VERIFICAÇÃO DA FORCA MOTRIZ DA PROPAGAÇÃO DE TRINCAS POR FADIGA: ΔK OU ΔK_{ef}? *

Julián Andrés Ortiz González[1]
Jaime Tupiassú Pinho de Castro[2]
Giancarlo Luis Gómez Gonzáles[2]

Resumo

Este estudo apresenta novos resultados que comprovam a confiabilidade e a repetibilidade das medições de cargas de abertura de trincas de fadiga obtidas em estudos anteriores [1,2], que foram usadas para questionar a hipótese proposta por Elber em 1970 de que a força motriz das trincas é a gama efetiva do fator de intensidade de tensões (ΔK_{ef}). Para isto, dois corpos de prova DC(T), um fino com 2 mm e o outro grosso com 30 mm de espessura, foram usados em ensaios de propagação de trincas por fadiga sob ΔK e K_{max} quase constantes, para simular condições dominadas por tensão ou deformação plana. Medições redundantes de ΔK_{ef} foram feitas usando uma série de extensômetros colados ao longo do ligamento residual à frente da ponta da trinca, por outro extensômetro colado na face traseira do DC(T), e por um sistema independente de correlação digital de imagens (DIC), que mede o campo de deslocamentos na face do espécimem. As cargas de abertura medidas pelos três sistemas independentes foram similares, comprovando assim que suas variações significativas observadas durante o crescimento da trinca são metrologicamente confiáveis. Este resultado comprova que a propagação daquelas trincas por fadiga não foi controlada por ΔK_{ef}. As consequências desta conclusão são detalhadamente discutidas neste trabalho.

Palavras-chave: Propagação de trincas por fadiga; Carga de abertura de trinca.

VERIFICATION OF THE DRIVING FORCE FOR FATIGUE CRACK GROWTH: ΔK OR ΔK_{eff}?

Abstract

This study presents new results that confirm the reliability and repeatability of fatigue crack-opening load measurements obtained in previously studies [1,2], which were used to question the hypothesis proposed by Elber in 1970 which assumes that the actual fatigue crack driving force is the effective stress intensity factor (ΔK_{eff}). Two DC(T) specimens with thicknesses 2 mm and 30 mm were used in fatigue crack growth tests under quasi-constant ΔK and K_{max} to simulated plane stress and plane strain conditions. Redundant measurements of ΔK_{eff} were performed by strain gages bonded along the crack growth path, by a strain gage bonded on the back face of the DC(T) specimen, and by a Digital Image Correlation (DIC) system that measures the displacement fields on the specimen surface. The crack opening loads measured by the three independent systems matched quite well, proving that their significant variations observed during the crack growth tests are metrologically reliable. This result demonstrated that the propagation of those fatigue cracks was not controlled by ΔK_{eff}. The consequences of this conclusion are discussed in detail in this work.

Keywords: Fatigue crack growth; Crack opening loads; Crack driving forces.

[1] *M.Sc. in Mechanical Engineering. Mechanical Engineering Department, Pontifical Catholic University of Rio de Janeiro (PUC-Rio), Rio de Janeiro, RJ, Brazil.*
[2] *Ph.D. in Mechanical Engineering, Mechanical Engineering Department, Pontifical Catholic University of Rio de Janeiro (PUC-Rio), Rio de Janeiro, RJ, Brazil.*

ISSN 1516-392X

1 INTRODUCTION

Recent studies [1,2] raised some questions about the validity of blindly assuming that the effective stress intensity factor (ΔK_{eff}) proposed by Elber [3] is indeed the actual fatigue crack driving force. These questions are based on simple but quite convincing experimental data that cannot be explained by Elber's hypothesis.
This study aims to reproduce the experiments performed in those previous studies to verify the reliability and repeatability of those measurements. For that, fatigue crack growth (FCG) tests with similar loading conditions were carried out on two 1020 steel Disk Shaped Compact DC(T) specimens with thicknesses 2 mm and 30 mm, to simulated plane stress and plane strain FCG conditions. These specimens were instrumented with strain gages bonded along the crack growth path ahead of its tip and on their back faces. In addition, a Digital Image Correlation (DIC) system was employed to obtain full-field strain measurements on the region around the crack tip during such FCG tests. Then, crack opening loads were redundantly measured on the two specimens by these three independent systems. The experimental results clearly demonstrated that the propagation of those fatigue cracks was **not** controlled by ΔK_{eff}, confirming in this way the questions raised before [1,2] about the general applicability of Elber's method to all FCG conditions. These studies are an important and necessary step to elaborate an appropriate model to make reliable FCG predictions under variable amplitude loading in practical applications.

1.1 Digital image correlation technique

Digital image correlation (DIC) [4] is currently the most popular and effective optical technique used in experimental mechanics to measure displacements and strains on the surface of stressed components.

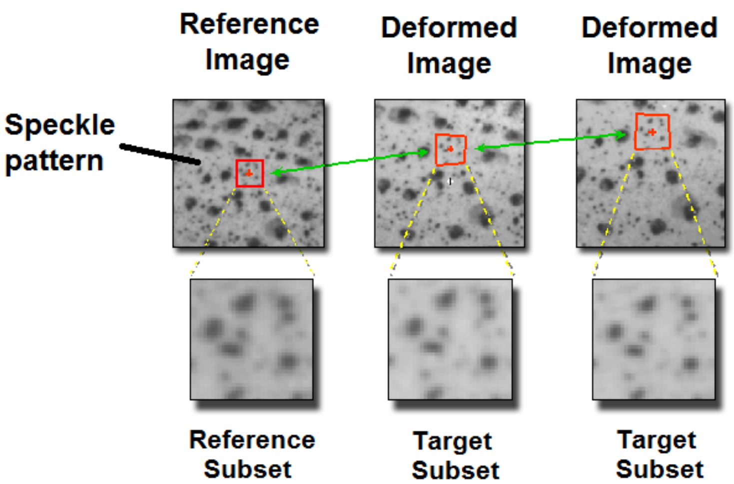


Figure 1. Principle of Digital Image Correlation [4].

In essence, the DIC technique compares (or correlates) two digital images of the material surface acquired at different loading stages, one image that corresponds to the undeformed state (called the reference image), and the other that corresponds to the final or to a partial loading stage (deformed image). The image correlation process works by matching small square subsets of the reference image to locations in the deformed image as illustrated in Fig. 1, by means of a cross correlation function. Once the location of all subsets in the deformed image is found, the displacement of each subset is determined, and from them the corresponding strain components can be obtained. For this technique to work adequately, the surface of the object must have a high-contrast granular morphology. Otherwise, the sample must be prepared beforehand by first painting its surface white and then applying over it a random pattern of small black dots (speckle pattern).

1.2 Measuring crack opening load

Elber [3] in his investigation observed that a fatigue crack subjected to positive loading cycles remains partially closed at lower load levels until fully opening at its so-called opening load (P_{op}). According to Elber, crack closure is plasticity-induced by the reaction of the elastic residual ligament that tends to compress the plastified envelopes that wrap fatigue cracks as they try to recover their previous shape when unloaded. So, when a crack closed by its residual ligament is reloaded, it should first gradually relieve the compressive loads transmitted through its faces until it reaches its opening load. Figure 2 shows a traditional P_{op} measurement. The crack opening load is determined at the point where the $P \times \delta_P$ curve takes on a constant slope for higher value loads, where δ_P is the load point displacement or any other quantity proportional to it, like the back face strain. So, the opening loads can be obtained from strain measurements or from a robust DIC analysis, following e.g. ASTM E647 [5] standard procedures.

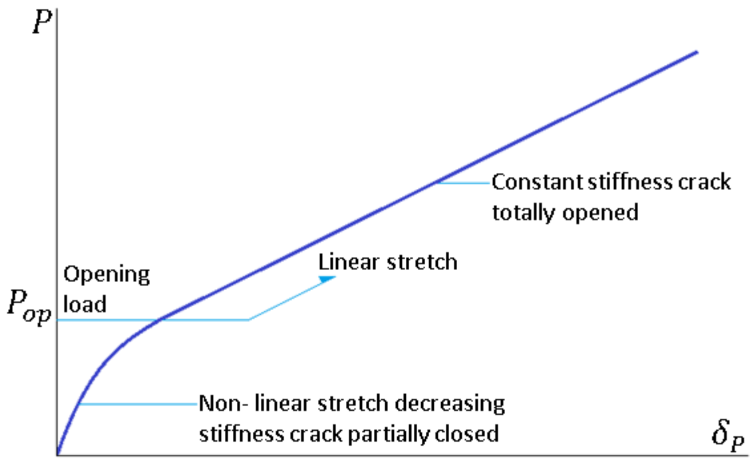


Figure 2. Load vs Displacement curve to determine the crack opening load.

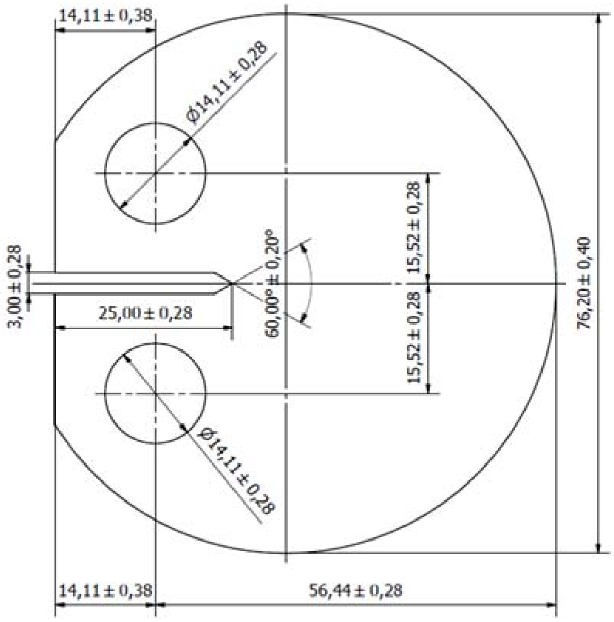
1.3 Fatigue Crack Closure considerations

According to Elber [3, 6], the crack opening loads vary with the plastic zone size, which depends of the stress state around the crack tip and is thus associated to the thickness of the cracked specimen. Hence, predictions of FCG da/dN rates based on the ΔK_{eff} are in principle affected by the specimen thickness [7-10]. To define the stress state ahead the crack tip, it is necessary to calculate the maximum size of its plastic zone (zp_{max}) and compare it with the specimen thickness (t). If $t \leq zp_{max}$, the crack grows under predominantly plane stress conditions, and if $t >> zp_{max}$ it grows under predominantly plane strain conditions. If neither such conditions are satisfied, the crack grows under a mixed state [7]. In this study, the samples were designed to obey plane stress (t = 2) and plane strain (t = 30) conditions, to analyze possible stress state effects near the crack tip on the FCG rate.

ISSN 1516-392X

2 MATERIALS AND METHODS

FCG tests were conducted on AISI 1020 steel 76mm diameter DC(T) specimens following standard ASTM procedures [5, 11]. The geometry, applied loads and material properties of the specimens are shown in Fig. 3.



Material: steel AISI 1020

C 0.2%; Mn 0.55%; Si 0.12%; Cu 0.18%; Cr 0.07; Ni 0.05; S 0.022%; P 0.019.

S_Y = 262 MPa.

ΔK = 20 MPa √m.

Plane stress t = 2 mm; R=0.1.

Plane strain t = 30 mm; R=0.1.

ΔK_{th} = 11.6 MPa √m; ΔK_C = 130 MPa √m.

Figure 3. DC(T) specimen geometry and material properties.

These tests were performed under a quasi-constant SIF range *ΔK* = 20 MPa√m and R = 0.1, using Eqs. (1-5). No overloads or similar events were applied on the tested specimens. Measurements of the crack length during testing were obtained using a travelling optical microscope and compliance methods [5].

$$K = \frac{P}{t\sqrt{w}} * \frac{\left(2+\frac{a}{w}\right)\left[0.76+4.8\frac{a}{w}-11.58\left(\frac{a}{w}\right)^2+11.43\left(\frac{a}{w}\right)^3-4.08\left(\frac{a}{w}\right)^4\right]}{\left(1-\frac{a}{w}\right)^{\frac{3}{2}}} \qquad (1)$$

$$zp_{max} = \frac{K_{max}^2}{\pi S_y^2}\begin{cases} t \le zp_{max}\,;\, plane\ stress \\ t > 2.5\left(\frac{K_{max}}{S_y}\right)^2 \ plane\ strain \end{cases} \qquad (2)$$

$$\Delta K_{th} < \Delta K \ and \ K_{max} \ll K_C \qquad (3)$$

$$\Delta K = K_{max} - K_{min} \qquad (4)$$

$$R = \frac{K_{min}}{K_{max}} \qquad (5)$$

where: *K* = stress intensity factor; *P* = force applied on the specimen; *t* = specimen thickness; *w* = specimen width; *a* = crack size; zp_{max} = maximum plastic zone (Irwin's

ISSN 1516-392X

estimate) [7]; S_Y = yield strength; K_{max} = maximum stress intensity factor; ΔK = stress intensity range; K_{min} = minimum stress intensity factor; $R = K_{min}/K_{max}$ = load ratio.
The samples were instrumented using a gage strip with several strain gages bonded ahead the crack tip (so on its growing path) and another strain gage located at the back face of the DC(T) specimen, as shown in Fig. 4.a. For the DIC analyses, the opposite sample surfaces were covered first with a uniform coat of white paint, over which small black dots were sprayed (see Fig 4.b). The DIC system used in this study, a Correlation Solutions VIC-3D [12], uses two 5-MP CCD cameras (Point Grey GRAS-50S5M) equipped with magnification lenses (Tamron SP AF180mm F/3.5). For image acquisition, the two cameras were placed in front of the specimen in a stereo configuration, as shown in Fig. 5.

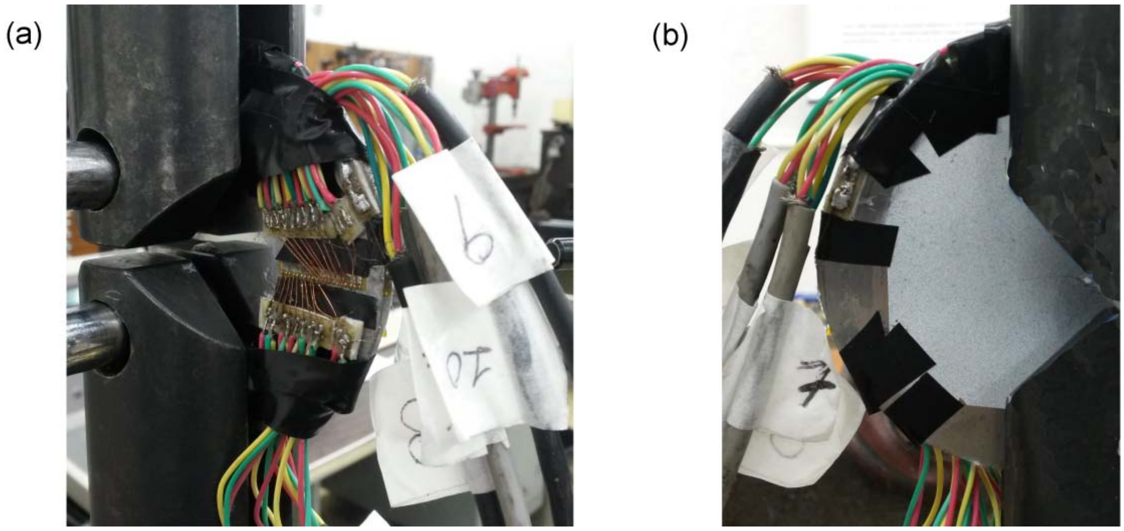


Figure 4. (a) Strain gages arrangements. (b) Speckle pattern used for DIC analysis

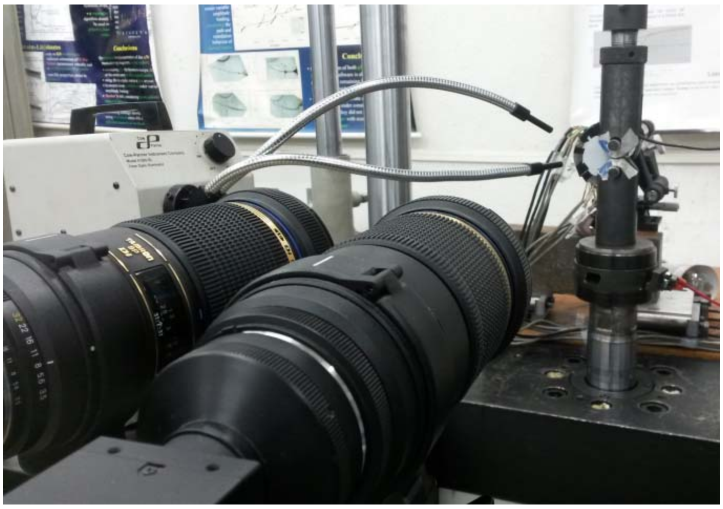


Figure 5. Experimental set-up.

The images were processed by the VIC-3D software to obtain the full field strain distribution around the crack tip (using subset = 37 pixels, step = 9 pixels, and strain window size = 15). Since the load is applied in the vertical direction, the vertical strain map is used to obtain the crack opening load (P_{op}). For that, two measurement points are located, one about 1 mm ahead the crack tip and other about 4 mm ahead the crack tip, see Fig. 6. Notice that the data points around the crack faces and too near the crack tip were excluded from these analyses to avoid their high noise level.

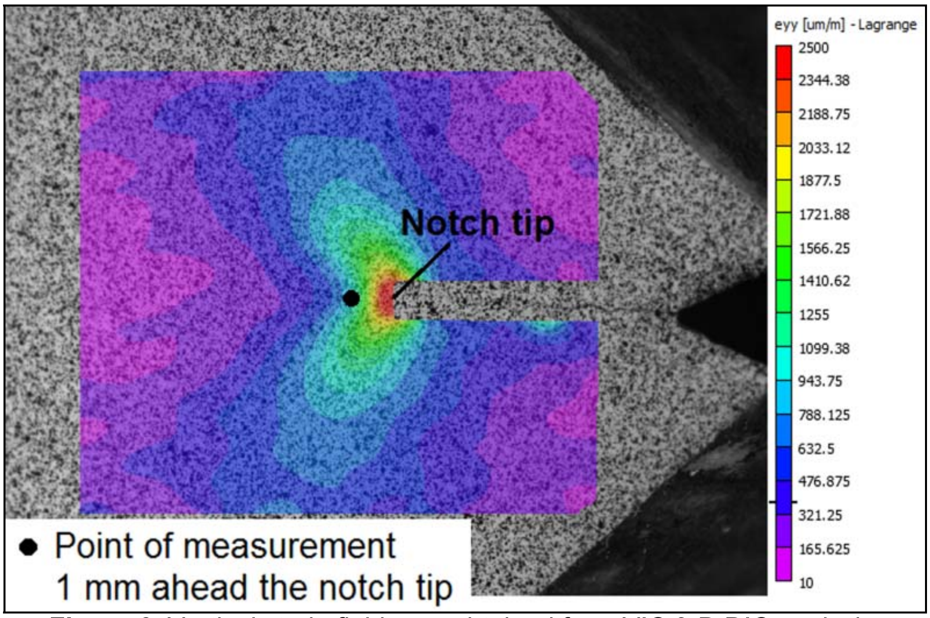


Figure 6. Vertical strain field map obtained from VIC 3-D DIC analysis.

3 RESULTS AND DISCUSSION

Figure 7 shows an example of a crack opening load (P_{op}) measurement using the strain data from the two strain gages arrangements (back face and near crack tip) and from the DIC analysis. It can be seen that the P_{op} loads determined by the three independent systems exhibits a quite good agreement. Similar behavior was found in all cases, verifying thus the reliability of the P_{op} measurements.

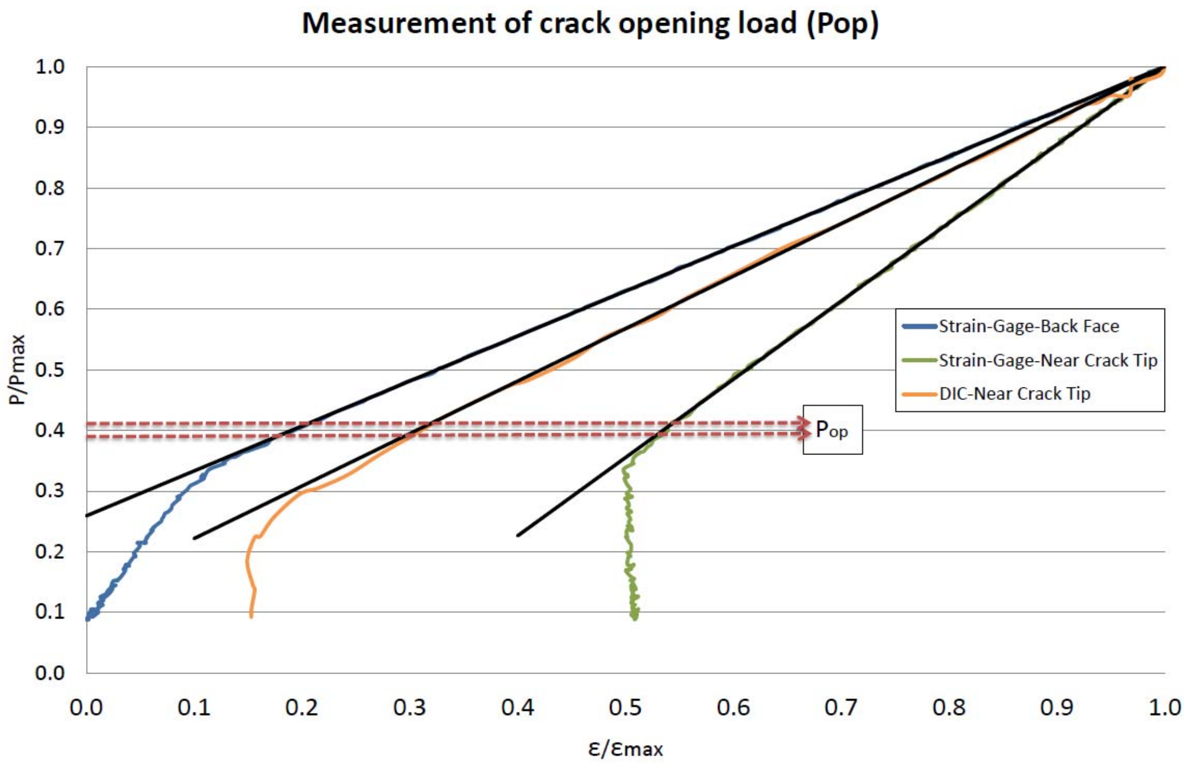


Figure 7. P_{op} measurements made from strain gage readings and from DIC analysis.

Figures 8 and 9 depict the main results obtained from the FCG tests for plane stress and plane strain, respectively. These figures show the evolution of the FCG rates and of the crack opening ratios K_{op}/K_{max} measured along the crack growth process. The results calculated from the strain gage readings from DIC analyses have the same trend along the entire crack path. From these experimental results, it can be seen that the behavior of the crack opening ratio K_{op}/K_{max} significantly ***decreased*** with the increase of the crack length, although the FCG rate remained approximately constant during the entire tests (about $1.3x10^{-5}$ mm/cycle). Therefore, such results clearly contradict Elber's hypothesis that ***assumes*** the effective stress intensity factor ΔK_{eff} as the actual fatigue crack driving force [3]. In addition, the experimental results obtained in previous studies [1,2] are plotted in the same figures as well, to shown the repeatability of these measurements. Moreover, notice that there is no significant difference in FCG rates in both specimens, even though in the thinner one the crack grew under plane stress and in the thicker one it grew under plane strain conditions, contradicting once more Elber's postulate that there should be a thickness effect on FGC rates depending on the dominant stress state around the crack tip [8].

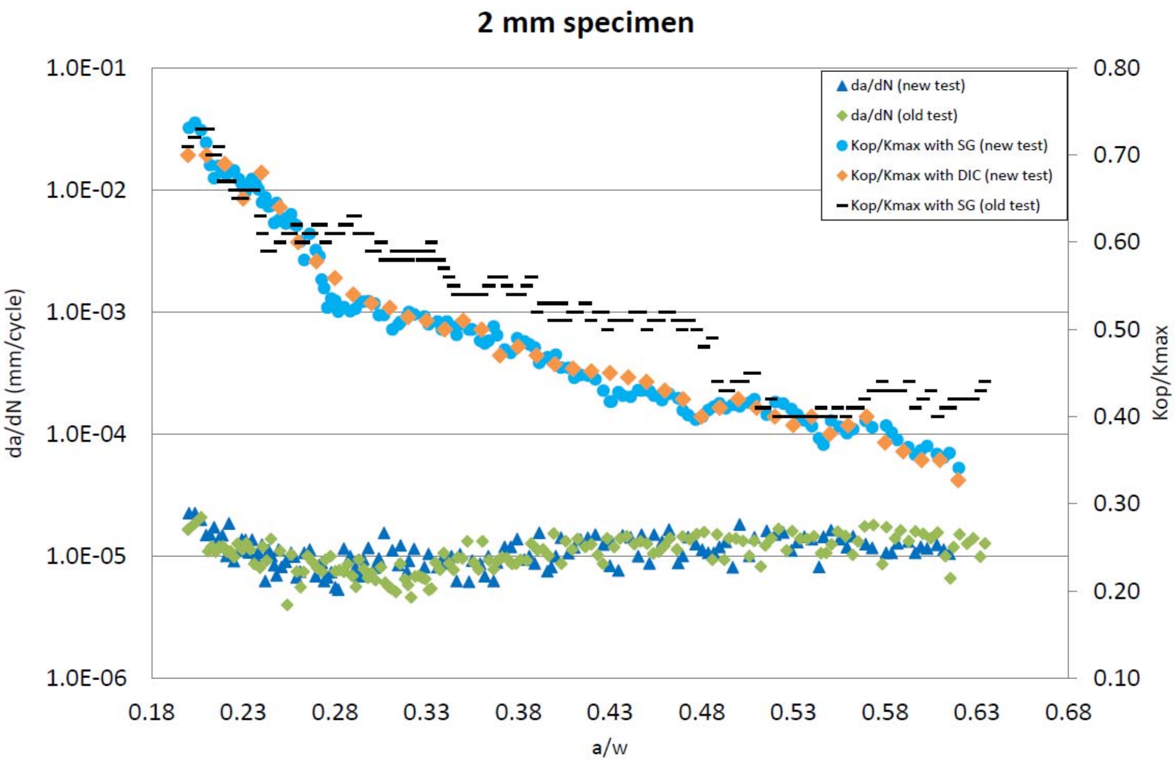


Figure 8. Data from the FCG experiment in plane stress

In the other hand, these experimental results confirm the stable behavior of the FCG rate under fixed ΔK and R, as originally proposed by Paris, and Vasudevan's idea that the actual FCG forces are ΔK and K_{max} [13, 14].
Another way to analyze the results of these experiments is shown in figures 10 and 11, which emphasizes that same FCG rate can be associated with different ΔK_{eff} values both in plane stress and plane strain. These figures clearly show that the decrease of the K_{op}/K_{max} ratio as the cracks increase in size does not affect the FGC rate, which directly contradicts the Elber's principle, and thus eventual FCG predictions based on it [15, 16].

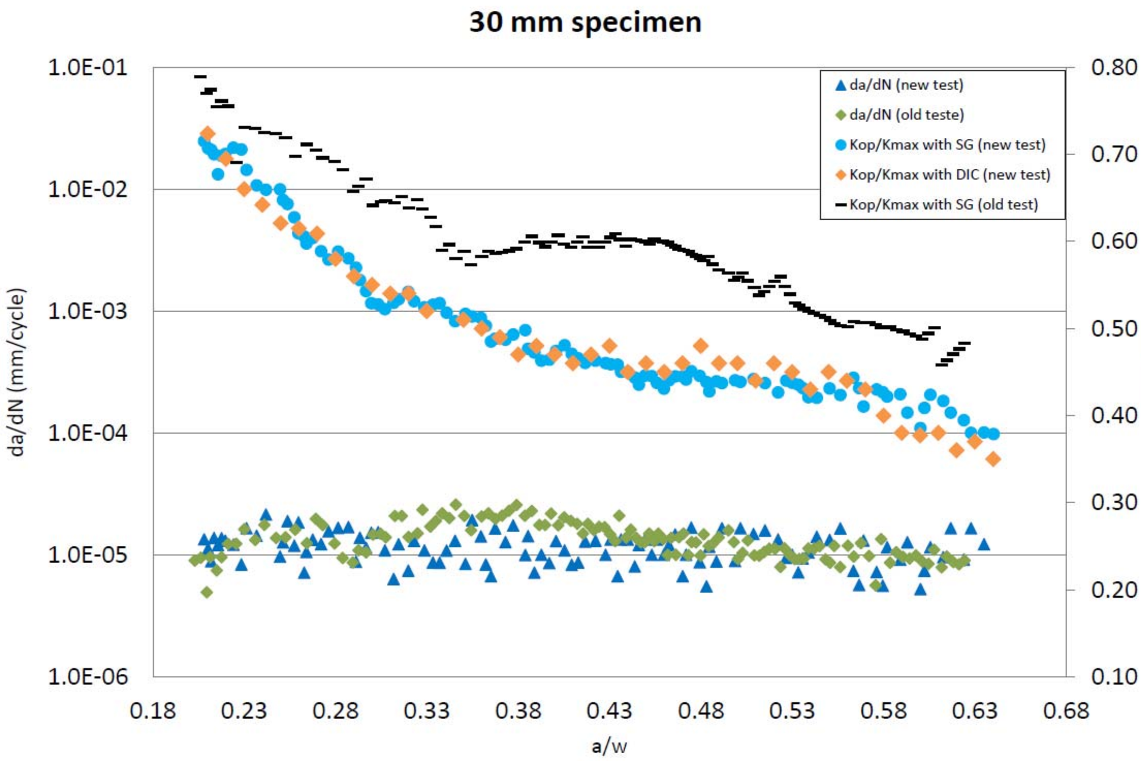


Figure 9. Data from the FCG experiment in plane strain

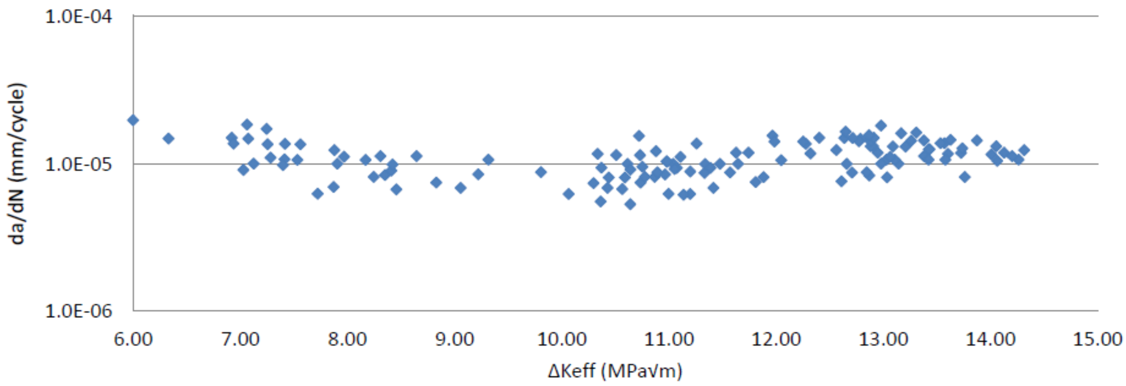


Figure 10. da/dn vs ΔK_{eff} in plane stress

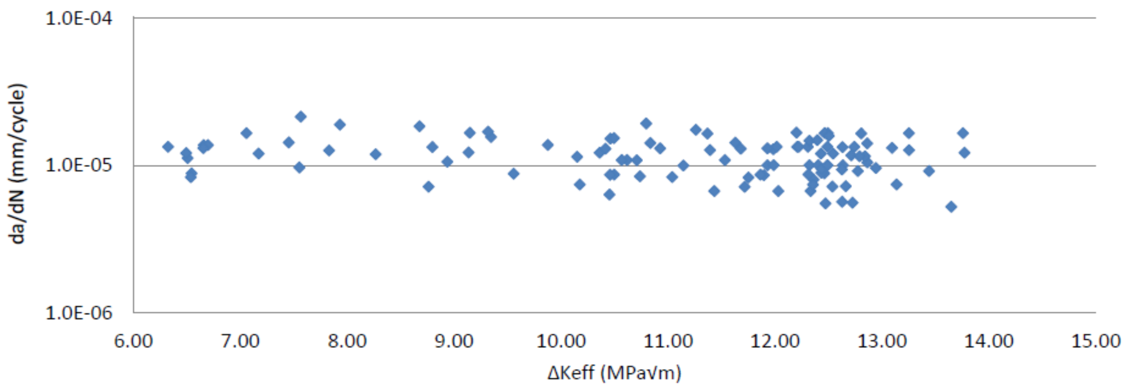


Figure 11. da/dn vs ΔK_{eff} in plane strain

4 CONCLUSIONS

Fatigue crack opening loads (P_{op}) were redundantly measured on FCG tests under fixed ΔK and R conditions, both under plane stress and plane strain conditions, by two strain gage arrangements, one bonded on the back face and the other bonded along the residual ligament of DC(T) specimens, and by a third independent DIC system. The P_{op} values obtained by these 3 methods showed no discrepancy, confirming the reliability and repeatability of the data obtained in similar previous studies. Since the ΔK_{eff} measured along those tests augmented significantly with the crack size (Figure 10 and 11), whereas the measured da/dN FCG rates remained practically constant, it can be concluded that Elber's effective stress intensity factor range is not the FCG controlling driving force for the analyzed cracks.

REFERÊNCIAS

1 Castro, J.T.P., Meggiolaro, M.A., and González, J.A.O., "Can ΔKeff be assumed as the driving force for fatigue crack growth?", Frattura ed Integritá Strutturale, (33), 97, 2015.
2 Castro, J.T.P., and González, J.A.O., "Avaliação da força motriz do crescimento de trincas por fadiga, com ensaios em deformação plana e em tensão plana, com ΔK constante, 70° Congresso Anual da ABM, Rio de Janeiro, RJ, Brasil, 2015.
3 Elber W. The Significance of Fatigue Crack Closure. Damage Tolerance of Aircraft Structures. 1971; 486: 230-242.
4 Sutton, M. A., Orteu, J. J., and Schreier, H., "Image Correlation for Shape, Motion and Deformation Measurements: Basic Concepts, Theory and Applications", Springer Science & Business Media, 2009.
5 ASTM E647. Standard Test Methods for Measurement of Fatigue Crack Growth Rates. ASTM Standards. 2013; 03.01.
6 Elber W. Fatigue Crack Closure Under Cyclic Tension. Engineering fracture mechanics. 1970; 2: 37-45.
7 Castro JTP, and Meggiolaro MA. Fadiga - Técnicas e Práticas de Dimensionamento Estrutural sob Cargas Reais de Serviço. Scotts Valley: CreateSpace; 2009.
8 NASGRO. Fracture Mechanics and Fatigue Crack Growth Analysis Software. Reference Manual. NASA. 2002. Version 4.02.
9 Skorupa M, Machniewicz T, Skorupa A. Applicability of the ASTM Compliance Offset Method to Determine Crack Closure Levels for Structural Steel. International Journal of Fatigue. 2007; 29: 1434–1451.
10 Vasudevan AK, Sadananda K, Louat N. Reconsideration of Fatigue Crack Closure. Scripta Metallurgica et Materialia. 1992; 27: 1663-1678.
11 ASTM E399. Standard Test Method for Linear-Elastic Plane-Strain Fracture Toughness K_{Ic} of Metallic Materials 2013; 03.01.
12 Correlated Solution Inc., VIC-3D 2010, http://www.correlatedsolutions.com /.
13 Paris PC, Erdogan F. A Critical Analysis of Crack Propagation Laws. Journal of Basic Engineering.1963; 85: 528-534.
14 K. Sadananda and a. K. Vasudevan, "Crack tip driving forces and crack growth representation under fatigue," Int. J. Fatigue, vol. 26, pp. 39–47, 2004.
15 Schijve J. Fatigue of Structures and Materials, 2nd Ed. Delft: Springer; 2009.
16 J. Newman, J, C, "A crack opening stress equation for fatigue crack growth," Int. J. Fract., vol. 24, pp. 131–135, 1984.