter of a circumferentially-cracked round bar (CCRB) subjected to tensile loading, for both symmetric [4-6] and non-symmetric cracks [3,7] where the ligament eccentricity produces additional bending stresses. These specimens have been successfully used to obtain the fracture toughness of different materials [2,3,8,9] where the eccentricity increases the scattering of the measurements [3]. They have been used to evaluate fatigue

crack propagation [9] and stress corrosion cracking (SCC) phenomena [10]. With regard to fatigue, the eccentricity reduces the time to reach the critical situation [11,12] and increasing the instability [13].
In spite of the afore-said references, there is a lack of information in the scientific literature regarding SIF values in points of the crack different from the central one. This paper tries to fill this gap by providing solutions along the crack front.

NUMERICAL MODELING

The finite element method (FEM) together with the MSC.Marc code was employed to obtain the SIF in cylindrical bars with a non-symmetric external annular crack under tensile loading. The resistant ligament, characterized as a circle, is not centered in relation to the bar axis, so a quarter of the solid was modeled (Fig. 1) with the adequate boundary conditions.

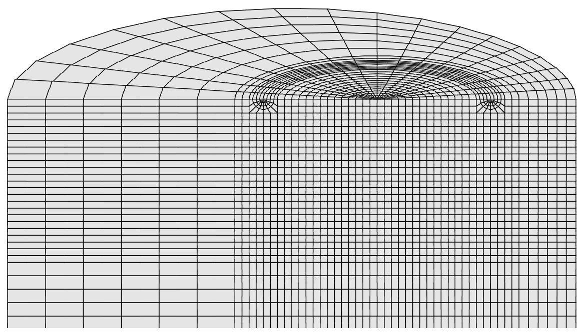

Figure 1: 3D mesh of the bar with a non-symmetric annular crack.

Isoparametric hexahedral elements with 20 nodes were used in the computations, and the middle nodes of the first core surrounding the crack tip were shifted to the quarter-point position to reproduce the $r^{-1/2}$ singularity. In addition, a mesh sensitivity analysis was performed.

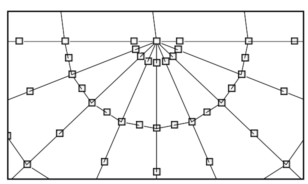

Figure 2: Detail of the finite element mesh in the vicinity of the crack tip.

The mode I (opening) SIF K_I was computed from the J integral by using the expression (for plane strain conditions),

$$K_I = \sqrt{\frac{EJ}{1-\nu^2}} \tag{1}$$

where E is the Young's modulus of the material and ν the Poisson coefficient.
The geometry of the cracked bar was characterized my means of the following parameters: bar diameter D, maximum crack depth a_{max}, minimum crack depth a_{min}, ligament diameter d,

$$d = D - a_{max} - a_{min} \tag{2}$$

and eccentricity, ε,

$$\varepsilon = \frac{a_{max} - a_{min}}{2} \tag{3}$$

The point A on the crack front is associated with the maximum crack depth a_{max} and the point B with the minimum crack depth a_{min} (Fig. 3).

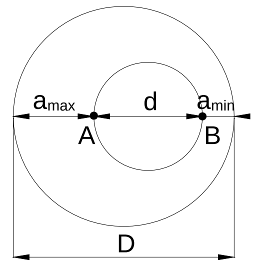

Figure 3: Cracked surface.

NUMERICAL RESULTS

Fig. 4 shows the dimensionless SIF $K_I/\sigma(\pi D)^{1/2}$ along the crack front (characterizing its points by means of the angle θ) for d/D=0.4 and for ε/D from 0 (symmetric case) to 0.200 with increments of 0.025 and Fig. 5 the axial displacement u_z on the deformed profile (showing the initial profile in black color).

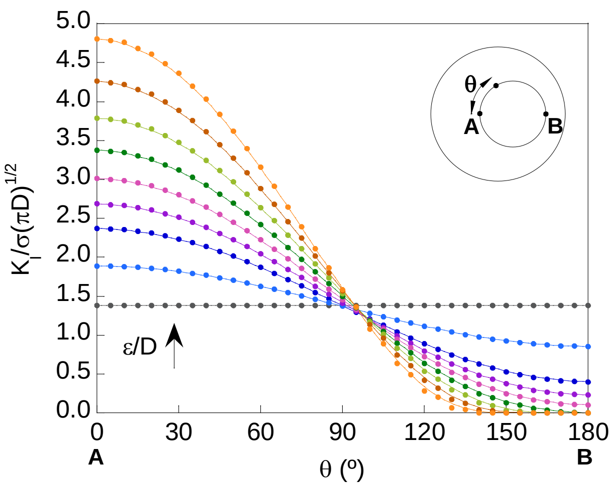

Figure 4: Dimensionless SIF along the crack front for d/D=0.4 and ε/D from 0 to 0.200 with increments of 0.025.

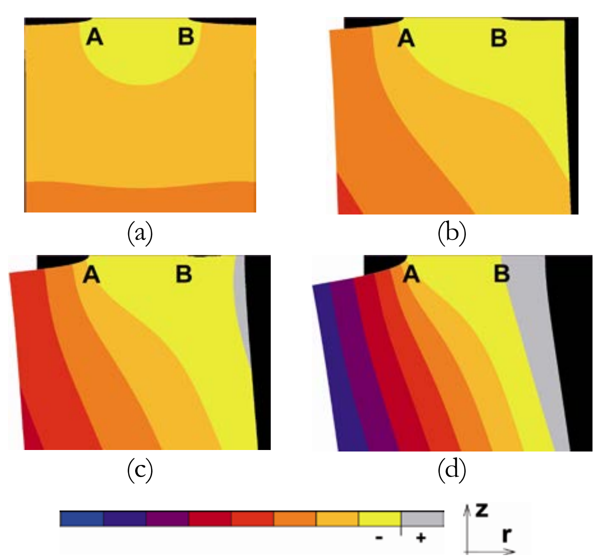

Figure 5: Displacement u_z for d/D=0.4: (a) ε/D=0; (b) ε/D=0.025; (c) ε/D=0.050; (d) ε/D=0.125.

For non-symmetric cracks, the eccentricity of the resistant ligament makes the SIF vary along the crack front, increasing from point B to point A. The increase of eccentricity raises the differences between SIFs at different points of the crack, thereby increasing even more the eccentricity itself when the cracks propagate by fatigue or SCC.
The tensile loading applied at the bar ends generates a bending stress caused by the eccentricity of the ligament, thus provoking a rotation in the sample. From ε/D=0.050 (Fig. 5c) partial contact appears between the crack faces, thereby reducing the trend of SIF increment with the eccentricity and for ε/D=0.125 (Fig. 5d) full contact takes place, so that the crack remains fully closed in the zone associated with the tip B (where the SIF is equal to zero).

CONCLUSIONS

As the eccentricity of the ligament increases, so does the difference between the SIF values along the crack front. From a certain value of the misalignment, as a consequence of the bending effect, the crack remains closed in the area near the point of lower depth B at which the SIF is equal to zero.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the financial support provided by the following Spanish Institutions: MICYT (Grant MAT2002-01831), MEC (Grant BIA2005-08965), MICINN (Grant BIA2008-06810), MINECO (Grant BIA2011-27870) and JCyL (Grants SA067A05, SA111A07 and SA039A08).

REFERENCES

[1] Standard Test Method for Linear-Elastic Plane-Strain Fracture Toughness K_{Ic} of Metallic Materials (ASTM E399), ASTM International, West Conshohocken, (2012).

[2] Stark, H.L., Ibrahim, R.N., Estimating fracture toughness from small specimens, Eng. Fract. Mech., 25 (1986) 395–401. DOI: 10.1016/0013-7944(86)90253-5.

[3] Ibrahim, R.N., Kotousov, A., Eccentricity correction for the evaluation of fracture toughness from cylindrical notched test small specimens, Eng. Fract. Mech., 64 (1999) 49–58. DOI: 10.1016/S0013-7944(99)00056-9.

[4] Benthem, J.P., Koiter, W.T., Asymptotic approximations to crack problems, in: G.C. Sih (Ed.), Method of Analysis and Solutions of Crack Problems, Noordhoft International Publishing, Croningen, (1973) 131–178.

[5] Gray, T.G.F., Convenient closed form stress intensity factors for common crack configurations, Int. J. Fract., 13 (1977) 65–75. DOI: 10.1007/BF00040876.

[6] Dieter, G.E., Mechanical Metallurgy SI edition, McGraw-Hill, Singapore, (1988).

[7] Mattheck, C., Morawietz, P., Munz, D., Stress intensity factors of sickle-shaped cracks in cylindrical bars, Int. J. Fatigue, 7 (1985) 45–47. DOI: 10.1016/0142-1123(85)90007-6.

[8] Ibrahim, R.N., Stark, H.L., Establishing K_{1c} from eccentrically fatigue cracked small circumferentially grooved cylindrical specimens, Int. J. Fract., 44 (1990) 179–188. DOI: 10.1007/BF00035515.

[9] Neelakantha, V.L., Jayaraju, T., Naik, P., Kumar, D., Rajashekar, C.R., Kumar, M., Determination of fracture toughness and fatigue crack growth rate using circumferentially cracked round bar specimens of Al2014T651, Aerosp. Sci. Tech., 47 (2015) 92–97. DOI: 10.1016/j.ast.2015.09.023.

[10] Rihan, R., Singh Raman, R.K., Ibrahim, R.N., Determination of crack growth rate and threshold for caustic cracking (K_{Iscc}) of a cast iron using small circumferential notched tensile (CNT) specimens, Mater. Sci. Eng. A, 425 (2006) 272–277. DOI: 10.1016/j.msea.2006.03.095.

[11] Zhao, Y., Kim, I., Choi, B.-H., Lee, J.-M., Variation of the fatigue lifetime with the initial notch geometry of circular notched bar specimens, Int. J. Fract., 167 (2011) 127–134. DOI: 10.1007/s10704-010-9532-3.

[12] Kim, I., Zhao, Y., Choi, B.-H., Lee, J.M., Lee, K.-S., Lee, J.-M., Numerical analysis of asymmetric fatigue crack growth behaviors of circular notched bar specimen resulting from various geometric misalignments, Eng. Fract. Mech., 108 (2013) 50–64. DOI: 10.1016/j.engfracmech.2013.04.015.

[13] Yngvesson, M., Eccentric circumferential cracks in cylindrical specimens, Int. J. Fract., 102 (2000) L9–L14. DOI: 10.1023/A:1007623622121.