# On DIC measurements of $\Delta K_{eff}$ 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 load $K_{op}$ 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 digital image correlation techniques. 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 $\Delta K_{eff}$ arguments.

**KEYWORDS.** Fatigue crack driving forces; opening load measurements; $\Delta K_{eff}$ limitations.

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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 importance may depend on many factors, among them at least the load and the overload (OL) ranges and maxima; the number of OL cycles; the sizes of the crack and of the uncracked residual ligament rl; the transversal constraints along the crack front; the previous residual stress state around the crack tip; the microstructure of the material; and the environment.

In many cases, a load order mechanism can be so dominant that the others may become negligible. But 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 it. Many fatigue experts defend that Elber's plasticity-induced crack closure (PICC) is the dominant cause for all load order effects on FCG [3-4], whereas others deny that PICC may be important in such problems [5].

Kemp says that tests to support (or to deny) that $\Delta K_{eff}$ is (or is not) the actual 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 crack closure, as well as various closure mechanisms and models proposed to quantify it. He also says that compliance techniques are the most reliable technique to measure $K_{op}$, that due to their complexity such tests must be carefully made and analyzed, and that the role of crack closure depends on many factors, such as the cracked component thickness, alloy strength, grain structure, crack morphology, loading conditions, and/or the environment. Hence, FCG rate predictions cannot assume that similar $\{\Delta K, K_{max}\}$ loading conditions induce identical opening loads in all cracked components. Therefore, if FCG rates are really controlled by the effective SIF range $\Delta K_{eff}$, crack closure dependence on too many factors could be a major issue for structural design and analyses.

Anyway, if PICC is indeed the dominant delay mechanism in FCG, OL should affect much more the cracked piece surfaces, since their plastic zones $pz_{OL}$ are larger in plane stress ($pl$-$\sigma$) than in plane strain ($pl$-$\varepsilon$) regions along the crack tip, due to variable plasticity-induced transversal contraction restrictions. Hence, FCG rate delays should be larger as well in thin pieces that work under predominantly $pl$-$\sigma$ conditions than in thick ones, where most of the crack front grows under $pl$-$\varepsilon$. 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 superficial 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 $\Delta K_{eff}$, and if $\Delta K_{eff}$ varies along the crack front due to higher OL-induced closure effects in the $pl$-$\sigma$ regions near the cracked component faces, why then the central part of the crack front that grows under $pl$-$\varepsilon$ at a higher $\Delta K_{eff}$ does not propagate faster and gradually increase its curvature? In some cases they can, see Fig. 1-2 [9].

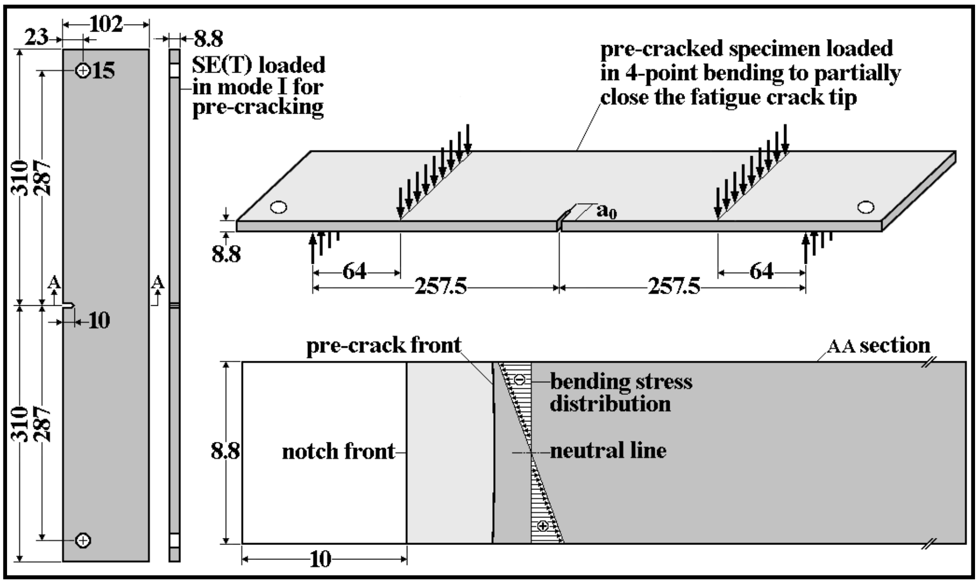


Fig. 1: Pre-cracked SE(T) specimen loaded in pure bending to partially close its crack.

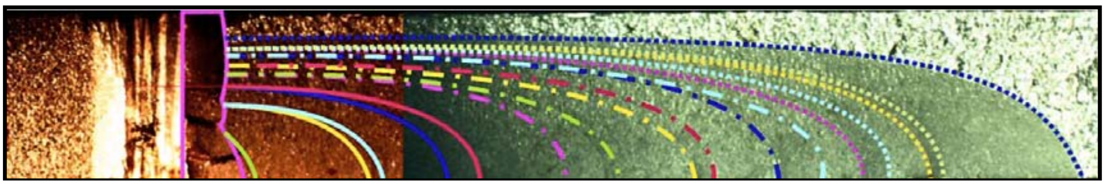

Fig. 2: Successive crack fronts propagated in transversal bending from an initially straight shape.

Figure 1 schematizes edge cracks initially grown in mode I 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 pulsating 4-point bending loads, to work as a flat beam with a side crack. Figure 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. Moreover, since the partial closure of the crack front is induced 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 a way severely distorted their initially (quasi) straight fronts while they grew after the load applied on the pre-cracked plates changed from pure tensile to pure transversal bending. Indeed, the successive crack fronts depicted in this figure 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 depending on the local value of the crack driving force along it. Questions like that indicate that the hypothesis "$\Delta K_{eff}$ controls FCG" cannot be accepted dogmatically, to say the least. It is not evident that all closed fatigue crack tips always remain unloaded, let alone that they can only grow after fully opened. Moreover, although only careful Kop measurements can identify if and how $\Delta K_{eff}$ 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 $\Delta K_{eff}$ in FCG 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 *rl* that forces the crack to close. Hence, whereas for a given geometry and crack size $\Delta K$ and $K_{max}$ can be calculated from $\Delta P$ and $P_{max}$ using catalog expressions, $\Delta K_{eff}$ cannot. Hence, the use of $\Delta K_{eff}$ 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 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 $\Delta K_{eff}$ in the complex structural components engineers must deal with. Since only simplified models are available to *estimate* $K_{op}$ values based on the ideal behavior of very simple geometries, this is indeed a major problem for $\Delta K_{eff}$-based FCG predictions.

## TESTS TO VERIFY IF $\Delta K_{EFF}$ 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 $\Delta K_{eff}$ controls FCG, and if closure is larger at the cracked piece surfaces, then the fatigue lives of thin pieces (with a large $pz/t$ ratio) that work under *pl-σ* FCG should be larger than the lives of similar but thicker pieces that work under equally fixed $\{\Delta K, R\}$ loading conditions in *pl-ε*. Even under such simple conditions, if the crack starts to grow under *pl-ε*, as it usually does, and gradually changes to a *pl-σ* 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 fatigue tests have been made to verify the actual role of $\Delta K_{eff}$ 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 *pl-σ* (making $pz/t \cong 1$) in the thin and *pl-ε* 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(T) specimens were cut from an as-received 76mm wrought round bar with yield strength $S_Y = 262MPa$ and ultimate tensile strength $S_U = 457MPa$. $\Delta K$ 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 by digital image correlation (DIC) techniques, see Fig. 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 Fig. 6 and 7. Figure 8 shows the crack faces of a thick specimen with homologous crack fronts.

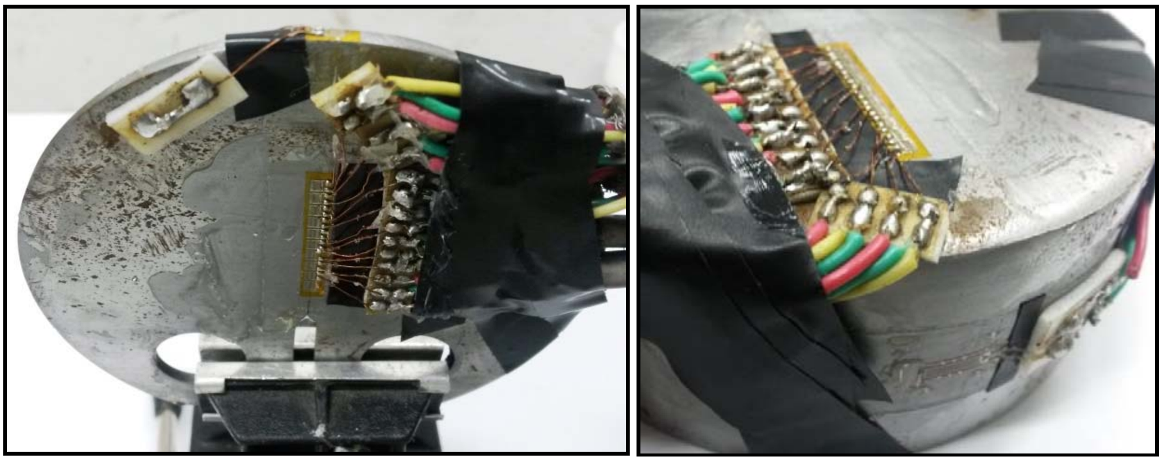

Fig. 3: Gage strips and back-face strain gages bonded on a thin and on a thick DC(T) specimens.

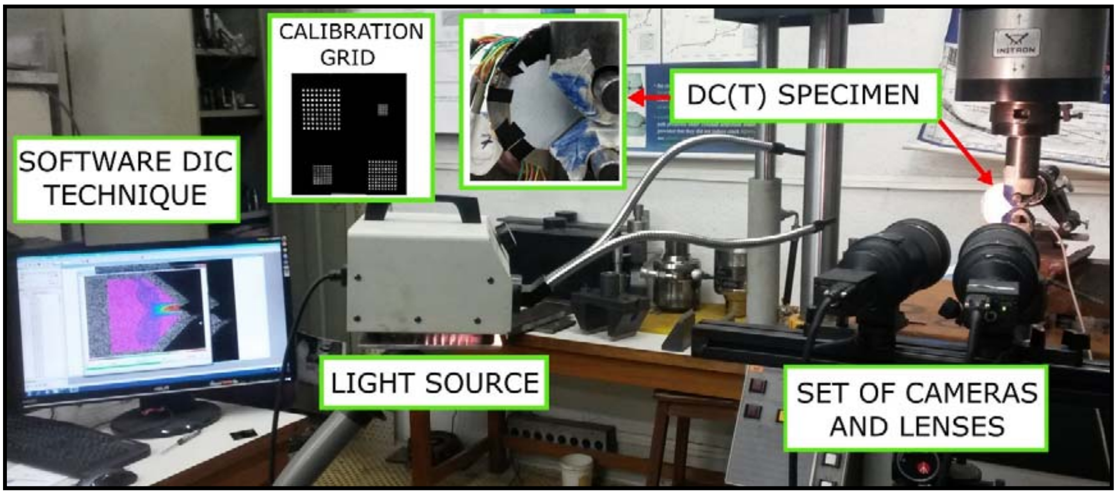


Fig. 4: Experimental setup used to measure the strain fields on the specimen surface with the DIC system, to redundantly measure the crack opening loads $K_{op}$.

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

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 Fig. 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 software written in LabView to apply the linearity subtractor procedures on the redundantly measured signals. Data acquisition was performed using National Instruments NI 9215, NI 9235, and cDAQ-9172 instruments.

For the DIC analyses in the new tests, 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 [12]. 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.

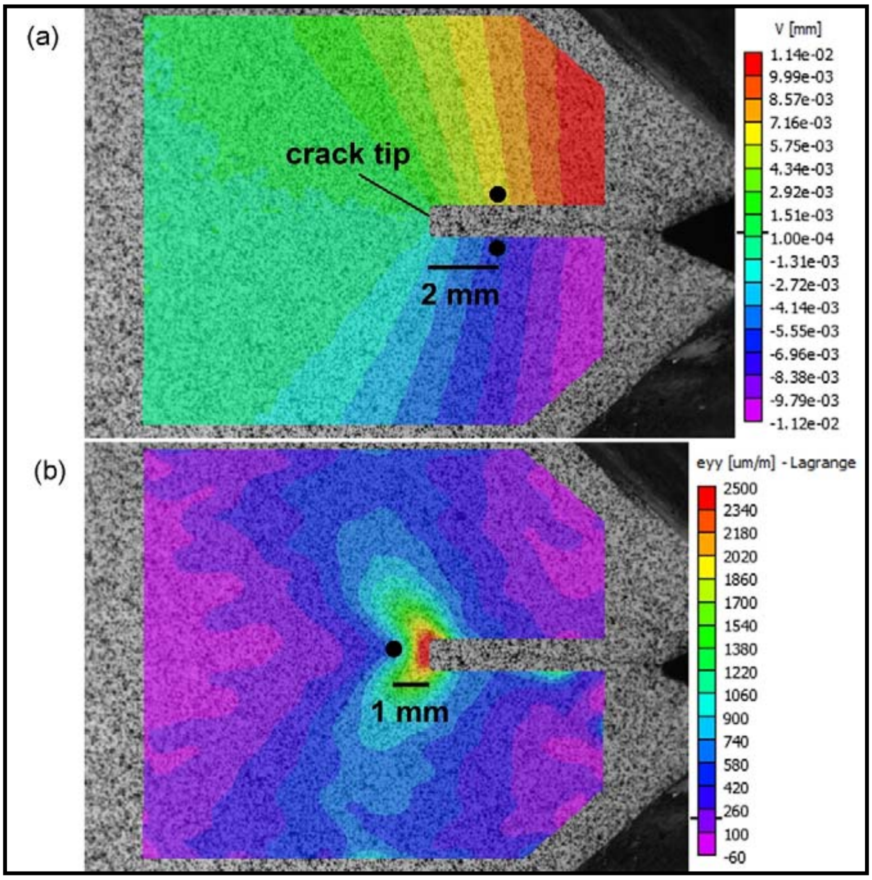


Fig. 5: (a) Vertical displacement and (b) strain field maps obtained from VIC-3D DIC analysis.

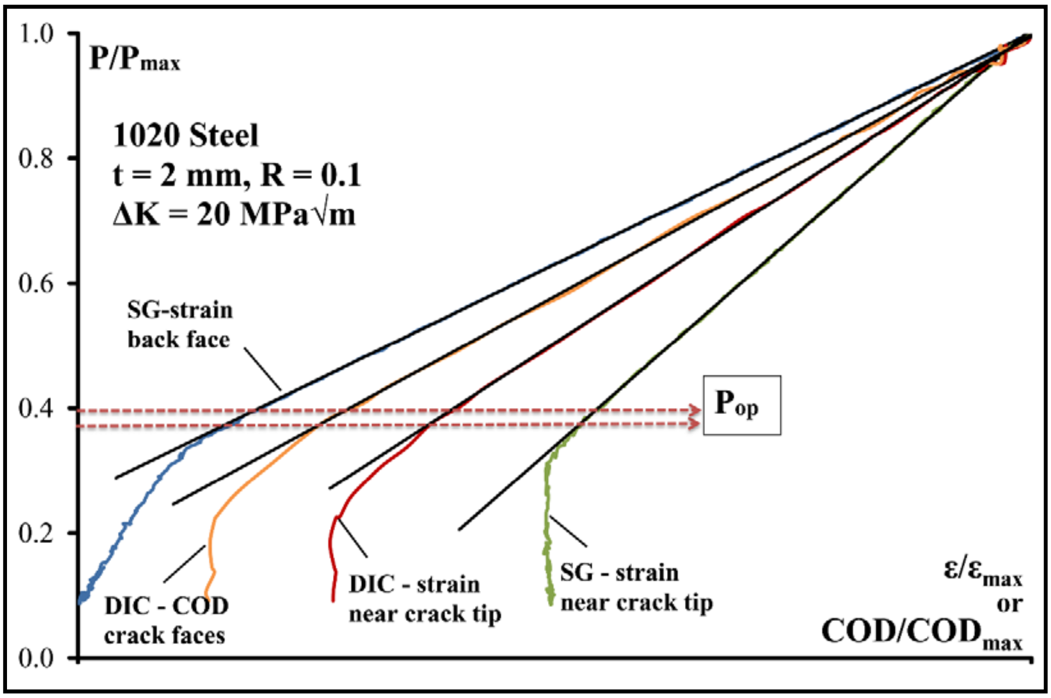


Fig. 6: Typical $P_{op}$ measurements made using the back-face and the near-field strain gage readings, as well as the signal obtained from the DIC analyses made in the new thin DC(T) specimen with $t = 2mm$, while the crack was propagating under nominally plane stress conditions.

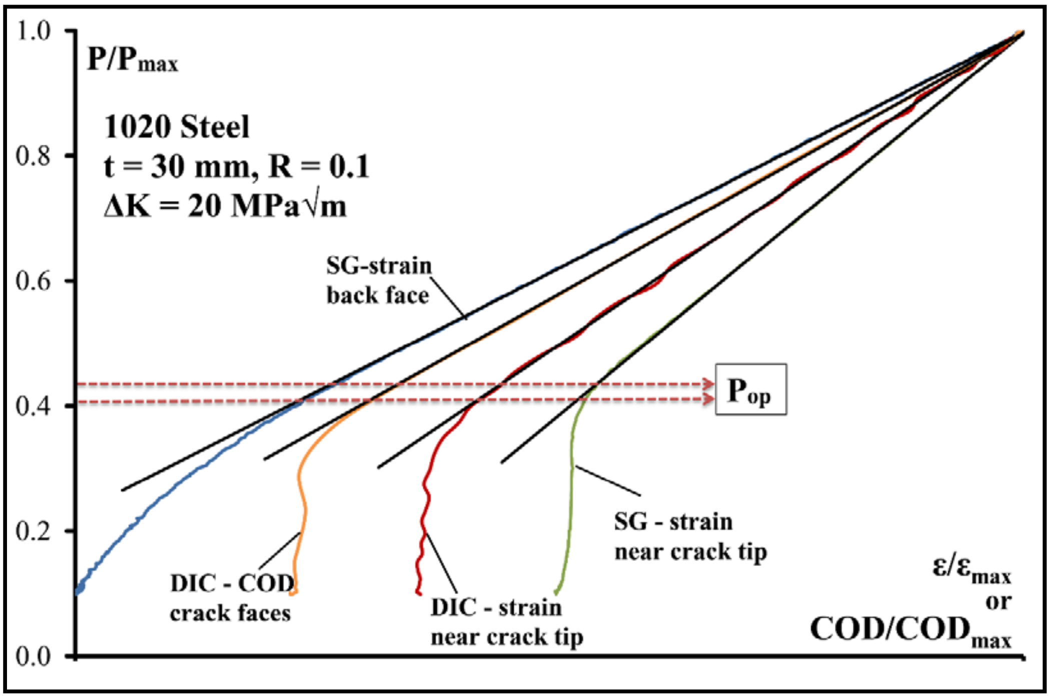


Fig. 7: Typical $P_{op}$ measurements made using the back-face and the near-field strain gage readings, as well as the signal obtained from the DIC analyses in the new thick DC(T) specimen with $t = 30mm$, while the crack was propagating under nominally plane strain conditions.

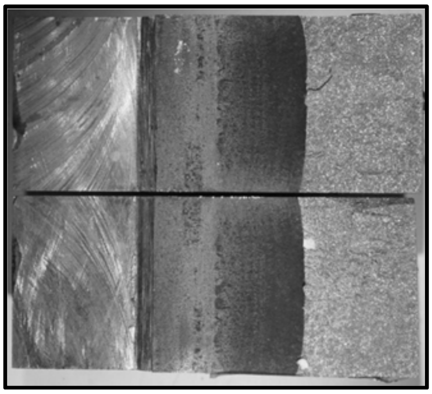

Fig. 8: Cracked surface of one thick specimen, showing its homologous successive crack fronts, evidence that it grew under an iso-driving force across the specimen thickness.

The measured FCG rates in all specimens remained essentially fixed and independent of their thickness, confirming the classic ASTM view that $da/dN \times \Delta K$ curves measured under fixed $R$-ratios can properly characterize the FCG of structural materials, at least when applied to the tested steel. It also confirms that $\{\Delta K, K_{max}\}$ can be considered as the FCG driving forces, so that $\Delta K$ can indeed be used as a similitude parameter in FCG predictions. Moreover, this data set can also be used to question the alternative view that FCG is driven by $\Delta K_{eff}$. Since those straightforward tests clearly show that the crack opening ratio $K_{op}/K_{max}$ steadily decreased as the crack size increased in both the thin and thick specimens, decreasing the (predominantly elastic) residual ligament that tends to close them, it can be concluded that $\Delta K_{eff} = K_{max} - K_{op}$ was not the FCG controlling driving force in this case.

Indeed, since CAL conditions $\{\Delta K, K_{max}\}$ were maintained during those tests, there is no doubt that $\Delta K_{eff}$ steadily increased as the cracks grew, because the decrease in $K_{op}/K_{max}$ 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.

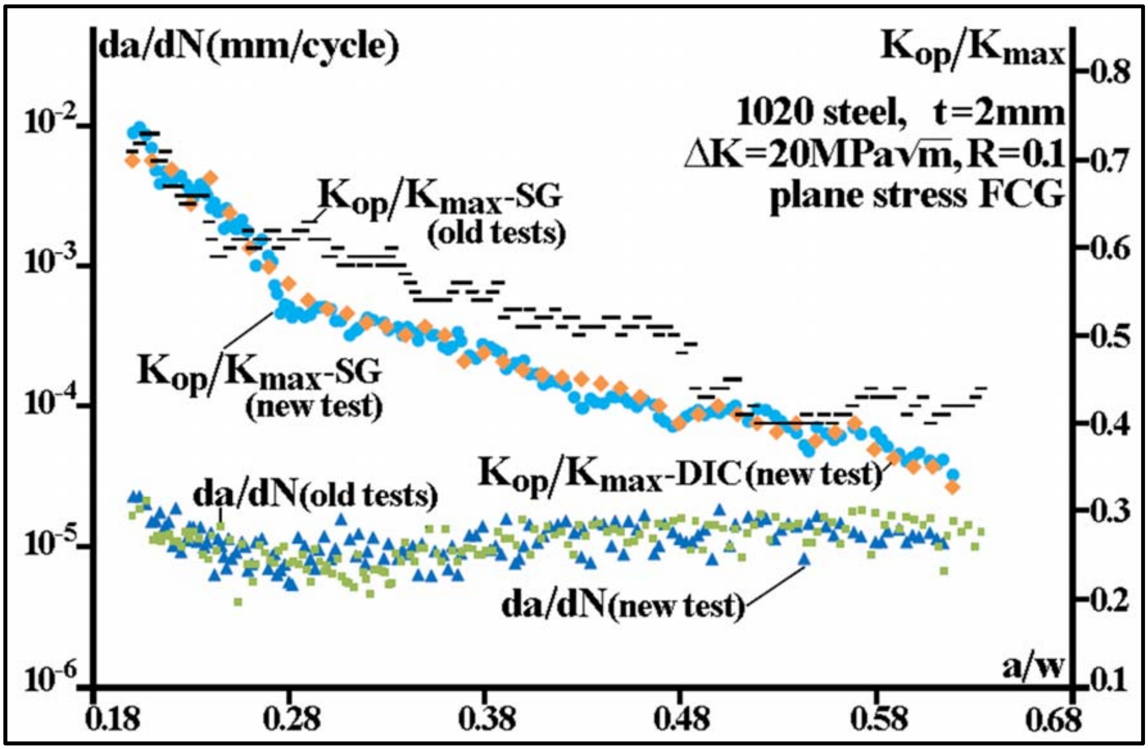


Fig. 9: FCG rates *da/dN* and crack opening ratios $K_{op}/K_{max}$ measured under quasi-constant $\{\Delta K = 20MPa\sqrt{m}, R = 0.1\}$ loading conditions by the four redundant techniques (near and far-field strain gages and DIC-based COD and strain fields) along the crack path in the thin DC(T) specimens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

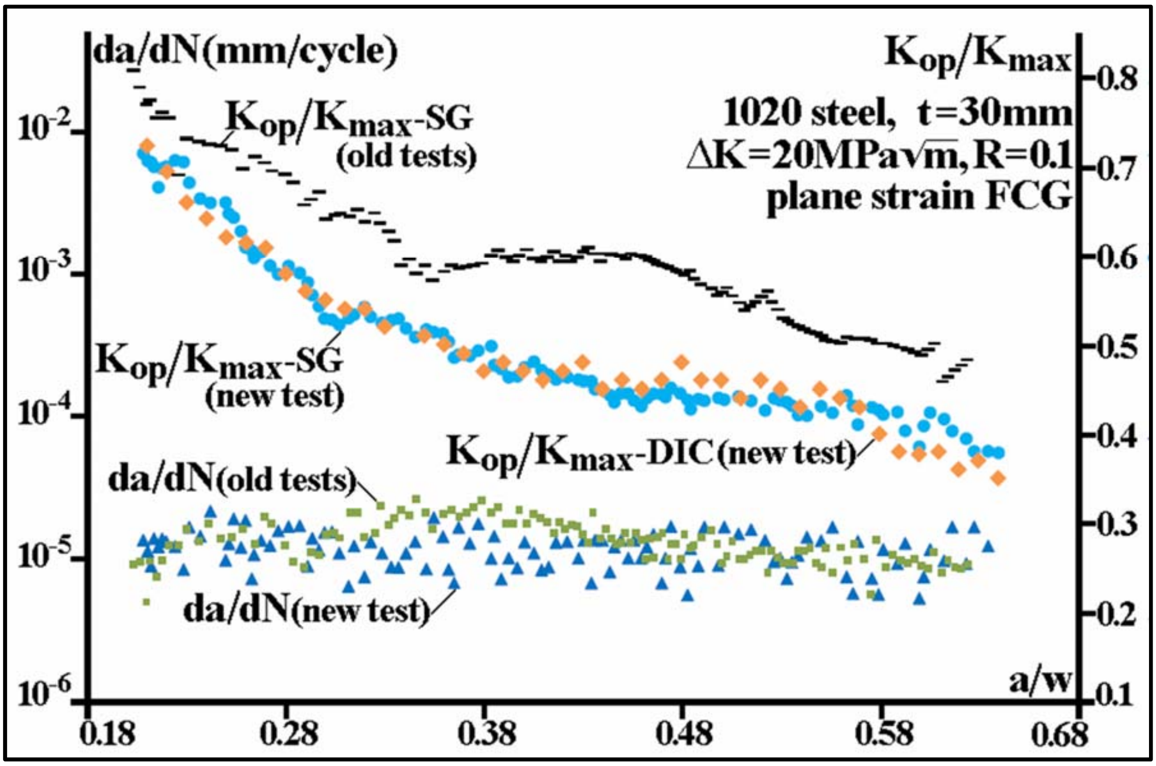


Fig. 10: FCG rates *da/dN* and crack opening ratios $K_{op}/K_{max}$ measured under quasi-constant $\{\Delta K = 20MPa\sqrt{m}, R = 0.1\}$ loading conditions by the four redundant techniques (near and far-field strain gages and DIC-based COD and strain fields) along the crack path in the thick DC(T)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

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 sensibility. Therefore, according to Kemp's [6] advices, these measurements can indeed be used to evaluate the actual $\Delta K_{eff}$ role in in those FCG tests, since they are based on direct crack closure measurements, not on indirect evidence of any sort.

The images collected for the DIC analyses were processed by the VIC-3D software using a subset window size of 35 pixels, a step size of 8 pixels, strain window size of 15, and cross correlation function of the normalized sum of squared differences. Since the load was applied in the vertical direction, the *v*-displacement and the corresponding $\varepsilon_y$ strain map were used to identify $K_{op}$. A pair of symmetrical points was located along the crack faces at 2 mm 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 1 mm ahead the crack tip, see Fig 5(b). Notice that the data points around the crack faces and too 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 $pl\text{-}\sigma$ and in the thicker ones under $pl\text{-}\varepsilon$ 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 $pl\text{-}\sigma$ or $pl\text{-}\varepsilon$ 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 plasticity-induced closure mechanisms. This $K_{op}$ variation can also be seen as still another reason to question the blind use of models that suppose that $\Delta K_{eff}$ 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 specimens but under slight different $\{\Delta K = 15MPa\sqrt{m}, R = 0.1\}$ quasi-constant loading conditions, see Fig 11 and 12. The very same $K_{op}/K_{max}$ decrease as $a/w$ increase trend indicates that this behavior is indeed representative of the tested material.

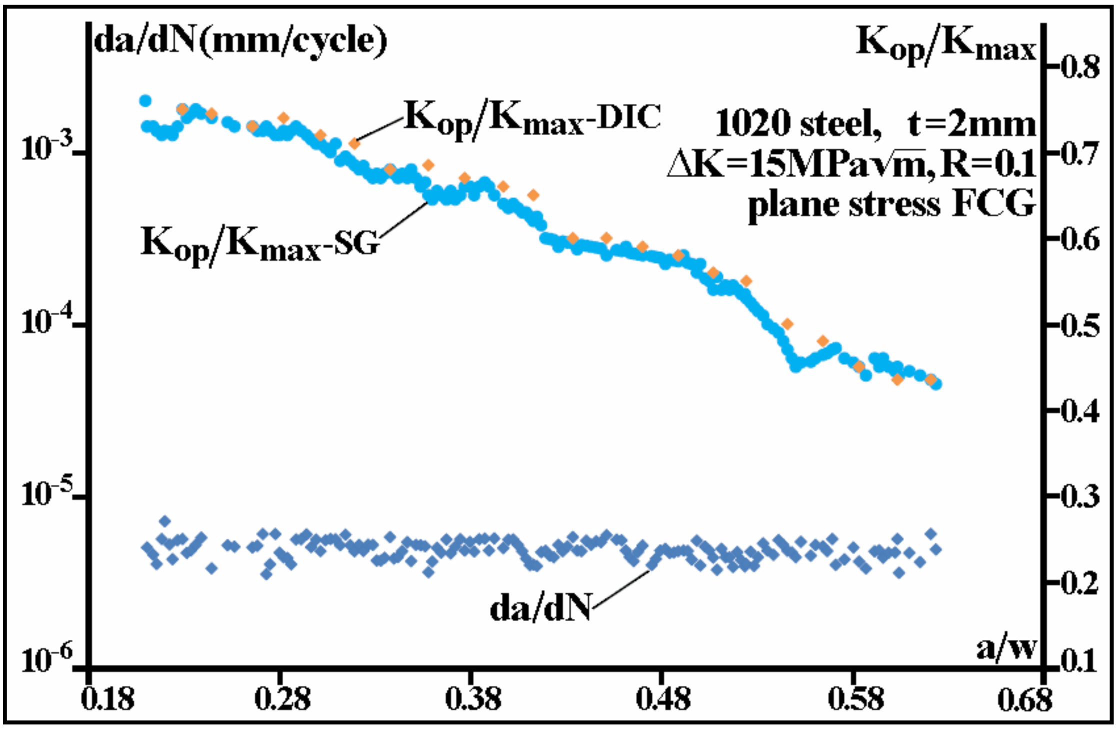


Fig. 11: FCG rates $da/dN$ and crack opening ratios $K_{op}/K_{max}$ measured under quasi-constant $\{\Delta K = 15MPa\sqrt{m}, R = 0.1\}$ loading conditions by the four redundant techniques (near and far-field strain gages and DIC-based COD and strain fields) along the crack path in the thin DC(T) specimen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

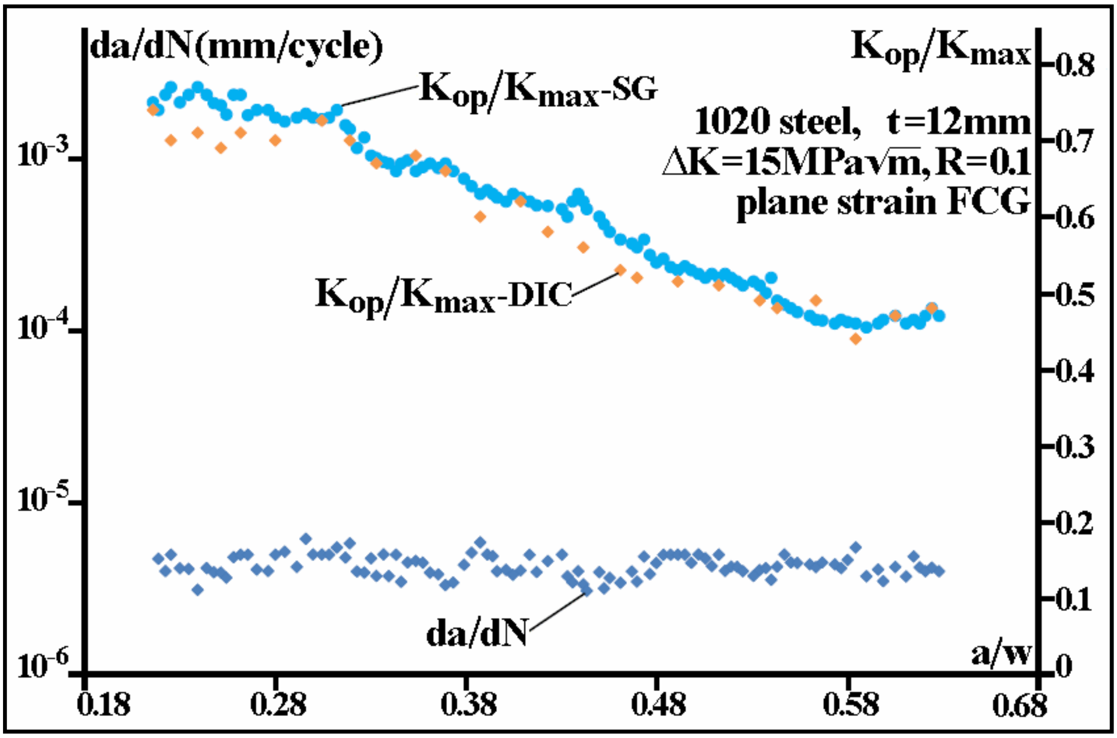


Fig. 12: FCG rates $da/dN$ and crack opening ratios $K_{op}/K_{max}$ measured under quasi-constant $\{\Delta K = 15MPa\sqrt{m},\ R = 0.1\}$ loading conditions by the four redundant techniques (near and far-field strain gages and DIC-based COD and strain fields) along the crack path in the thick DC(T)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

## 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, so that partially closed crack tips do not necessarily pin the entire crack fronts, as assumed by many $\Delta K_{eff}$ models based on simplified 2D PICC arguments. Then fatigue crack growth rates $da/dN$ and crack opening loads $K_{op}$ were redundantly measured on FCG tests under quasi-constant $\Delta K$ 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 linearity subtractor technique to enhance the $K_{op}$ 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 $K_{op}$ by far and by near-field measurements. However, to avoid any doubts about the $K_{op}$ measurements' quality, a third independent DIC-based technique was used in a new set of tests. The $K_{op}$ values obtained by these three redundant methods showed no discrepancy, confirming the reliability and repeatability of the data obtained in the measurements. Since the $\Delta K_{eff}$ 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.

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