



On DIC measurements of ΔK_{eff} to verify if it is the FCG driving force

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ABSTRACT. Redundant data obtained under quasi-constant $\{\Delta K, K_{max}\}$ loading conditions is used to verify if the effective stress intensity factor (SIF) range $\Delta K_{eff} = K_{max} - K_{op}$ is indeed the fatigue crack driving force. The crack opening SIF K_{op} is measured along the entire crack path on DC(T) low carbon steel specimens by a series of strain gages bonded along the crack paths, by a strain gage bonded on their back faces, and by a digital image correlation technique. All such measurements showed a significant K_{op} decrease as the crack sizes increased, while the fatigue crack growth rates remained essentially constant both in the thin and thick specimens, a behavior that cannot be explained by ΔK_{eff} arguments.

KEYWORDS. Fatigue crack driving forces; opening load measurements; ΔK_{eff} limitations.



Citation: González, J.A.O., Castro, J.T.P., Gonzáles, G.L.G., Meggiolaro, M.A., Freire, J.L.F. On short cracks that depart from elastoplastic notch tips, *Frattura ed Integrità Strutturale*, 41 (2017) 227-235.

Received: 28.02.2017

Accepted: 03.05.2017

Published: 01.07.2017

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INTRODUCTION

It is well known that the order of load events can much affect fatigue crack growth (FCG) lives, inducing sequence effects by several mechanisms. Such mechanisms can act along the crack faces, so *before* the crack tip (like fatigue crack closure induced by plasticity, roughness, phase transformation, and/or oxidation); or at the crack tip (such as blunting, kinking, or bifurcation of the crack tip); or else ahead of the crack tip (like residual stresses and/or strains in the uncracked residual ligament) [1-2]. Moreover, these mechanisms are not exclusive, and their relative importance may depend on many factors, among them at least: load and overload (OL) ranges and maxima; number of OL cycles; crack and uncracked residual ligament (r_l) sizes; transversal constraints along the crack front; residual stresses around the crack tip; material microstructure; and environment.

In many cases, a load order mechanism can be so dominant that the others may become negligible. However, in other cases such mechanisms can compete (e.g. OL-induced crack tip bifurcation can reduce the subsequent opening load and decrease crack closure effects), or else act symbiotically (e.g. plasticity-induced martensitic transformation tends to increase the material volume inside the plastic zones and thus the residual stresses ahead, as well as the crack opening loads behind the crack tip). Since so many variables can affect the FCG behavior under variable amplitude loads (VAL), there is yet no consensus on how to model properly this most important practical problem. Many fatigue experts defend

that Elber's plasticity-induced crack closure (PICC) is the sole or at least the dominant cause for all load order effects on FCG, whereas many others deny that PICC may be even relevant in such problems, or in FCG for that matter. Since this work does not aim to review or analyze such conflicting claims, see for instance [3-5] for a small sample of the arguments that support them. The objective here is to propose and analyze a simple and easily reproducible test that can clearly identify the actual role of crack closure in FCG, at least under constant amplitude loads (CAL).

Kemp states that tests to support (or to deny) that the effective SIF range ΔK_{eff} is (or is not) the FCG driving force should always include proper closure measurements [6]. He evaluates mechanical (compliance), optical, ultrasonic, electrical (potential drop), and metallographic techniques used to measure opening loads P_{op} , and lists many closure mechanisms and models used to quantify it. He says that compliance techniques are the most reliable to measure P_{op} , but claims that such tests must be carefully made and analyzed. He also says that, besides on P_{op} , crack closure depends on many factors, such as the cracked component thickness, alloy strength, grain structure, crack morphology, load conditions, and/or the environment. Therefore, if FCG rates are really controlled by ΔK_{eff} , crack closure dependence on too many factors could be a major issue for structural design and analyses, since FCG rate predictions cannot assume that similar $\{\Delta K, K_{max}\}$ loading conditions induce identical opening loads (and thus ΔK_{eff}) in all cracked components.

Moreover, if PICC is indeed the FCG driving force, due to variable plasticity-induced transversal contraction restrictions, K_{op} should be larger and FCG rates should be lower in thin pieces, i.e. under predominantly plane stress ($p/l-\sigma$) conditions, than in thick ones, where most of the crack front grows under plane strain ($p/l-\epsilon$). Likewise, OLs should affect much more the cracked piece surfaces, because their plastic zones p_{OL} are larger in $p/l-\sigma$ than in $p/l-\epsilon$ regions along the crack tip. Some authors even attribute all or most OL-induced delay effects in thick pieces to their surface behavior [7-8].

However, not all load order phenomena can be well explained by surface PICC arguments. An important detail can illustrate this claim: how the delayed crack fronts can remain almost parallel after OLs, as they usually do. Indeed, if the crack is driven by ΔK_{eff} , and if ΔK_{eff} varies along the crack front due to higher OL-induced closure effects in $p/l-\sigma$ regions near the cracked component faces, why then do the central parts of the crack fronts that grow under $p/l-\epsilon$ at a higher ΔK_{eff} not propagate faster and gradually increase their curvature? In some cases they do, see Figs. 1-2 [9].

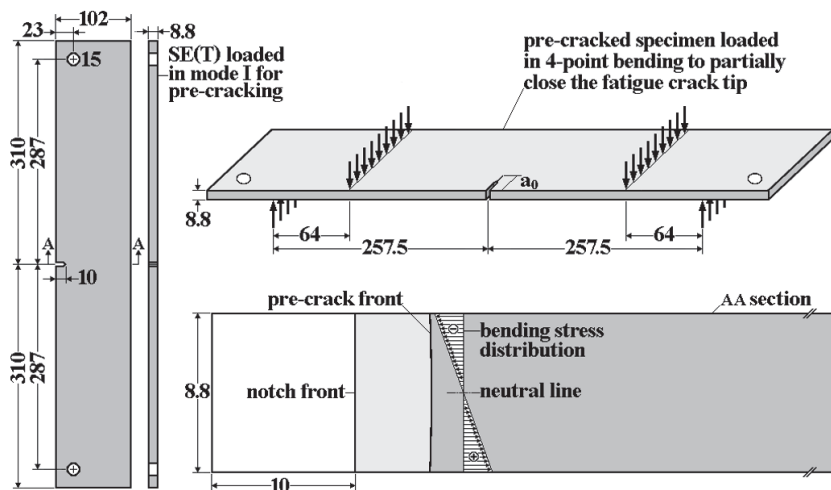


Figure 1: Pre-cracked SE(T) specimen loaded in pure bending to partially close its crack.

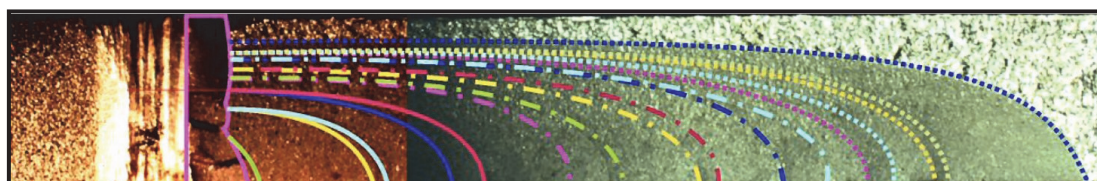


Figure 2: Successive crack fronts propagated in transversal bending from an initially straight shape.

Fig. 1 schematizes edge cracks initially grown in SE(T) specimens under pure tension loads at $R \cong 0.05$, generating approximately straight fronts. Then these pre-cracked specimens were repositioned and reloaded under 4-point bending (maintaining the same R), to work as a flat beam with a side crack. Fig. 2 shows the resulting crack fronts.



These figures clearly demonstrate that a partially closed fatigue crack can grow in the portion of its front that opens under tensile loads, while the portion that is under compression stands still. These bent cracks partially close their fronts under the compressive stresses induced by the bending loads, so they can verify how fatigue cracks grow under variable driving forces along their fronts. In fact, since the partial closure of the crack front is induced by compression caused by external bending loads, it occurs independently of Elber's PICC or of any other type of internal closure mechanism. The cracks tested in such way severely distorted their initially (quasi) straight fronts while they grew after changing the load applied on the pre-cracked plates from pure tensile to pure transversal bending. Indeed, the successive crack fronts depicted in Fig. 2 clearly show that, although the pre-crack front was initially almost linear, it slowly assumed an increasingly elongated L-shape after propagating partially closed during its subsequent 2D FCG under pulsating bending loads. This is exactly the expected behavior of a crack front that gradually advances by fatigue influenced by the *local* value of the crack driving force, which clearly varies along it. Questions like that indicate that the hypothesis " ΔK_{eff} controls FCG" cannot be accepted dogmatically, to say the least. Moreover, it is not evident that all closed fatigue crack tips always remain unloaded, let alone that they can only grow after fully opened. Albeit only careful K_{op} measurements can identify if and how ΔK_{eff} affects FCG, to prove PICC is their *only* cause it must be separated from other closure mechanisms whereas all other delay mechanisms must be ruled out as well.

To question the actual role of ΔK_{eff} in FCG certainly is a most important practical issue. Traditional da/dN procedures assume fatigue cracks loaded under fixed $\{\Delta K, K_{max}\}$ grow under identical rates in any piece of a given material. The SIF-based similarity principle could not be used in FCG modeling if that was not so. However, identical loading conditions do not imply in identical crack opening loads, since P_{op} may depend e.g. on the thickness and on the size of the residual ligament r_l that forces the crack to close. So, whereas for a given geometry and crack size ΔK and K_{max} can be calculated from ΔP and P_{max} using catalog expressions, ΔK_{eff} cannot. Hence, the use of ΔK_{eff} to predict FCG can pose major problems in practical applications. In other words, albeit Elber's PICC remains the most popular mechanism to explain load order effects on FCG under VAL, there are reasonable doubts whether it is the sole or even if it is the main one, which are explored in the following simply because they are too important to be ignored. Moreover, the main problem with this concept is how to use it in practice: there is no foolproof universal method yet to reliably calculate K_{op} and ΔK_{eff} in the complex structural components engineers must deal with. Since only simplified models are available to *estimate* K_{op} values based on an idealized behavior of very simple geometries, this is indeed a major problem for ΔK_{eff} -based FCG predictions.

TESTS TO VERIFY IF ΔK_{EFF} IS THE ACTUAL FCG DRIVING FORCE

Although Elber's PICC certainly is a plausible mechanism to explain many peculiarities of the FCG behavior, it has, at least, some limitations. Indeed, if ΔK_{eff} controls FCG, and if closure is larger at the cracked piece surfaces, then the fatigue lives of thin pieces (with a large $p\bar{z}/t$ ratio) that work under $p/l-\sigma$ FCG should be larger than the lives of similar but thicker pieces that work under equally fixed $\{\Delta K, R\}$ loading conditions in $p/l-\varepsilon$. Even under such simple conditions, if the crack starts to grow under $p/l-\varepsilon$, as it usually does, and gradually changes to a $p/l-\sigma$ dominated stress state as its size increases, then FCG rates should vary in the same piece between these two limit cases. Hence, not even experimental $da/dN \times \Delta K_{eff}$ data would provide enough information on the FCG behavior of structural materials. In fact, without the K -similarity it would be very difficult to reliably model FCG lives of most structural components even in very simple practical applications.

Simple and easily reproducible FCG tests have been performed to verify the actual role of ΔK_{eff} in FCG. Cracks were grown under quasi-constant $\{\Delta K, R\}$ in thin and thick DC(T) SAE 1020 steel specimens, carefully measuring FCG rates da/dN and crack opening loads P_{op} along the crack path. The thickness t of the specimens was chosen to guarantee $p/l-\sigma$ (making $p\bar{z}/t \cong 1$) in the thin and $p/l-\varepsilon$ conditions in the thicker ones (making $t > 2.5(K_{max}/S_Y)^2$), assuming this classic ASTM E399 requirement can be used in fatigue as well. All the DC(I) specimens were cut from an as-received 76mm wrought round bar with yield strength $S_Y = 262MPa$ and ultimate tensile strength $S_U = 457MPa$. ΔK and R were maintained almost fixed adjusting the load at small crack increments, following standard ASTM E647 procedures. The crack length was measured by compliance and by optical methods, using a strain gage bonded on the back face of the specimens and a traveling microscope. In four tests, the crack opening load P_{op} was redundantly measured by compliance techniques using linearity subtractor procedures [8, 10-11] on the signals of the back-face strain gage, and of a strip with several gages bonded ahead of the notch tip, see Fig. 3. In other four specimens, the opening loads were also simultaneously measured using digital image correlation (DIC) techniques, see Figs. 4 and 5. The P_{op} values measured by

the near and the far-field gages, as well as by the DIC analyses, showed no significant discrepancy, meaning that practically the same value was obtained from all of them, see Figs. 6 and 7. Fig. 8 shows the crack faces of a thick specimen with homologous or quasi-parallel crack fronts, which indicate a constant driving force along them.

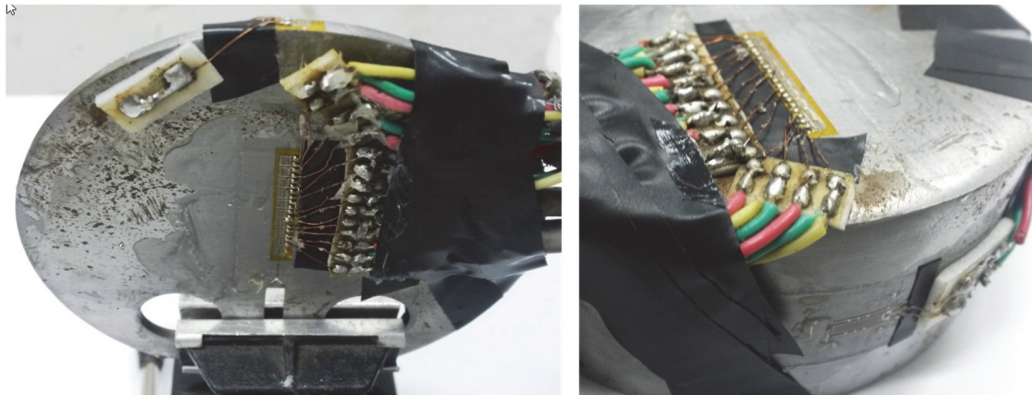


Figure 3: Gage strips and back-face strain gages bonded on a thin and on a thick DC(T) specimens.

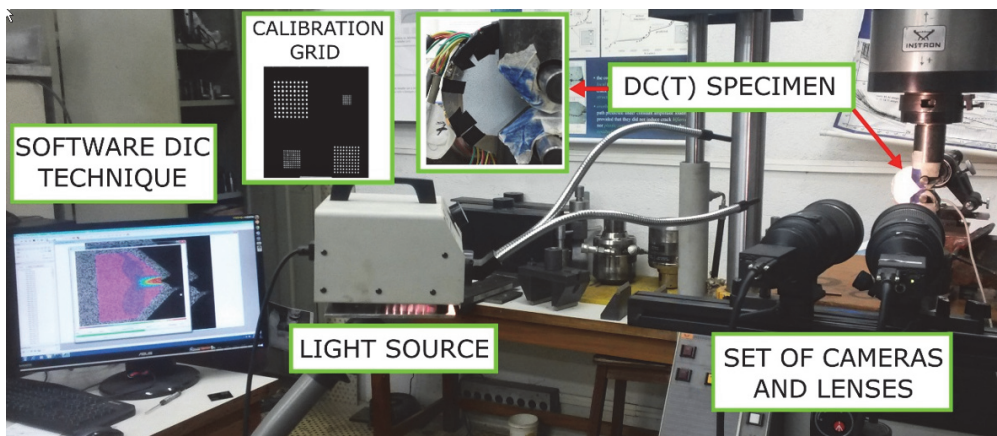


Figure 4: Experimental setup used to measure the strain fields on the specimen surface with the DIC system, to redundantly measure the crack opening loads K_{op} .

The thin $t = 2\text{mm} < p\bar{z}_{max} = (1/\pi)(K_{max}/S_Y)^2 = (1/\pi)[20/(0.9\cdot 262)]^2 \cong 2.3\text{mm}$ DC(T) specimens were loaded under quasi-constant $\{\Delta K = 20\text{MPa}\sqrt{m}, R = 0.1\}$ conditions, to grow fatigue cracks under nominally $pI-\sigma$ conditions (using Irwin's $p\bar{z}$ estimate, assuming it can define $pI-\sigma$ states in FCG as well). The cracks grew in the thicker specimens in a nominally $pI-\sigma$ state under identical $\{\Delta K = 20\text{MPa}\sqrt{m}, R = 0.1\}$ loads (their $t = 30\text{mm} > 2.5\cdot(K_{max}/S_Y)^2 = 2.5\cdot[20/(0.9\cdot 262)]^2 \cong 17.9\text{mm}$).

FCG rates da/dN and crack opening ratios K_{op}/K_{max} measured along the crack path are shown in Figs. 9 and 10, where the crack size is quantified by a/w , the ratio between the crack length a and the original ligament size w , measured from the load line. Three thin and three thick specimens were tested, two of each (called old tests in Figs. 9 and 10) using only strain gages to measure K_{op} . The differential in such simple tests was the careful K_{op} measurements, made using a piece of software written in LabVIEW to apply the linearity subtractor procedures on the redundantly measured signals [11]. The data acquisition was performed using National Instruments NI 9215, NI 9235, and cDAQ-9172 instruments [12].

To apply the DIC technique, the specimen surfaces opposed to the strain gage strip were first covered with a coat of white paint, over which small black dots were uniformly sprayed, see Fig. 4. The commercial DIC system from Correlated Solutions used for these measurements include two 5-MP Point Grey GRAS-50S5M CCD cameras with two Tamron SP AF180mm F/3.5 lenses, an adjustable double fiber-optic light source, calibration grids, a suitable data acquisition system, and the software package VIC-3D [13]. The digital cameras were mounted on an adjustable tripod in front of the specimen. Before starting the DIC tests, an accurate stereo calibration of the system is needed, and it was performed using standard precision calibration grids. About 25 image pairs of a grid with 9×9 dots and dot spacing of 0.89 mm were acquired during this calibration procedure.

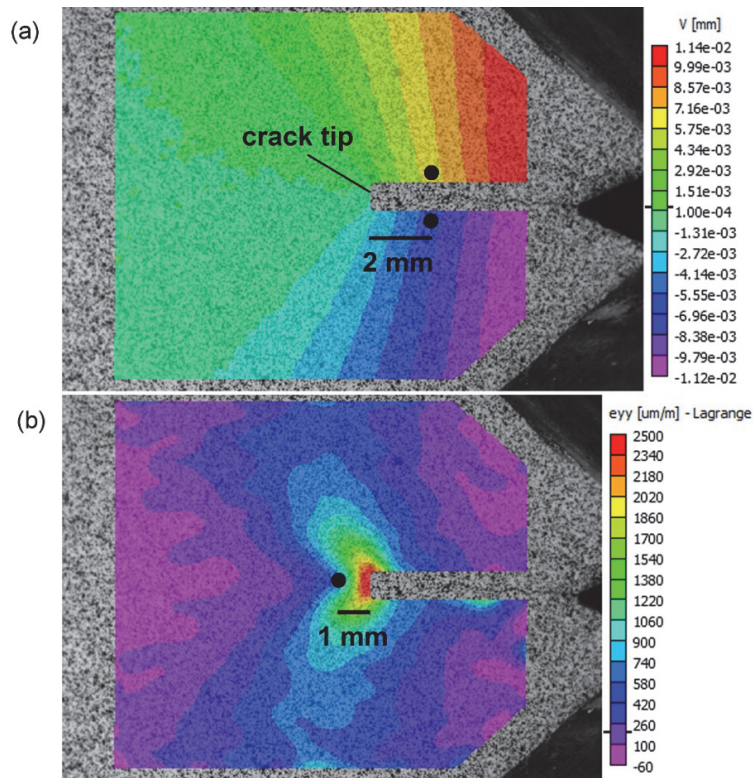


Figure 5: (a) Vertical displacement and (b) strain field maps obtained from VIC-3D DIC analysis.

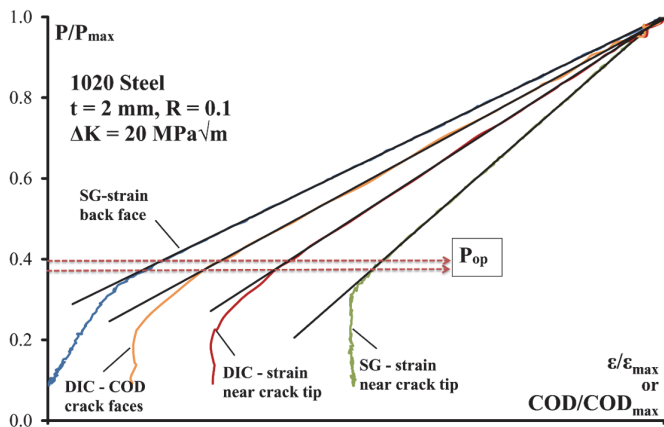


Figure 6: Typical P_{op} measurements made using redundant and independent back-face and near-field strain gage readings, as well as the signal obtained from the DIC analyses performed in the new thin DC(I) specimen with $t = 2\text{mm}$, while the crack was propagating under nominally plane stress conditions.

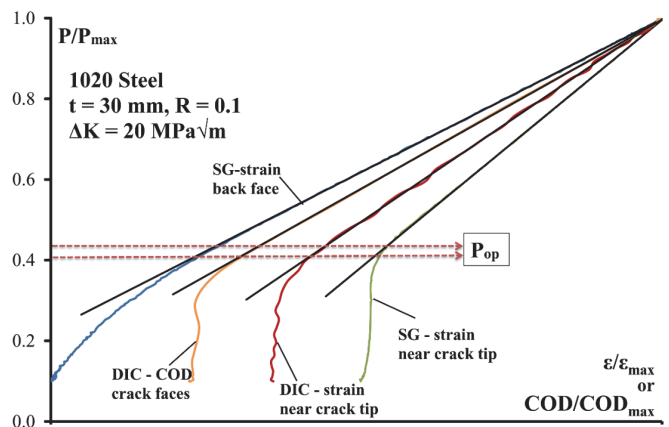


Figure 7: Typical P_{op} measurements made using redundant and independent back-face and near-field strain gage readings, as well as the signal obtained from the DIC analyses in the new thick DC(I) specimen with $t = 30\text{mm}$, while the crack was propagating under nominally plane strain conditions.

The FCG rates measured in all thin and thick specimens remained essentially fixed (and independent of their thickness) during the entire FCG process. This result confirms the classic ASTM view that $da/dN \times \Delta K$ curves measured under fixed R-ratios can properly characterize the FCG of structural materials independent of the specimen geometry, at least when applied to the tested steel. Moreover, it also confirms, or at least cannot deny, that $\{\Delta K, K_{max}\}$ can be considered as the FCG driving forces, so that ΔK can be used as a similitude parameter in FCG predictions. On the other hand, this data can also be used to question the alternative view that FCG is driven by ΔK_{eff} . Those unambiguous tests clearly show that the crack opening ratio K_{op}/K_{max} significantly and steadily decreased as the crack size increased in both the thin and the thick specimens, decreasing the size of the predominantly elastic residual ligament that forces their closure. So, it can be

concluded that $\Delta K_{eff} = K_{max} - K_{op}$ was not the FCG controlling driving force in this case. Indeed, since ΔK_{eff} significantly increased while the FCG rate da/dN essentially remained fixed while the cracks grew, ΔK_{eff} could not possibly be their driving force.

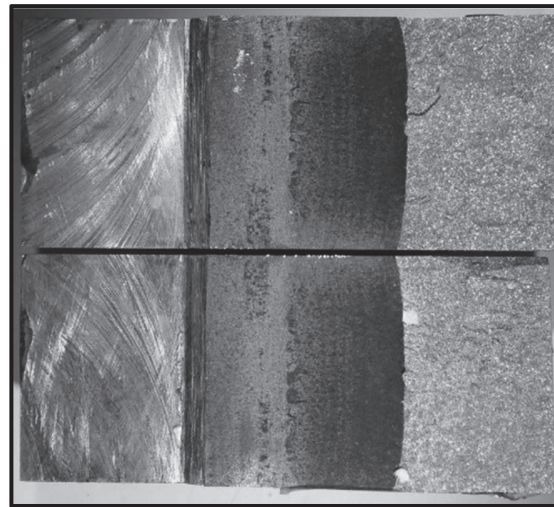


Figure 8: Cracked surfaces of one of the thick specimens, showing their successive homologous or quasi-parallel crack fronts, clear evidence that all of their points across the specimen thickness grew under iso-driving force conditions.

In fact, since CAL conditions $\{\Delta K, K_{max}\}$ were maintained during those tests, there is no doubt that ΔK_{eff} steadily increased as the cracks grew, because the decrease in the K_{op}/K_{max} ratio is beyond the (small) uncertainty of the measured data. Moreover, despite their slightly lower R-ratios, notice that the opening loads were a little bit higher along the crack path in the thicker than in the thinner test specimens, or under plane strain instead of plane stress conditions, contrary to what could be expected beforehand using PICC models.

Notice that such tests used the very same technique proposed by Elber to identify crack closure [3], and Paris and Herman's linearity-subtractor ideas to enhance the K_{op} identification [8, 10-11]. If these techniques can be used to support Elber's arguments, they can also be equally used to question them. Moreover, they used independent and redundant compliance and DIC techniques to measure the fatigue crack opening loads, to avoid questions about their sensitivity. Therefore, according to Kemp's [6] advices, these measurements can indeed be used to evaluate the actual ΔK_{eff} role in those FCG tests, since they are based on direct crack closure measurements, not on indirect evidence of any sort.

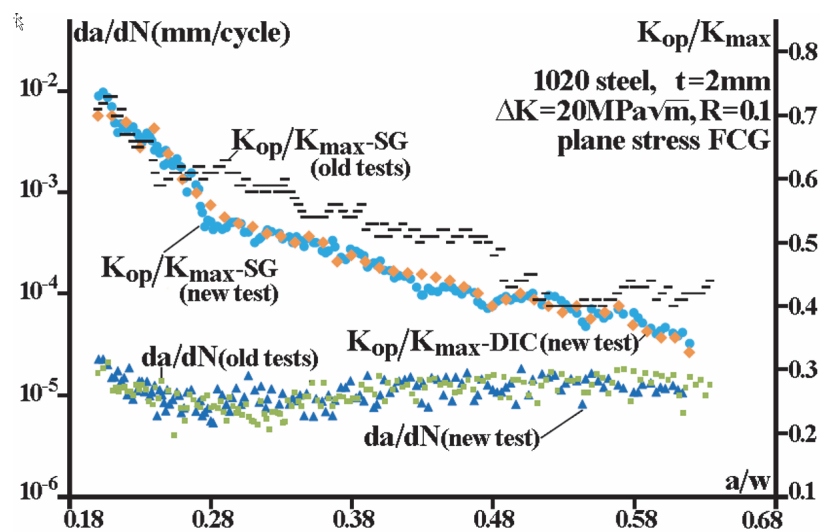


Figure 9: FCG rates da/dN and crack opening ratios K_{op}/K_{max} measured under quasi-constant $\{\Delta K = 20MPa\sqrt{m}, R = 0.1\}$ loading conditions by the four redundant techniques (near and far-field strain gages and DIC-based COD and strain fields) along the crack path in the thin DC(T) specimens ($t = 2mm$), supposedly under plane stress conditions.

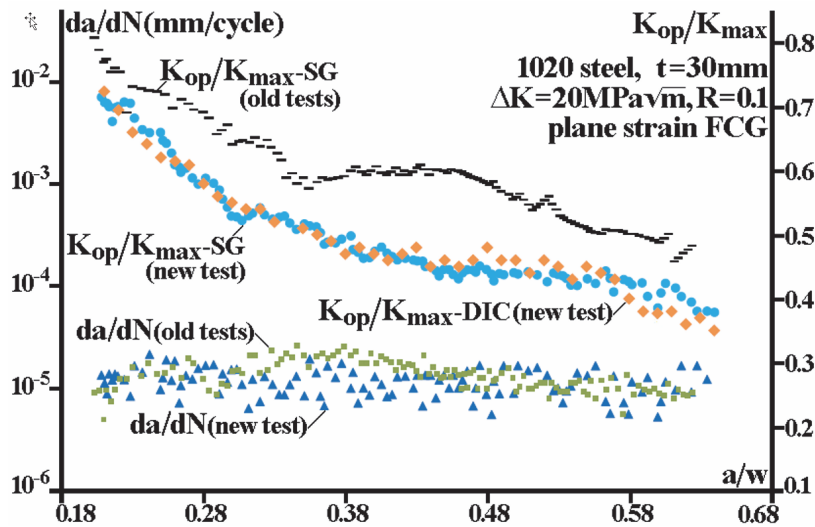


Figure 10: FCG rates da/dN and crack opening ratios K_{op}/K_{max} measured under quasi-constant $\{\Delta K = 20MPa\sqrt{m}, R = 0.1\}$ loading conditions by the four redundant techniques (near and far-field strain gages and DIC-based COD and strain fields) along the crack path in the thick DC(I) specimens ($t = 30mm$), supposedly under plane strain conditions.

The images collected for the DIC analyses were processed by the VIC-3D software using a 35-pixel subset window size, an 8-pixel step size, a 15-pixel strain window size, and normalized sum of squared differences cross correlation functions. Since the load was applied in the vertical direction, the v -displacement and the corresponding ε_y strain map were used to identify K_{op} . A pair of symmetrical points was located along the crack faces at $2mm$ behind the crack tip to obtain crack opening displacement (COD) measurements from the v -displacement field, see Fig. 5(a), whereas the strain history in the y -direction was obtained from a point located at $1mm$ ahead the crack tip, see Fig. 5(b). Notice that the data points around the crack faces and very near the crack tip were excluded from these analyses, to avoid their intrinsically high noise level.

No significant difference was observed in the FCG rates measured in all specimens. Indeed, in all of them it was found that $da/dN \cong 10^{-5}mm/cycle$, albeit in the thinner specimens the crack grew under $pI-\sigma$ and in the thicker ones under $pI-\varepsilon$ conditions, showing that, at least in those tests, the FCG rates are not dependent on the dominant stress state around the crack tip. Moreover, notice that the K_{op}/K_{max} behavior is not identical in all specimens tested under $pI-\sigma$ or $pI-\varepsilon$ conditions, see Figs. 9 and 10 once again. This indicates that K_{op} is not a property of the geometry/load pair. Instead, it can vary in nominally identical specimens submitted to equal loading conditions not only with the relative crack size a/w , but it can also depend on local details along the crack path, probably because it is also affected by non-PICC mechanisms. This K_{op} variation can also be seen as still another reason to question the blind use of models that suppose that ΔK_{eff} can always be assumed as the one and sole FCG driving force in all fatigue problems.

Finally, to confirm those statements, yet other two tests were performed in similar thin and thick DC(I) specimens, but under slightly different $\{\Delta K = 15MPa\sqrt{m}, R = 0.1\}$ quasi-constant loading conditions, see Figs. 11 and 12. The very same trend, namely K_{op}/K_{max} decreases as a/w increases, measured as described above by the same redundant DIC and compliance techniques, indicates that this behavior is indeed representative of the tested material.

Notice that the quasi-constant da/dN ratios measured in those tests are smaller than the ratios measured in the former tests performed under a higher ΔK , exactly as expected. Notice as well that, although the thick specimen in this new test is thinner than the thicker specimens used in the former tests, it still obeys the plane-strain requirements due to its lower K_{max} .

CONCLUSIONS

Simple and easily reproducible tests were used to experimentally check if the actual fatigue crack driving force is indeed the effective stress intensity range $\Delta K_{eff} = K_{max} - K_{op}$, as defended by many fatigue experts. First, a fatigue crack with an initially straight front was propagated with part of this front closed by bending loads, to show that even if some parts of the crack front remain closed, its opened parts can grow by fatigue. This strong evidence indicates

that FCG is promoted by local driving forces along the crack front, so that partially closed crack tips do not necessarily pin the entire crack fronts, as assumed by many ΔK_{eff} models based on simplified 2D PICC arguments. Then, fatigue crack growth rates da/dN and crack opening loads P_{op} were redundantly measured on FCG tests under quasi-constant ΔK and R conditions, in thin and thick DC(T) specimens, to simulate plane-stress and plane-strain FCG conditions. The opening loads were measured by Elber's compliance techniques, using Paris and Hermann's linearity subtractor technique to enhance the P_{op} identification. Initially, two strain-gages, one bonded on the back face and the other bonded ahead of the crack along the residual ligament of the specimens, were used to identify P_{op} by far and by near-field measurements. However, to avoid any doubts about the P_{op} measurements' quality, a third independent DIC-based technique was used in a new set of tests. The P_{op} values obtained by these three redundant methods showed no discrepancy, confirming the reliability and repeatability of the data obtained in the measurements. Since the ΔK_{eff} measured along those tests augmented significantly with the crack size, whereas the measured FCG rates da/dN remained practically constant, it can be concluded that Elber's effective stress intensity factor range was not the controlling driving force for the analyzed tests.

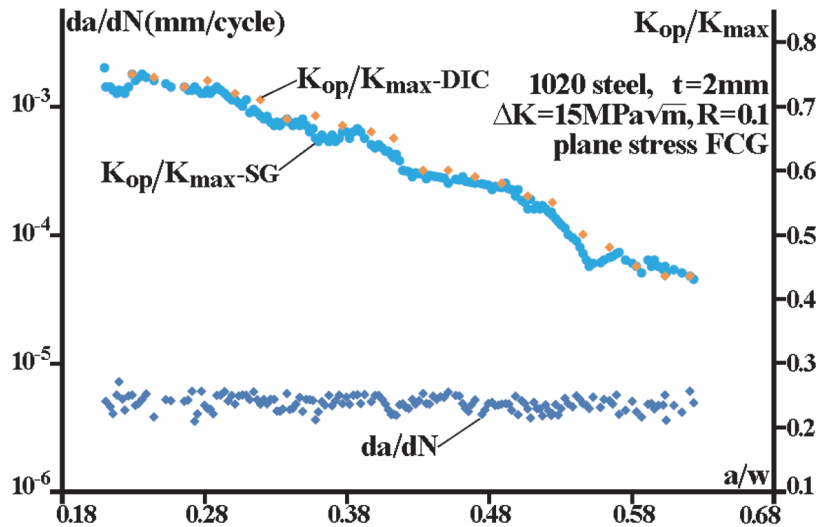


Figure 11: FCG rates da/dN and crack opening ratios K_{op}/K_{max} measured under quasi-constant $\{\Delta K = 15MPa\sqrt{m}, R = 0.1\}$ loading conditions by the four redundant techniques (near and far-field strain gages and DIC-based COD and strain fields) along the crack path in the thin DC(T) specimen with $t = 2mm$, supposedly under plane stress conditions.

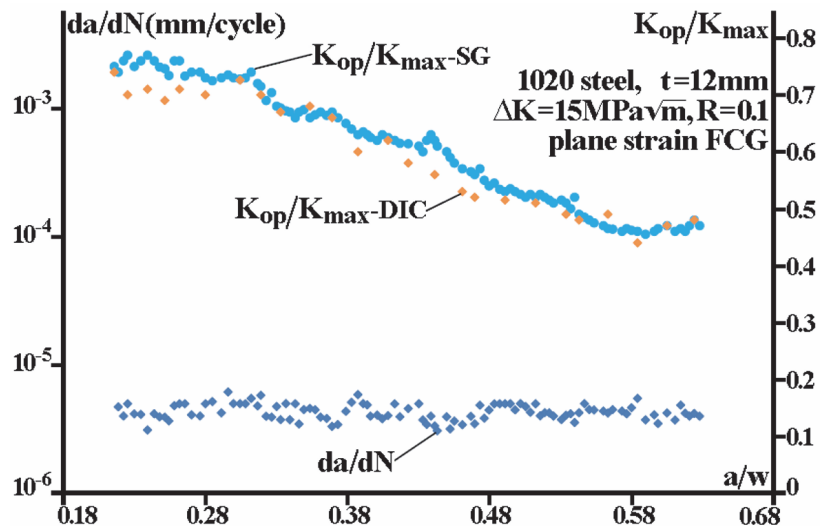


Figure 12: FCG rates da/dN and crack opening ratios K_{op}/K_{max} measured under quasi-constant $\{\Delta K = 15MPa\sqrt{m}, R = 0.1\}$ loading conditions by the four redundant techniques (near and far-field strain gages and DIC-based COD and strain fields) along the crack path in the thick DC(T) specimen with $t = 12mm$, supposedly under plane strain conditions.



ACKNOWLEDGEMENT

G.L.G. González gratefully acknowledge the support of the CNPq–Conselho Nacional de Desenvolvimento Científico e Tecnológico, Brazil (reference 152795/2016-2).

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