# Residual life predictions of repaired fatigue cracks

Hao Wu
*Mechanics Laboratory of Lille, Ecole Polytech'Lille, University of Lille1 – France*
Jaime Tupiassú Pinho de Castro
*Department of Mechanical Engineering, Pontifical Catholic University of Rio de Janeiro, Rio de Janeiro/RJ – Brazil*
Abdelatif Imad
*Mechanics Laboratory of Lille, Ecole Polytech'Lille, University of Lille1 – France*
Marco Antonio Meggiolaro
*Department of Mechanical Engineering, Pontifical Catholic University of Rio de Janeiro, Rio de Janeiro/RJ – Brazil*
Benseddiq Nourredine
*Mechanics Laboratory of Lille, Ecole Polytech'Lille, University of Lille1 – France*

## Abstract

The stop-hole method is a simple and economic repair technique widely used to retard or even to stop the propagation of a fatigue crack in structural components that cannot be replaced immediately after the detection of the crack. Its principle is to drill a hole at or close to the crack tip to transform the crack into a notch, reducing in this way its stress concentration effect. The fatigue life increment that can be achieved with this technique can be modeled by assuming that it is equal to the number of cycles required to re-initiate the crack at the resulting notch root, which depends at least on the crack size and on the hole diameter. To study the effectiveness of this repair method, classical $\epsilon$N techniques are adapted to explain the results of several experiments carried out on aluminum plates, taking into account short crack concepts. The comparison among the experimental and the calculation results show that the life increment caused by the stop-holes can be effectively predicted in this way.

Keywords: Stop-hole, crack repair, $\epsilon$N method, short cracks, notch sensitivity.

## 1 Introduction

The so-called stop-hole method is a traditional and popular emergency repair technique that has been employed for a long time to extend the fatigue life of cracked structural components that cannot be

Mechanics of Solids in Brazil 2009, H.S. da Costa Mattos & Marcílio Alves (Editors)
Brazilian Society of Mechanical Sciences and Engineering, ISBN XXX-XX-XXXXX-XX-X

replaced as soon as the crack is discovered, a situation that is not uncommon when dealing with huge components which cannot be stocked nor are shelf available [1–5]. This classical resource is used by many maintenance crews all over the world, since it is relatively inexpensive, simple and fast to apply. Moreover, particularly on remote field conditions, it is frequently the last resort or the only practical option available. In its simplest form, this method consists of drilling a hole in the vicinity of, or centred at the crack tip, to transform the crack into a notch. The stop-hole can in this way increase the residual fatigue life of the cracked structure in comparison to the life it would have if not repaired.

However, in most practical cases the size and the location of the stop-hole are decided in a completely empirical or arbitrary way, totally dependent on the crew experience, beliefs and skill. In consequence, sometimes the stop-hole works very well, producing significant life increments and effectively extending the cracked component service campaign, delaying its replacement time. But in other cases, their results can be disappointing, or even harmful. Therefore, a simple and reliable calculation method to predict beforehand the results of this handy emergency repair technique can be quite useful in real-life situations.

But the appropriate modelling of this apparently trivial problem is not that simple. Several parameters can influence the fatigue life increment caused by the stop-hole. Among them, it is important to mention at least the radius, the position and the surface finish of the hole; the type and the size of the crack; the geometry and the mechanical properties of the component; the history, the type and the magnitude of the load; and the residual stresses around the stop-hole border, since they can all influence the effectiveness of the repair. The purpose of this work is to study a particular case of this complex set, the effect of the stop-hole size. As it turns out to be, even this relatively simple problem presents some quite interesting modelling challenges.

As a general rule, the increase of the stop-hole diameter contributes to decrease the value of the stress concentration factor $K_t$ of the resulting notch, but it also increases the nominal stresses in the residual ligament of the repaired component. Indeed, the originally cracked component is transformed into a notched one after the repair, but it loses material in this process. If the stop-hole is too big, the nominal stress increase can overcome the $K_t$ decrease, compromising its utility. On the other hand, if the stop-hole diameter is too small, the $K_t$ reduction may not be effective. Moreover, it also may not remove the residual stresses associated with the plastic zones which always follow a fatigue crack tip. But this balance is even more delicate, since small stop-hole diameters are associated with smaller notch sensitivities $q$, which decrease the resulting $K_t$ effect in the fatigue crack (re)initiation life. This effect is quantified by the so-called fatigue stress concentration factor $K_f$, classically defined by [6–10]

$$K_f = 1 + q \cdot (K_t - 1) \tag{1}$$

However, when a long crack is repaired by a relatively small stop-hole, it forms an elongated notch with a high $K_t$, which is associated with a steep stress/strain gradient around its root. Consequently, its notch sensitivity $q$ cannot be well predicted by the classical Peterson recipe [11]. Therefore, the model for predicting the residual fatigue life of repaired cracked structures must take this fact into account, as shown below.

## 2 Experimental program

A set of fatigue tests was carried out on modified SE(T) specimens of thickness $B = 8$ mm and width $W = 80$ mm, see Fig. 1, to measure the number of cycles required to re-initiate the crack after repairing it by drilling a stop-hole of diameter $2\rho$ centred at the tip of the original crack, when it reached a pre-established length $a$. This process causes a local delay on the crack propagation rate, and effectively increases its fatigue life. The tested material was an Al alloy 6082 T6, with yielding strength $S_Y$ = *280MPa*, ultimate tensile strength $S_U$ = *327MPa*, Young's modulus *E* = *68GPa,* and area reduction *RA* = *12%*. The specimens were cut on the LT direction, and the fatigue tests were carried out under constant load range $\Delta P$ at $R = P_{min}/P_{max} = 0.57$. This high $R$-ratio was chosen to avoid any crack closure interference on the crack propagation behavior. The test frequency was set at 30Hz.

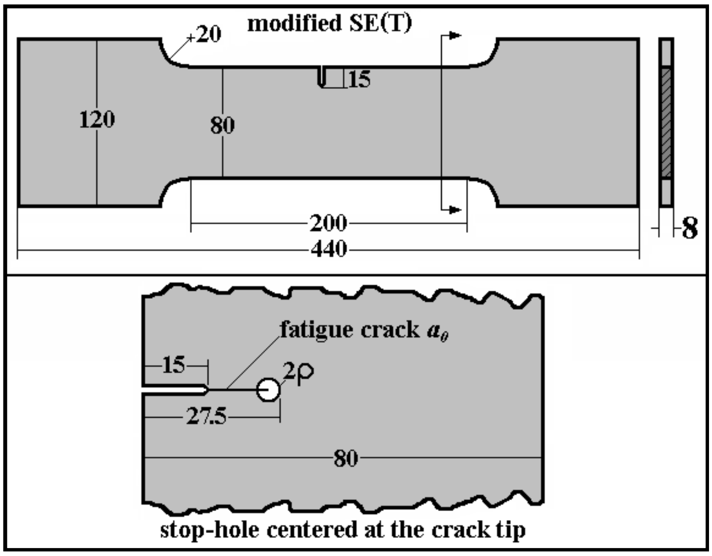


Figure 1: The tested specimens.

After propagating the crack until it achieved the correct length, the specimen was carefully removed from the testing machine, and then fixed and positioned on a milling machine, to machine the 2, 5 or 6 mm stop-holes. Great care was taken to precisely center the drill at the fatigue crack tips. The drilling operation was made at low feedings with plenty refrigeration, and after that the stop-hole was reamed to achieve a 1.5$\mu$m diameter accuracy. The specimen was then re-mounted on the test machine, and finally the fatigue test was restarted at the same previous conditions, meaning that the load range $\Delta P$ was always maintained constant, before and after the drilling of the stop-holes. All necessary precautions were followed to avoid introducing residual stresses by any means during this

Mechanics of Solids in Brazil 2009, H.S. da Costa Mattos & Marcílio Alves (Editors)
Brazilian Society of Mechanical Sciences and Engineering, ISBN XXX-XX-XXXXX-XX-X

crack repair process, designed to generate notches with the same length $a_n$ = $a_0$ + $\rho$ = *27.5* mm ⇒ $a_n/W$ = *27.5/80* = *0.344*, see Table 1.

Table 1: Loads and nominal stresses $\sigma = P/B(W - a_n)$ associated with the pseudo stress intensity range applied on the notch, $\Delta K^* = 0.838 \cdot \Delta P$ (in MPa$\sqrt{\text{m}}$, calculated using $a_n/W = 0.344$ and $\Delta P$ in kN in the standard E-647 SE(T) stress intensity factor formula [12]) after introducing the stop-hole.

| $\Delta K^*$ (MPa$\sqrt{\text{m}}$) | 6 | 7.4 | 7.5 | 8 | 8.1 | 9 | 10.1 | 13.5 | 14 |
|---|---|---|---|---|---|---|---|---|---|
| $\Delta P$ (kN) | 7.163 | 8.835 | 8.954 | 9.551 | 9.671 | 10.75 | 12.06 | 16.12 | 16.71 |
| $P_{min}$ (kN) | 16.66 | 20.55 | 20.82 | 22.21 | 22.49 | 24.99 | 28.04 | 37.48 | 38.87 |
| $P_{max}$ (kN) | 9.496 | 11.71 | 11.87 | 12.66 | 12.82 | 14.24 | 15.98 | 21.37 | 22.16 |
| $\Delta\sigma$ (MPa) | 17.06 | 21.04 | 21.32 | 22.74 | 23.03 | 25.58 | 28.71 | 38.38 | 39.80 |
| $\sigma_m$ (MPa) | 31.14 | 38.40 | 38.92 | 41.52 | 42.03 | 46.70 | 52.41 | 70.06 | 72.65 |

Twenty-three specimens were tested, and in all of them a number of (delay) cycles $N_d$ had to be spent until a new crack was able to reinitiate from the stop-hole edge. Fig. 2 shows some typical crack propagation curves measured in 3 specimens with different stop-hole radii, all tested under the same loading conditions: the beneficial influence of the stop-holes and the effect of their diameter is clearly identified in this figure. Table 2 summarizes the number of delay cycles $N_d$ caused by the stop-holes under the several testing conditions studied in this program. Note that $N_d > 2 \cdot 10^6$ cycles means that the tests were interrupted if a fatigue crack was not detected at the stop-hole root after this life.

Table 2: Number of measured delay cycles $N_d$ after introducing the stop-hole.

| $\rho$ = *1* mm | | $\rho$ = *2.5* mm | | $\rho$ = *3* mm | |
|---|---|---|---|---|---|
| $\Delta K^*$ MPa$\sqrt{\text{m}}$ | $N_d$ $\times 10^3$ cycles | $\Delta K^*$ MPa$\sqrt{\text{m}}$ | $N_d$ $\times 10^3$ cycles | $\Delta K^*$ MPa$\sqrt{\text{m}}$ | $N_d$ $\times 10^3$ cycles |
| 6.0 | > *2000* | 7.5 | > *2000* | 8.5 | > *2000* |
| 7.4 | *980, 724, 580* | 8.1 | 1800 | 9.0 | 1150, 960 |
| 8.0 | *600, 560, 510* | 10.1 | 355, 270 | 10.1 | 611, 580 |
| 10.1 | 119, 84 | 13.5 | *65, 58, 37* | 14.0 | 60, 32 |

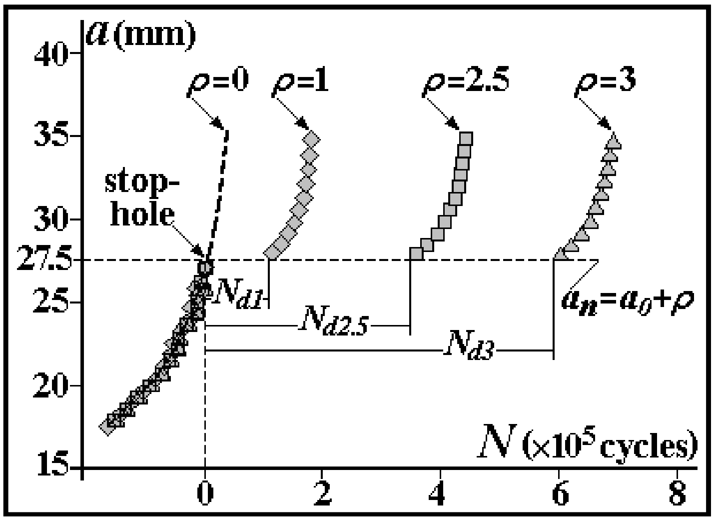


Figure 2: Typical effect of the stop-hole on the subsequent fatigue crack propagation.

## 3 The basic stop-hole model

The fatigue crack re-initiation lives at the stop-hole roots can be modeled by $\epsilon N$ local strain procedures, using (i) the cyclic properties of the 6082 T6 Al alloy, namely the four Coffin-Manson parameters $\sigma'_f$, $b$, $\epsilon'_f$ and $c$, $\sigma'_f = 485$ MPa, $b = -0.0695$, $\epsilon'_f = 0.733$, $c = -0.827$, and the coefficient and exponent of the cyclic Ramberg-Osgood stress-strain curve, $H' = 443$ MPa, $h' = 0.064$ [13]; (ii) the nominal stress history (see table 3); and (iii) the stress concentration factor $K_t$ of the notches generated by repairing the cracks drilling a stop-hole at their tips. Such factors can be estimated by Inglis, giving for hole radii $\rho = 1$, 2.5 or 3 mm, respectively

$$K_t \cong 1 + 2\sqrt{(a/\rho)} = 11.49, 7.63 \text{ or } 7.06 \qquad (2)$$

The classical $\epsilon N$ models neglect hardening transients, supposing that the fatigue behavior can be described by an unique Ramberg-Osgood cyclic stress/strain $\sigma\epsilon$ curve, whose parameters $H'$ and $h'$ can also be used to describe the elastic-plastic hysteresis loop $\Delta\sigma\Delta\epsilon$ curves. These equations should model both the nominal and the notch root cyclic stress/strain behavior, to avoid the logical inconsistency of using two different models for describing the same material (Hookean for the nominal and Ramberg-Osgood for the notch root stresses), and also the significant prediction errors that can be introduced at higher nominal loads by such a regrettably widespread practice [14]. Moreover, as all the studied stop-hole radii were much bigger than the cyclic plastic zones which followed the original fatigue crack tips, it is also reasonable to suppose that they did remove all the damaged material ahead of the cracks and that the material at the resulting notch root can be treated as virgin.

The stop-hole can be modeled by first calculating the stresses and strains maxima and ranges at the notches roots according to a proper stress/strain concentration rule, which should then be used to calculate the crack re-initiation lives by some $\Delta\epsilon\times N$ rule, considering the influence of the static or mean load component. Neglecting this effect could lead to severely non-conservative predictions, as the $R$-ratio used in the tests was quite high. All the required fatigue life calculations were made using the ViDa software, as summarized in figures 3-5, which show that the lives predicted by Morrow El, Morrow EP and SWT are similar in this case (but it must be emphasized that such a similarity cannot be assumed beforehand, since in many other cases these rules can predict very different fatigue lives!), whereas the Coffin-Manson predictions are highly non-conservative, thus absolutely useless.

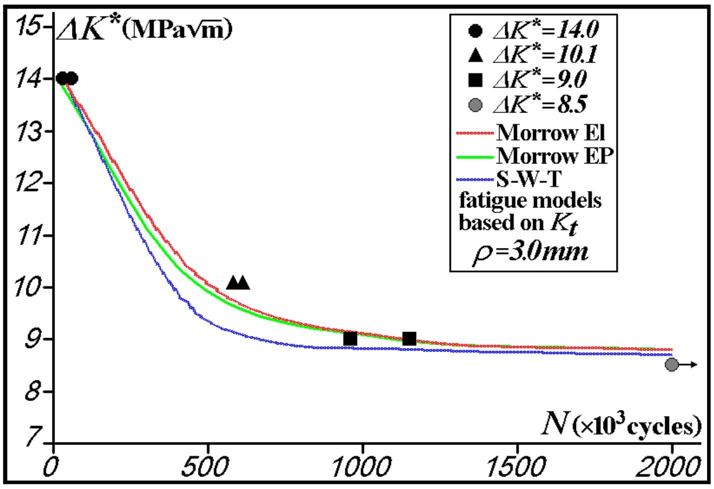


Figure 3: Predicted and measured crack re-initiation lives at the stop-holes roots of radius $\rho$ = *3.0mm*, using the $K_t$ of the repaired crack.

For the two bigger stop-holes (with radii $\rho$ = *3.0* and $\rho$ = *2.5mm*) the predictions reproduce quite well the measured fatigue crack re-initiation lives. In fact, so well that it is worth to point out that the curves in those plots result from calculated life predictions, not from data fitting. But the predictions obtained by the same calculation procedures for the smaller stop-hole with $\rho$ = *1.0mm* are much more conservative. This behavior is a little bit surprising, but since for design purposes this performance is not really that bad, the relatively simple procedure used above could probably be recommended as a useful design tool, at least based on the limited but representative data measured,.

There are few mechanical reasons which can explain the better than expected fatigue lives obtained from the specimens with the $\rho$ = *1mm* stop-holes. Significant compressive residual stresses could be one of them. But all the holes were drilled and reamed following identical procedures, and the bigger stop-hole lives were well predicted supposing $\sigma_{res}$ = *0*. Therefore, it is difficult to justify why high compressive residual stresses would be present only at the smaller stop-holes roots. The same can

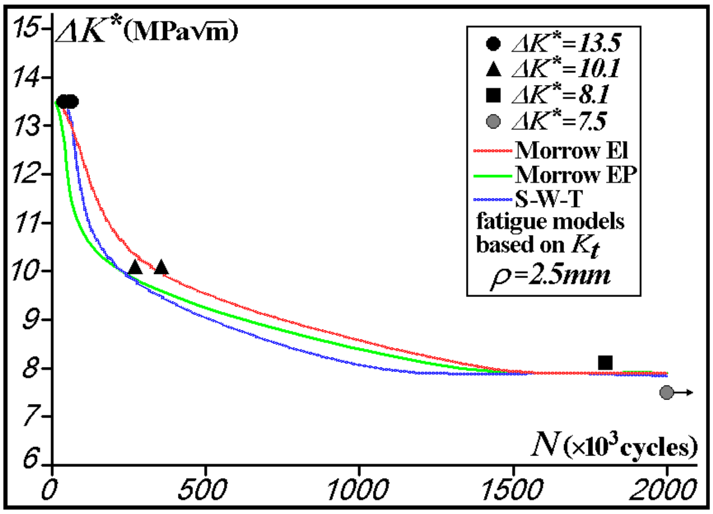


Figure 4: Predicted and measured crack re-initiation lives at the stop-holes roots of radius $\rho$ = *2.5mm*, using $K_t$ of the repaired crack.

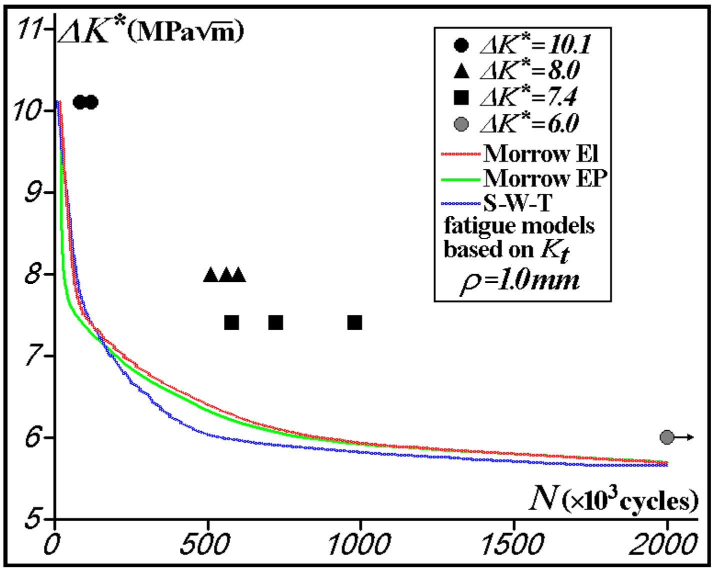


Figure 5: Predicted and measured crack re-initiation lives at the stop-holes roots of radius $\rho$ = *1.0mm*, using the $K_t$ of the repaired crack.

be said about the surface finish of the stop-holes. However, the smaller stop-holes generate a notch with a bigger $K_t$ and with a much steeper stress gradient near their roots. This effect can significantly affect the growth of short cracks and, consequently, the fatigue notch sensitivity [11], mechanically explaining the measured behavior, as follows.

## 4 Analytical prediction of the notch sensitivity

Long cracks grow under a given $\Delta\sigma$ and $R$ set when $\Delta K = \Delta\sigma\sqrt{(\pi a)}\cdot f(a/w) > \Delta K_{th}(R)$, where $\Delta K_{th}(R)$ is the propagation threshold at that $R$-ratio. Therefore, short cracks (which have $a \cong 0$) must propagate in an intrinsically different way, as otherwise $\Delta K(a\to 0, R) > \Delta K_{th}(R) \Rightarrow \Delta\sigma \to \infty$, which is a non-sense, as a stress range $\Delta\sigma > 2S_L(R)$ can generate and propagate a fatigue crack, where $S_L(R)$ is the fatigue limit of the material at $R$. To conciliate the fatigue limit (e.g.) at R = 0, $\Delta S_0 = 2S_L(0)$, with the propagation threshold under pulsating loads $\Delta K_0 = \Delta K_{th}(0)$, a small "short crack characteristic size" $a_0$ [15] can be summed to the actual crack size $a$ to obtain

$$\Delta K_{\mathrm{I}} = \Delta\sigma\sqrt{\pi(a + a_0)} \tag{3}$$

These equations correctly predict that the biggest stress range which does not propagate a micro-crack is the fatigue limit: if $a << a_0$, $\Delta K_I = \Delta K_0 \Rightarrow \Delta\sigma \to \Delta S_0$. However, when the crack departs from a notch, as usual, its driving force is the stress range at the notch root $\Delta\sigma$, not the nominal stress range $\Delta\sigma_n$, which is generally used on the $\Delta K$ expressions. As in these cases the factor $f(a/w)$ includes the stress concentration effect of the notch, it is better to define $f(a/w)$ separating it in two parts: $f(a/w) = \eta\cdot\phi(a)$, where $\phi(a)$ quantifies the stress gradient effect near the notch, with $\phi(a\to 0)\to K_t$, while the constant $\eta$ quantifies the free surface effect, to obtain

$$\Delta K_{\mathrm{I}} = \eta\cdot\varphi(a)\cdot\Delta\sigma_n\sqrt{\pi(a + a_0)} \tag{4}$$

Using the traditional definition $\Delta K = f(a/w)\cdot\Delta\sigma\sqrt{(\pi a)}$, an alternate way to model the short crack effect is to suppose that the fatigue crack propagation threshold depends on the crack size, $\Delta K_{th}(a, R = 0) = \Delta K_{th}(a)$, through a function given by

$$\frac{\Delta K_{th}(a)}{\Delta K_0} = \frac{\Delta\sigma\sqrt{\pi a}\cdot f(a/w)}{\Delta\sigma\sqrt{\pi(a+a_0)}\cdot f(a/w)} = \sqrt{\frac{a}{a+a_0}} \Rightarrow \Delta K_{th}(a) = \frac{\Delta K_0}{\sqrt{1+(a_0/a)}} \tag{5}$$

However, an additional adjustable parameter $\gamma$ in the $\Delta K_{th}(a)$ expression allows a better fitting of the experimental data [16]

$$\Delta K_{th}(a) = \Delta K_0\left[1 + (a_0/a)^{\gamma/2}\right]^{-1/\gamma} \tag{6}$$

If $S'_L$ and $S_L = S'_L/K_f$ are the fatigue limits measured in standard (non-notched, polished) and in similar but notched *SN* specimens, $K_t \geq K_f = 1 + q\cdot(K_t - 1)$, where $q$ is the notch sensitivity factor, which can be modeled using the short crack behavior, since it can be associated to tiny cracks which can initiate at the notch root but do not propagate if $2S'_L/K_t < \Delta\sigma < 2S'_L/K_f$ [17]. For example, the stress intensity factor of a crack that departs from a circular hole of radius $\rho$ in a Kirsh (infinite) plate loaded in mode I is given by [17]

$$\Delta K_{\mathrm{I}} = \eta \cdot \varphi\left(a/\rho\right) \cdot \Delta\sigma\sqrt{\pi a} = 1.1215 \cdot \varphi\left(a/\rho\right) \cdot \Delta\sigma\sqrt{\pi a} \tag{7}$$

where $\phi(a/\rho) \equiv \phi(x)$ is given by:

$$\varphi(x) = \left(1 + \frac{0.2}{(1+x)} + \frac{0.3}{(1+x)^6}\right) \cdot \left(2 - 2.354\frac{x}{1+x} + 1.206\left(\frac{x}{1+x}\right)^2 - 0.221\left(\frac{x}{1+x}\right)^3\right) \tag{8}$$

Note that this equation (8) yields $\lim_{a\to 0} \Delta K_{\mathrm{I}} = 1.1215 \cdot 3 \cdot \Delta\sigma\sqrt{\pi a}$ and $\lim_{a\to\infty} \Delta K_{\mathrm{I}} = \Delta\sigma\sqrt{\pi a/2}$, exactly as expected. Thus, if $a_0 = (\Delta K_0/\eta \cdot \Delta S_0\sqrt{\pi})^2$, any crack departing from a Kirsh hole will propagate when

$$\Delta K_I = \eta \cdot \varphi\left(a/\rho\right) \cdot \Delta\sigma\sqrt{\pi a} > \Delta K_{th} = \Delta K_0 \cdot \left[1 + (a_0/a)^{\gamma/2}\right]^{-1/\gamma} \tag{9}$$

The propagation criterion for these fatigue cracks can then be rewritten as [11]

$$\varphi\left(\frac{a}{\rho}\right) > \frac{\left(\frac{\Delta K_0}{\Delta S_0\sqrt{\rho}}\right) \cdot \left(\frac{\Delta S_0}{\Delta\sigma}\right)}{\left[\left(\eta\sqrt{\frac{\pi a}{\rho}}\right)^{\gamma} + \left(\frac{\Delta K_0}{\Delta S_0\sqrt{\rho}}\right)^{\gamma}\right]^{1/\gamma}} \equiv g\left(\frac{a}{\rho}, \frac{\Delta S_0}{\Delta\sigma}, \frac{\Delta K_0}{\Delta S_0\sqrt{\rho}}, \gamma\right) \tag{10}$$

Therefore, $K_f = \Delta S_0/\Delta\sigma$ can be calculated from the material fatigue limit $\Delta S_0$ and crack propagation threshold $\Delta K_0$, and from the geometry of the cracked piece by

$$\begin{cases} \varphi(a/\rho) = g(a/\rho, \Delta S_0/\Delta\sigma, \Delta K_0/\Delta S_0\sqrt{\rho}, \gamma) \\ \frac{\partial}{\partial a}\varphi(a/\rho) = \frac{\partial}{\partial a}g(a/\rho, \Delta S_0/\Delta\sigma, \Delta K_0/\Delta S_0\sqrt{\rho}, \gamma) \end{cases} \tag{11}$$

This system can be solved for several combinations of materials and hole radii, given by $\Delta K_0/\Delta S_0\sqrt{\rho}$ and $\gamma$, to obtain the Kirsh plate notch sensitivity as a function of the hole radius $\rho$ and material fatigue properties. Figure 6 compares the $q$ values calculated in this way with the traditional Peterson curves.

This analytical approach includes the $\gamma$ Bazant's exponent which allows a better fitting of the short crack propagation data, and it can be generalized to deal with other notch geometries, an important step here, since the stop-hole repaired cracks are similar to an elongated semi-elliptical notch, not to a Kirsh hole. The stress intensity factor of a crack $a$ which departs from such a notch with semi-axes $b$ and $c$, with $a$ and $b$ in the same direction perpendicular to the (nominal) stress $\Delta\sigma$, is given by

$$\Delta K_{\mathrm{I}} = \eta \cdot F\left(a/b, c/b\right) \cdot \Delta\sigma\sqrt{\pi a} \tag{12}$$

where $\eta = 1.1215$ is the free surface correction factor and $F(a/b, c/b)$ is the geometric factor associated to the notch stress concentration, which can be calculated as a function of the non-dimensional parameter $s = a/(a + b)$ and of $K_t$, given by [11]

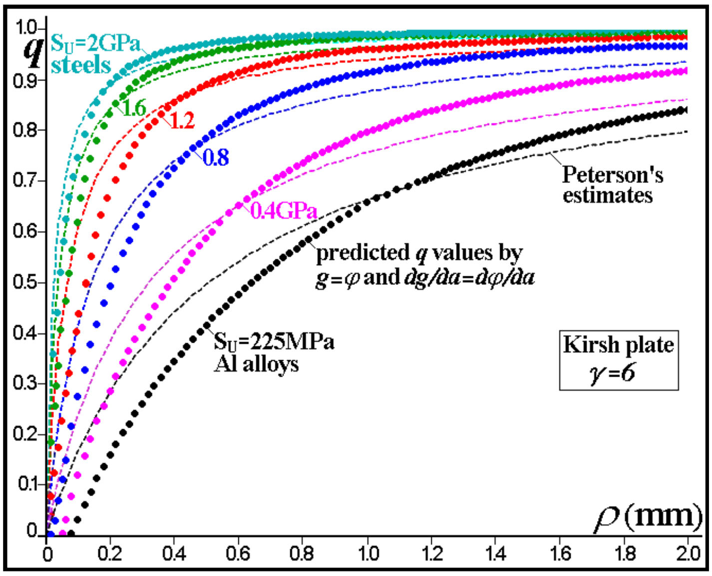


Figure 6: Notch sensitivity $q$ as a function of the Kirsh hole diameter $\rho$, estimated using mean $\Delta K_0$, $\Delta S_0$ and $S_U$ from 450 steels and aluminium alloys for $\gamma$ = *6*.

$$K_t = \left(1 + 2\frac{b}{c}\right) \cdot \left[1 + \frac{0.1215}{(1 + c/b)^{2.5}}\right] \tag{13}$$

An analytical expression for the *F(a/b, c/b)* of deep semi-elliptical notches with $c \leq b$ was fitted to a series of finite element numerical calculations

$$F(\frac{a}{b}, \frac{c}{b}) \equiv f\,(K_t, s) = K_t \sqrt{\frac{1 - \exp(-K_t^2 \cdot s)}{K_t^2 \cdot s}} \tag{14}$$

Making $g = \phi$ and $\partial g/\partial a = \partial\phi/\partial a$ in (11), one can calculate the smallest stress range $\Delta\sigma$ required to initiate and propagate a fatigue crack from the notch root at a given combination of $\gamma$ and $\Delta K_0/\Delta S_0\sqrt{\rho}$, which can be used to calculate $K_f = \Delta S_0/\Delta\sigma$ and $q$. Indeed, in the lack of compressive residual stresses at the notch border, the mechanical reason for stopping a crack initiated at that border (when it reaches a size $a_{st}$) is the stress gradient near the notch root: to stop the crack it is necessary that the stress range decrease due to the gradient near the border overcomes the effect of increasing the crack size: a short crack $a < a_{st}$ departing from the notch boundary stops when it reaches

$$\Delta K_I = \eta \cdot \varphi(a_{st}) \cdot \Delta\sigma\sqrt{\pi a_{st}} = \Delta K_0 \cdot \left[1 + (a_0/a_{st})^{\gamma/2}\right]^{-1/\gamma} \tag{15}$$

Traditional notch sensitivity estimates suppose that the sensitivity $q$ depends only on the notch root $\rho$ and the material ultimate strength $S_U$. However, as shown in Fig. 7, the sensitivity of semi-elliptical notches, besides depending on $\rho$, $\Delta S_0$, $\Delta K_0$ and $\gamma$, is also strongly dependent on the $c/b$ ratio. Moreover, there are reasonable relationships between $\Delta S_0$ and $S_U$, but not between $\Delta K_0$ and $S_U$. This means that (e.g.) two steels with same $S_U$ but different $\Delta K_0$ can behave in a way not predictable by the traditional estimates. The curves in figure 8 are calculated for typical Al alloys with mean ultimate strength $S_U = 225MPa$, fatigue limit $S_L = 90MPa \Rightarrow \Delta S_0 = 2S_L S_R/(S_L + S_R) = 129MPa$, propagation threshold $\Delta K_0 = 2.9MPa\sqrt{m}$, and $\gamma = 6$. Note that the corresponding Peterson's curve is well approximated by the semi-circular $c/b = 1$ notch.

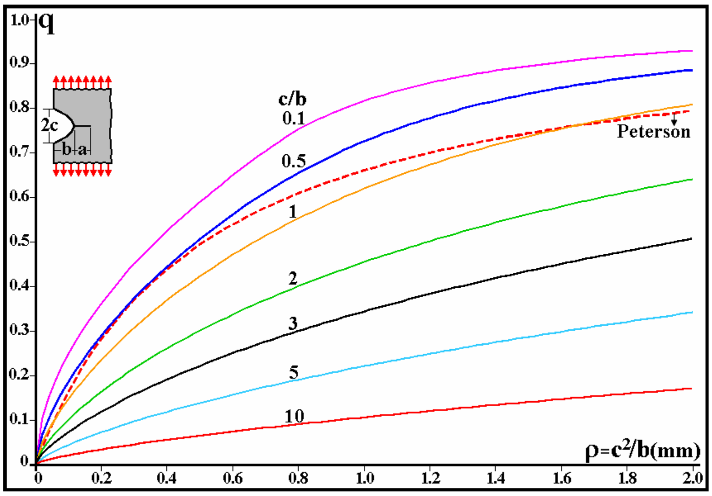


Figure 7: Notch sensitivity $q$ versus the semi-elliptical notch tip radius $\rho$ for plates of typical Al alloys ($\Delta S_0 = 129MPa$, $\Delta K_0 = 2.9MPa\sqrt{m}$, $\gamma = 6$) loaded in mode I.

## 5 The improved stop-hole model

An improved model for predicting the effect of the stop holes on the crack re-initiation fatigue lives can be generated by using: (i) a semi-elliptical notch with $b = 27.5mm$ and $\rho = c^2/b = 1$, 2.5 or $3mm$ to simulate the stop-hole repaired specimens; (ii) the mechanical properties of the 6082 T6 Al alloy studied in this work; (iii) equation (11) to calculate the notch sensitivity and equation (15) for the stress intensity factor of the repaired specimens; and finally (iv) $K_f$ instead of $K_t$ in the $\epsilon N$ model.

The predictions generated by such an improved model are presented in Fig. 8, 9 and 10. Since $q \cong 1$ for the $\rho = 3.0$ and $\rho = 2.5mm$ stop-holes, the predictions obtained using their calculated $K_f = 7.0$ and $K_f = 7.2$, respectively, are as good as those obtained using their estimated $K_t$. However,

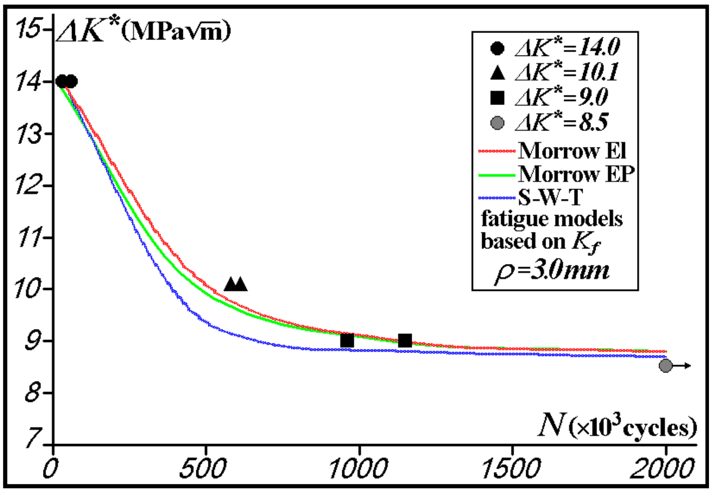


Figure 8: Predicted and measured crack re-initiation lives at the stop-holes roots of radius $\rho$ = *3.0mm*, using the $K_f$ (instead of $K_t$) of the repaired crack.

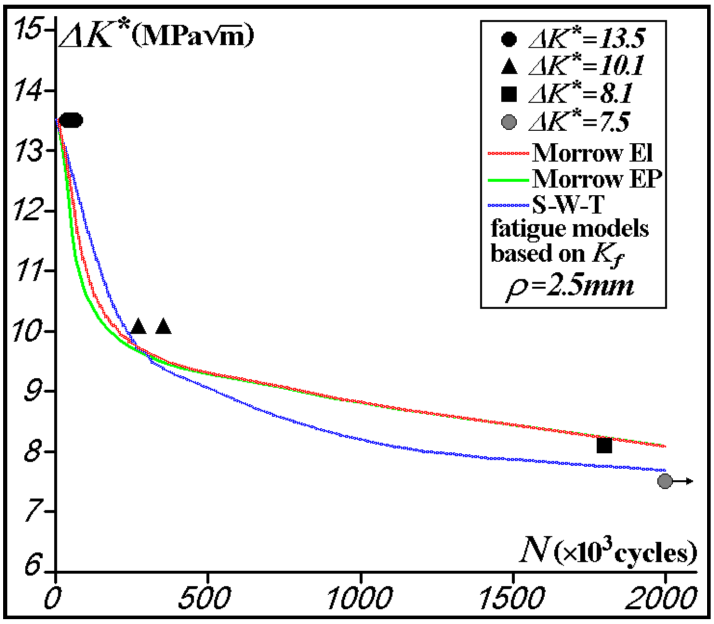


Figure 9: Predicted and measured crack re-initiation lives at the stop-holes roots of radius $\rho$ = *2.5mm*, using the $K_f$ (instead of $K_t$) of the repaired crack.

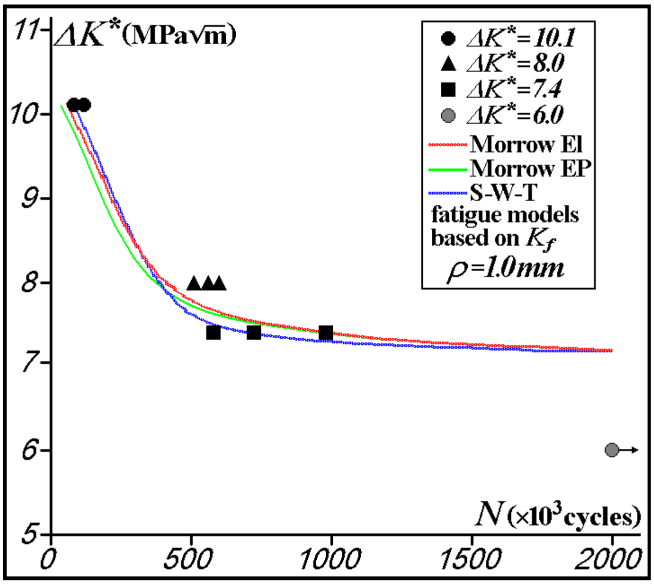


Figure 10: Predicted and measured crack re-initiation lives at the stop-holes roots of radius $\rho$ = *1.0mm*, using the $K_f$ (instead of $K_t$) of the repaired crack.

the overly conservative initial predictions formerly obtained for the smaller $\rho$ = *1mm* stop-hole, which were generated using its estimated $K_t \cong$ *11.5*, are much improved when the notch sensitivity effect quantified by its properly calculated $K_f$ = *8.3* (considering the important influence of the elongated involving notch geometry) is used in the fatigue crack re-initiation calculations.

The Al 6082 T6 fatigue limit and fatigue crack propagation threshold under pulsating loads required to calculate $K_f$ are estimated as $\Delta K_0 = 4.8\,MPa\sqrt{m}$ and $\Delta S_0$ = *110MPa*, following traditional structural design practices [7-10, 22-24], and the Bazant's exponent was chosen, as recommended by Meggiolaro et al. [11], as $\gamma$ = *6*.

## 6 Conclusion

Classical $\epsilon$N techniques were used with properly estimated properties to reproduce the measured fatigue crack re-initiation lives after stop-hole repairing several modified SEN(T) specimens. The predicted lives were not too dependent on the mean load $\epsilon$N model, and the larger stop-hole measured lives could be well reproduced using the stress concentration factor $K_t$ in the Neuber/Ramberg-Osgood system. But such an approach yielded grossly conservative prediction for the smaller stop-hole life improvements. This problem was solved using the fatigue stress concentration factor $K_f$ of the resulting notch instead of $K_t$ in that system. However, the notch sensitivity $q$ required to estimate $K_f$ must be calculated in a proper way, considering the very important effect of the elongated notch geometry, since classical $q$ estimates are only valid for approximately semi-circular notches.

## Acknowledgments

CNPq has provided research scholarships for Castro,JTP and Meggiolaro,MA.

## References

[1] Zeljko, D., Comparison of fatigue crack retardation methods. *Eng Failure Analysis*, **3(2)**, pp. 137–147, 1996.
[2] Naned, V., Stjepan, J. & Vatroslav, G., Validation of crack arrest technique by numerical modeling. *Int J Fatigue*, **19(4)**, pp. 283–291, 1997.
[3] Ghfiri, R., Amrouche, A., Imad, A. & Mesmacque, G., Fatigue life estimation after crack repair in 6005 AT-6 aluminium alloy using the cold expansion hole technique. *Fatigue Fract Eng Mater Struct*, **23**, p. 911, 2000.
[4] Song, P.S. & Shieh, Y.L., Stop drilling procedure for fatigue life improvement. *Int J Fatigue*, **26(12)**, pp. 1333–1339, 2004.
[5] Anggit, M., Chobin, M., Akihide, S. & K., R., A crack-growth arresting technique in aluminum alloy. *Eng Failure Analysis*, **15(4)**, pp. 302–310, 2008.
[6] Peterson, R.E., *Stress Concentration Factors*. Wiley, 1974.
[7] Dowling, N.E., *Mechanical behavior of materials*. Prentice-Hall: New Jersey, 1999.
[8] Shigley, J.E., Mischke, C.R. & Budynas, R.G., *Mechanical Engineering Design*. McGraw-Hill, 7th edition, 2004.
[9] Juvinall, R.C. & Marshek, K.M., *Fundamentals of Machine Component Design*. Wiley, 4th edition, 2005.
[10] Norton, R.L., *Machine Design, An Integrated Approach*. Prentice-Hall, 3rd edition, 2005.
[11] Meggiolaro, M.A., Miranda, A.C.O. & Castro, J.T.P., Short crack threshold estimates to predict notch sensitivity factors in fatigue. *Int J Fatigue*, **29(9-11)**, pp. 2022–2031, 2007.
[12] ASTM E647, *Standard test method for measurement of fatigue crack growth rates, ASTM Standards*. ASTM Standards v. 03.01, 2007.
[13] Borrego, L.P., Ferreira, J.M., Pinho da Cruz, J.M. & Costa, J.M., Evaluation of overload effects on fatigue crack growth and closure. *Eng Fract Mech*, **70(11)**, pp. 1379–1397, 2003.
[14] Meggiolaro, M.A. & Castro, J.T.P., Evaluation of the errors induced by high nominal stresses in the classical $\epsilon$n method. *Fatigue 2002*, ed. A.F. Blom, 2, pp. 1451–1458, 2002. EMAS 2002.
[15] El Haddad, M.H., Topper, T.H. & Smith, K.N., Prediction of non-propagating cracks. *Eng Fract Mech*, **11**, pp. 573–584, 1979.
[16] Bazant & P., Z., Scaling of quasibrittle fracture: asymptotic analysis. *Int J Fract*, **83(1)**, pp. 19–40, 1997.
[17] Frost, N.E., Marsh, K.J. & Pook, L.P., *Metal fatigue*. Dover, 1999.