THE EFFECT OF OVERLOADS AND UNDERLOADS ON FATIGUE CRACK GROWTH

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Resumo. O efeito de cargas de amplitude variável na propagação de fendas por fadige tem sido objecto de vários estudos, concluindo-se que em geral conduzem a retardamentos na presença de sobrecargas e acelerações na presença de subcargas. Os mecanismos de alteração da propagação das fendas estão identificados mas a duração dos efeitos é objecto de continuados estudos relacionados com os modelos de propagação.
Neste estudo efectuaram-se ensaios de propagação de fendas em provetes de aço carbono normalzado Ck45 (DIN) do tipo M(T) segundo ASTM E647. Os carregamentos incluiam sobreceargas e subcargas (N=1) em que se fez variar o número de ciclos de amplitude constante (n=9, 99, 999 ou 9 999) existentes entre as alterações de carga. Experimentalmente determinou-se o grau de retardamento ou aceleração que foi obtido. A modelização da propagação de fendas efectuada, tendo em conta os modelos baseados no fecho de fenda e na dimensão da zona de plasticidade na frente da fenda, permite avaliar o efeito da existencia dos picos de carga.

Abstract. The effects of variable amplitude loading have been summarized as leading to retardation of crack growth or acceleration of crack growth due to respectively overloads and underloads, but these effects remain very load and material sensitive. Analysis carried out through the crack closure calculations have been performed but are not fully satisfactory on the description of the related phenomena.
This presentation relates to a study where fatigue crack growth tests were carried out on specimens made of a mild steel, C45 (DIN), using M(T) specimens according to ASTM E647.
In order to fully understand the effect of variable amplitude loading within a block loading, a wide range of fatigue tests were carried out, where not only the variations of overloads and underloads were used (N=1) but also the variation of the number of constant amplitude loading cycles (n=9, 99, 999 and 9 999). Results show the amount of retardation or acceleration related to each block loading where the effect of load variation is observed. Analysis of the results is carried out with models based on crack closure effects and the dimension of crack tip plasticity and allow to assess the effect of variable amplitude loading on crack growth.

1. INTRODUCTION

The design of machine elements and mechanical structures subjected to variable loading in service life is usually performed using classical concepts of machine design, such as material data obtained through constant amplitude fatigue loading tests. Application of fatigue materials data, obtained from constant amplitude tests, to design of components subjected to variable amplitude loading conditions, which is common in service loading, has been performed through the use of damage accumulation concepts, such as Palmgren-Miner rule.

In mechanical components subjected to severe loading conditions, the generalization of damage tolerance is of prime importance in order to maintain the reliability of structures and mechanical components. Damage tolerance is based on fracture mechanics, where crack growth calculations are carried out through the use of stress intensity factors, fracture toughness and fatigue crack growth data, these data being already available on data bases and associated software.

The effect of variable amplitude loading on fatigue crack growth remains a problem not completely solved. The main studies are related to the effect of tensile overloading on aircraft components and structures in light alloys, and several semi-empirical and theoretical models have been proposed [1]. Models based on either experimentally determined retardation factors applied to Forman's crack growth law or on effective stress intensity factors based on Elber's concept of crack closure [2], with opening loads calculated either by strip-yield models or finite element models, are available in the literature [3].

Compressive overloading effects on fatigue crack growth in steels have been reported in the literature [4], and show that for high compressive loads the crack opening load may be negative, which implies that higher crack growth rates are obtained [5].

In order to estimate the effect of the retardation or acceleration of fatigue crack growth in multiple overloads and underloads a wide range of fatigue tests were carried out, where not only the variations of overloads and underloads were used (N=1) but also the variation of the number of the baseline cycles (n=9, 99, 999 and 9 999), in order to fully understand the remaining effect of an overload and underload during subsequent crack growth. A modelisation taking into account the closure load induced by the overloads and its effect on the baseline cycles is considered.

2. EXPERIMENTAL PROCEDURE

2.1 Material and specimens

The material used is a normalized medium carbon steel, DIN Ck 45. The chemical composition and mechanical properties are presented, respectively in tables 1 and 2. Tests were carried out in a 100kN Instron servo-hydraulic testing machine at a frequency of 10 Hz in load control mode.

Table 1. Chemical composition of DIN Ck45 steel

C	Mn	Cr	Ni	Ti	Cu	Si	P	S
.41	.76	.09	.08	.01	.19	.23	.01	.02

Table 2. Mechanical properties of DIN Ck 45 steel

σ_y (MPa)	σ_u (MPa)	A (%)
350	600	25

The specimens are middle-crack tension (M(T) type), 10 mm thick and 60 mm width, in accordance with the Standard Test Method for Measurement of Fatigue Crack Growth Rates, (ASTM E 647-98). The central notch was 10 mm long and was made by electrical-discharge machining. A fatigue precracking was conducted till the crack length was approximately 15 mm long.

Crack growth measurements were made by an optical microscope associated with a stroboscopic illumination at the frequency of testing.

2.2 Loading conditions

Several series of block loading were programmed on the servo-hydraulic fatigue machine software, in order to study the behavior of tension overloads or compression overloads either as single events within a block loading or with tension/compression and compression/tension overload. The length of the block loading is variable, between 10 and 10 000 cycles, function of the number of cycles between overloads, and were established in order to study the remaining influence on crack growth of the overload. A stress ratio of R=0.1 was used for the cycles of constant amplitude loading for all tests. Loading conditions are summarized in table 3 and were established as follows:

- a tension overload of 93 kN, followed by 9 or 99 or 999 or 9 999 cycles of constant amplitude loading, corresponding to 55% of the maximum load of 60 kN and minimum load of 6 kN, with a stress ratio of R=0.1;
- a compression underload of –27 kN, corresponding to the same compression overload with respect to the minimum load of the constant amplitude cycle, followed by 9 or 99 or 999 or 9 999 constant amplitude cycles;
- a tension overload of 93 kN and a compression underload of –27 kN followed by 9 or 99 or 999 or 9 999 constant amplitude cycles;
- a compression underload of –27 KN and a tension overload of 93 kN followed of 9 or 99 or 999 or 9 999 constant amplitude cycles;

Table 3. Number of cycles within a block, defining the loading conditions

Over/underload	Baseline cycles			
+1	9	99	999	9 999
-1	9	99	999	9 999
+ 1-1	9	9	999	9 999
- 1+1	9	9	999	9 999

4. RESULTS

In order to fully characterize the crack growth behaviour of the normalized Ck 45 steel, a series of tests of constant amplitude were carried out. Two stress ratios were used and can be found in Romeiro et al [5] and are summarized as follows:

R=0.1, the stress ratio of the constant amplitude cycles, and the following crack growth relation was obtained:

$$da/dN = 4.56e^{-9}(\Delta K)^{3.1} \qquad (1)$$

where $\Delta K = K_{max}-K_{min}$ is the stress intensity factor range.

a stress ratio of R=0.7, which will be used as the reference crack growth data when analysis will be carried out with the use of the effective stress intensity factor $\Delta K_{eff} = K_{max}-K_{op}$, given by:

$$da/dN = 8.91e^{-9}(\Delta K_{eff})^{3} \qquad (2)$$

where K_{op} is the stress intensity factor calculated from the load for which the crack is fully open.

The results of fatigue crack growth tests using the block loading described above will be presented as the crack length as a function of the number of cycles, a usual way to present variable amplitude loading for which it is not possible to define a constant amplitude within a block load. The following figures will show the crack growth results in two ways: either by type of overloading/underloading where only the number of cycles between the overloads is changed for each loading block, or comparing crack growth data for the different types of overloading but maintaining the number of cycles between overloads or underloads.

4.1 Overloads

It has been pointed in literature that an overload causes a delay in crack growth, and the results in figure 1 show this effect. As a reference for crack growth, figure 1 also presents the crack growth data, obtained with constant amplitude loading (CA) using equation (1) for the same loading case as the constant amplitude cycles. But these results also show that the global retardation effect depends on the number of overloads and consequently on the number of lower amplitude loading cycles. For the four block loading cycles presented in figure 1, it is to note that a faster crack growth is obtained with 9 999 cycles of baseline cycles between overloads than with 999 cycles, therefore the highest retardation effect is obtained with and interval between overloads of 999 cycles. These results mean that on the 9 999+1 cycles the retardation effect is only applicable during part of the crack growth

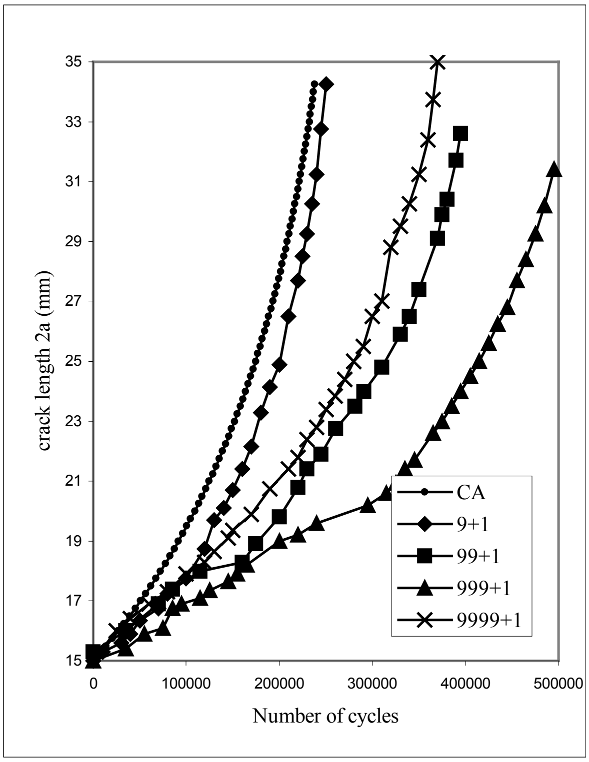

Fig.1. Crack growth with overloads

4.2 Underloads

This effect is presented on figure 2, where CA also represents the constant amplitude loading for a stress ratio of R=0.1. It is known that some acceleration in crack growth may appear for significant compressive loads within a block loading and this effect is observed in the present results, with the exception of the crack growth data obtained with 9 999 constant amplitude cycles between underloads. But, there is no significant difference on the acceleration effect for 9, 99 and 999 cycles of baseline cycles between underloads. This acceleration effect is due to the fact that the cycle with the underloads is no more at a stress ratio of R=0.1 but at a negative stress ratio of R= -0.45. With negative stress ratio the opening loads according to Elber crack closure model, are zero or negative depending of the magnitude of minimum stress and stress ratio.

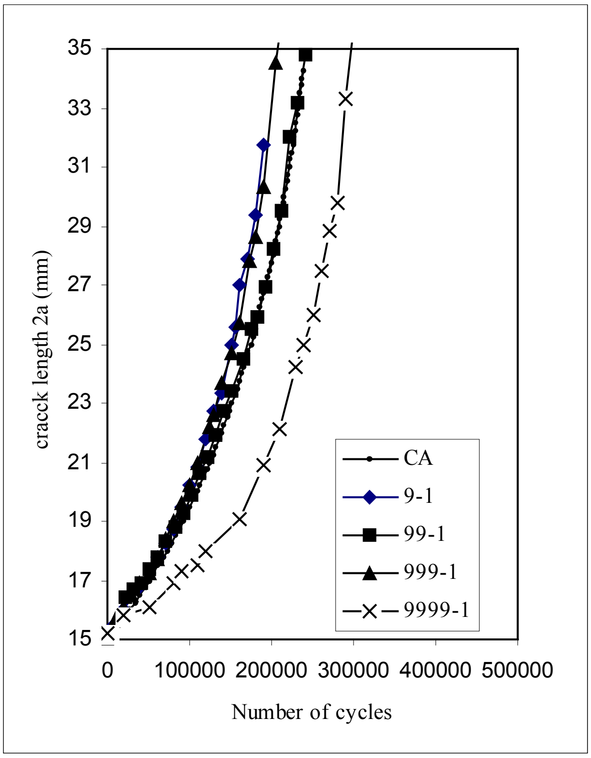

Fig. 2. Crack growth with underloads

4.3 Overload and underload effect

The following results, presented in figures 3 and 4, show the effect of the simultaneous presence of either an overload followed by an underload presented in figure3 or of an underload followed by an overload presented in figure 4.

It can be seen that both retardation and acceleration effects are considerable reduced with the simultaneous presence of overloads and underloads. This effect must be related with the cyclic crack tip plasticity appearing during the reversal of load cycles because in this case a stress ratio of R= -0.3 is present during the underload/overload cycle and again a very reduced opening load may appear.

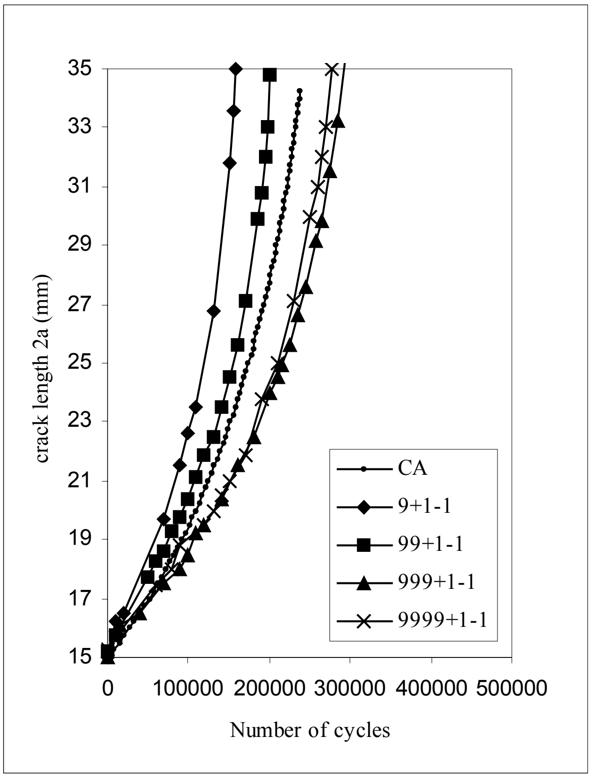

Fig. 3. Crack growth with overload/underload

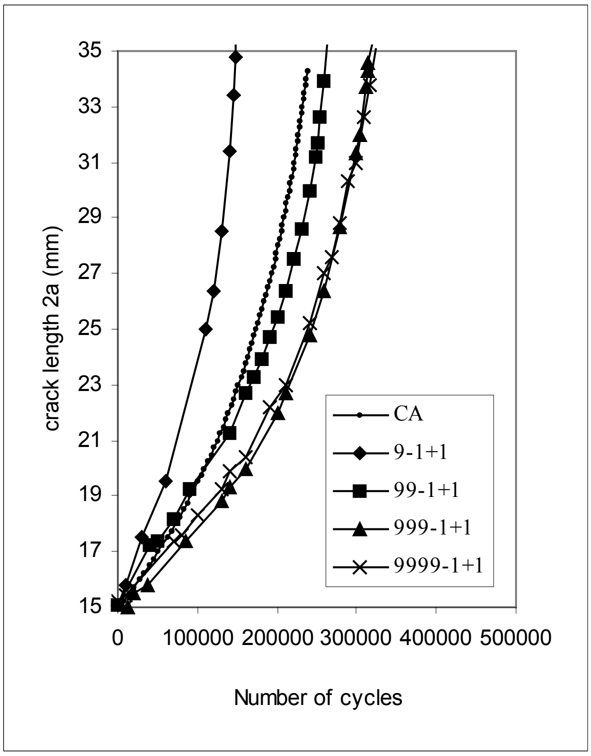

Fig. 4. Crack growth with underload/overload

4.4 Influence of spacing cycles

The previous results can also be presented and analysed for the same number of the baseline cycles between the overload/ubderload in order to search their influence. This analysis is important since in this way the influence of the loading change is put in more evidence. The crack growth results of the loading blocks where only 9 cycles are present in the block are presented in figure 5. The results show the small change in the crack growth rate when the compression underload cycles are present.

In figure 6, comparisons of crack growth rates are shown for 99 cycles of interval between overloads/underloads and these results confirm the conclusion already present for the previous figure, i. e. the influence of compression loading is to make null the retardation effect due to overloading.

The effect of the perturbation in crack growth is somewhat amplified for the case of 999 cycles of constant amplitude cycles, meaning that the effect is maximum for the load cases studied.

Finally figures 8, show that the effect of the change in crack growth rate due to the perturbation of constant amplitude loading becomes negligible as the number of constant amplitude cycles of the loading block between the overload/underload increases, as is evident when 9 999 constant amplitude cycles are present between overloads or underloads or with both loadings in any order.

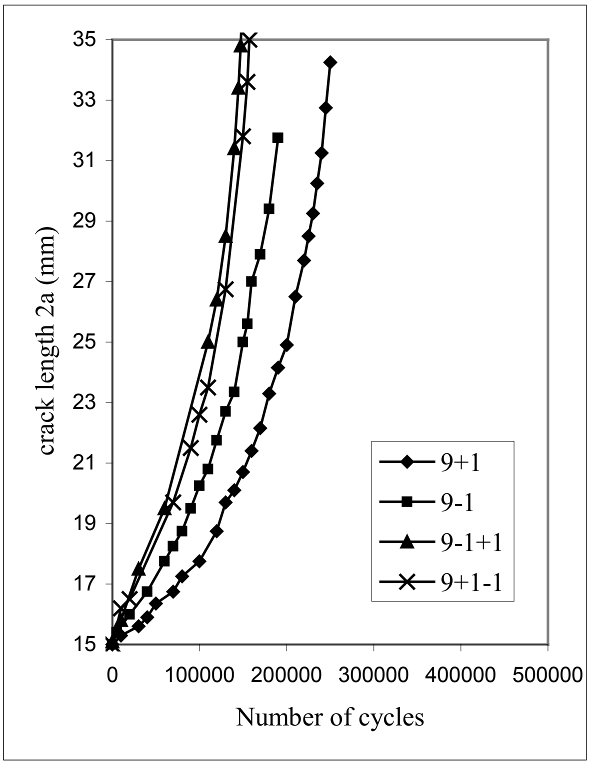

Fig. 5. Crack growth with 9 cycles of constant amplitude loading

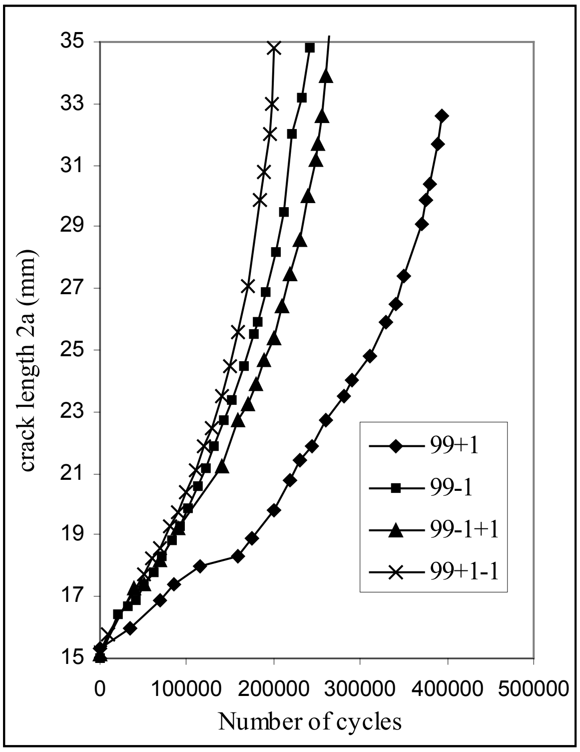

Fig.6. Crack growth with 99 cycles of constant amplitude loading

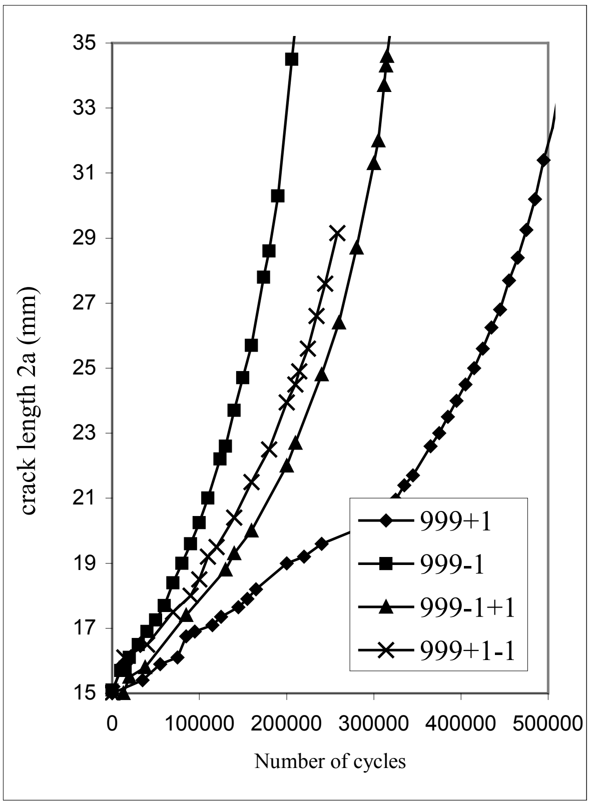

Fig.7. Crack growth with 999 cycles of constant amplitude loading

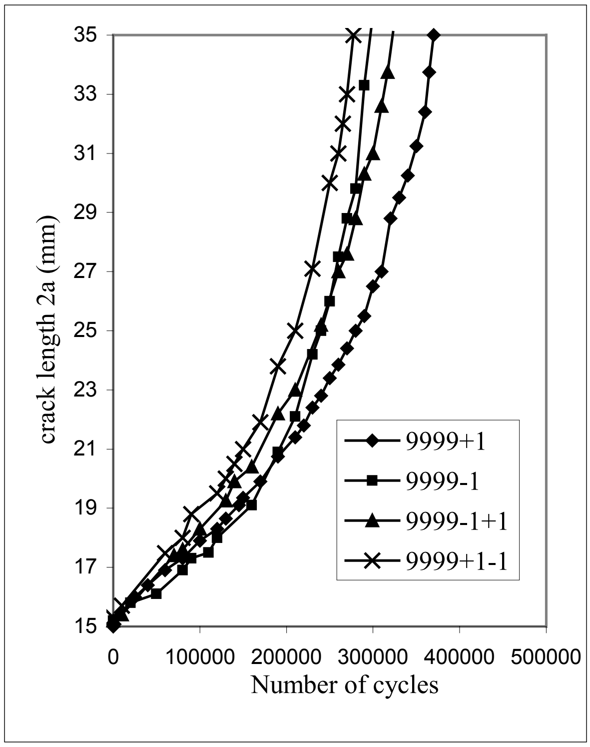

Fig.8. Crack growth with 9 999 cycles of constant amplitude loading

5. ANALYSIS AND DISCUSSION

Several models for prediction of fatigue crack growth under variable amplitude loading which includes the sequence effect, have been proposed. These models are always based on the crack tip plasticity induced by the stress singularity at the crack tip. But, the way followed by the different models to take into account the crack tip plasticity is substantially different.

In this work we will follow the models that take into account the plasticity-induced crack closure, meaning that crack growth rate will change according to the size of the crack tip plasticity that induces crack closure. The determination of the size and shape of the plasticity at the crack tip and of the plasticity-induced crack closure has been recently object of research on mild steels [8]. Using finite element methods and plasticity models, including kinematic or isotropic hardening and Bauschinger effects, Pommier et al [8] conclude that the cyclic plastic behaviour of the material strongly affect the crack behaviour after an overload or an underload. The present study, we will calculate the dimension r_y on crack growth direction of the crack tip plastic by the Irwin model, as:

$$r_y = \frac{1}{2\alpha\pi}\left(\frac{K_{max}}{\sigma_y}\right)^2 \quad (3)$$

where α is plane stress/plane strain constraint factor.

The sequence effect will be taken into account while the crack growth remains on the crack tip plasticity effect of the previous cycles.

The crack growth models based on the crack closure concept are based on the effective stress intensity factor range $\Delta K_{eff} = K_{max}-K_{op}$, calculated from the difference between the naximum stress intensity factor K_{max} during a cycle and the stress intensity factor calculated with the load for which the crack is fully opened K_{op}. One of the equations most used for the crack growth predictions with this model, is the one described on the Nasgro manual [6]:

$$\frac{da}{dN} = \frac{C(1-f)^n}{(1-R)^n}\Delta K^n \frac{\left(1-\frac{\Delta K_{th}}{\Delta K}\right)^p}{\left(1-\frac{\Delta K}{(1-R)K_c}\right)^q} \tag{4}$$

where $f=(K_{op}/K_{max})$, ΔK_{th} is the threshold of crack growth and K_c is the critical stress intensity factor. This equation reduces to the simple Elber equation:

$$da/dN = C(\Delta K_{eff})^n \tag{5}$$

when the crack growth is under constant stress ratio and maintained under the linear part of the crack growth. An essential part of the crack growth prediction is the determination of the load P_{op} within a cycle for which the crack is fully opened and therefore ready to start crack growth.

We will determine the plasticity-induced opening load by the following equation, which was established through the so-called strip-yield model. This is an analytical/numerical model proposed by Newman, and that has been proved to give accurate crack growth predictions on high strength aluminum alloys under variable amplitude loading representative of specific spectrum for aircraft structures. The proposed equations are [7]:

$$\begin{aligned} P_{op} &= P_{max}\left(A_0 + A_1 R + A_2 R^2 + A_3 R^3\right) \quad \text{if} \quad R \geq 0 \\ P_{op} &= P_{max}\left(A_0 + A_1 R\right) \quad \text{if} \quad -2 \leq R < 0 \end{aligned} \tag{6}$$

where R is the stress ratio and the constants A_i are a function of the flow stress of the material σ_0, calculated as the average between the uniaxial yield stress and ultimate tensile strength, the maximum applied stress σ_{max} within a cycle and the constraint factor α, which is a variable between 1 and 3 to take into account the plane stress/plane strain effect, and are given by:

$$\begin{aligned} A_0 &= \left(0.825 - 0.34\alpha + 0.05\alpha^2\right)\left(\cos\frac{\pi\sigma_{max}}{2\sigma_0}\right)^{1/\alpha} \\ A_1 &= \left(0.415 - 0.07\alpha\right)\left(\frac{\sigma_{max}}{\sigma_0}\right) \\ A_2 &= 1 - A_0 - A_1 - A_3 \\ A_3 &= 2A_0 + A_1 - 1 \end{aligned} \tag{7}$$

The constraint factor α, is calculated through crack growth experimental data at R=0.1, equation (1), that shall be the same as equation (2) when calculations of crack growth are carried out through equations (5) to (7). This model has been applied to a wide range of materials and is also described on Nasgro code manual for crack growth. An application of this model for prediction of opening loads during negative stress ratios can be found in Romeiro et al [5].

Predictions of crack growth are now carried out using a computer program that makes a cycle by cycle calculation of crack growth using equations (5) to (7) and where at each cycle the dimension of the crack tip plasticity of the actual cycle and of the previous cycle is compared. While the crack is growing on the crack tip plastic zone of a previous cycle, the opening load on equation (6) for crack growth is calculated with the maximum load of the previous cycle. As soon as the crack is growing within the current crack tip plastic zone, the opening load is calculated through the maximum stress of the current cycle. In this way the sequence effect is taken into account allowing to explain the remaining effect of overloads during constant amplitude cycles.

For the four loading blocks with overloading, represented on figure 1, predictions of crack growth for the same loading conditions are presented in figure 9. They show very consistent results between experimental crack growth results and predictions. A retardation effect is predicted and this retardation effect increases from an interval of 9 cycles to 999 cycles of constant amplitude loading, but the amount of retardation predicted for the loading block of 999+1 is smaller than the experimental observed. It is to be noted that a higher crack growth rate is predicted for 9 999+1 loading block than for the 999+l loading block as experimental observed, which confirms the correction of the proposed model. The discrepancies between predicted retardation and experimental one may be explained because of the sensitivity of the proposed model to the effective size of the crack tip plastic zone. Improvement of the model can be achieved with more accurate calculations, such finite element methods and plasticity models [8] of the dimension of the crack tip plastic zone, which in this study is calculated by equation (3), a simplified model due to Irwin.

Further analysis is now needed in order to have the effect of multiple overloads or underloads which also seems to affect the crack growth rate with variable amplitude loading.

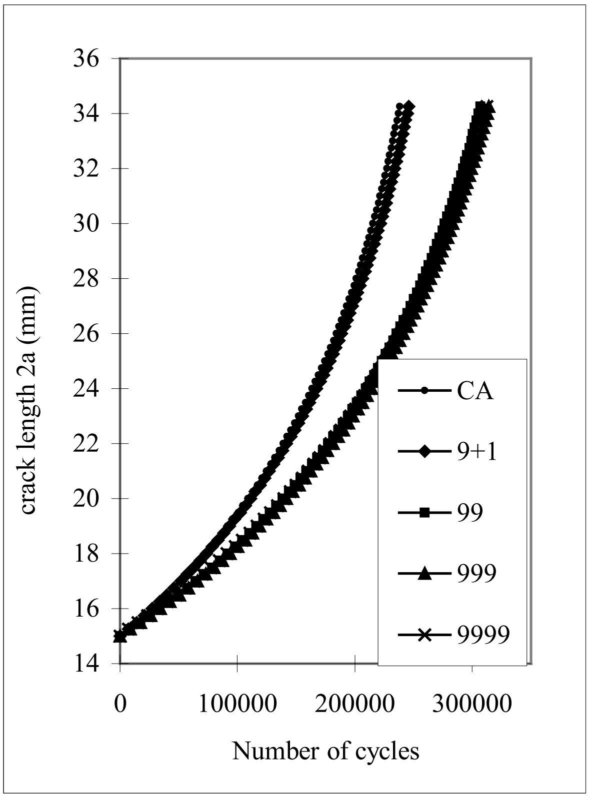

Fig. 9. Crack growth predictions for blocks with overloads

6. CONCLUSIONS

A series of fatigue crack growth tests were carried out under loading blocks including overloads and underloads, and the following conclusions may be expressed:

The retardation effect due to an overload is explained through the effect of the plasticity induced crack closure that also explains the amount of retardation that is achieved with several overloads during a block loading.

Acceleration of crack growth was obtained with underloads and this effect is explained through the crack opening loads that may be zero or negative during negative stress ratio.

Small changes in crack growth were obtained with both overloads/underloads or underloads/overloads and this effect is also explained through the negative stress ratio.

Predictions of fatigue crack growth of block loadings with overloads applied at different intervals of constant amplitude cycles, using Elber and plasticity-induced crack closure models helped to calculate the sequence effect due to an overload.

7. REFERENCES

[1] Freitas, M., Reis, L. and Gonçalo, H., "Damage tolerance analysis of PoAF aircrafts to assess the severity of the usage" Anales de la Mecanica de la Fractura. Volume 16, Año 1999, 113-118 (1999).

[2] Elber, W., "Fatigue crack closure under cyclic tension", Engineering Fracture Mechanics, Volume 2, 37-45 (1970)

[3] Dominguez,, J. Y Zapatero, J. "Introducción al análisis del comportamiento de grietas a fatiga bajo cargas de amplitud variable", Volume 16, Año 1999, 49-64 (1999).

[4] Buschermohle, H., Memhard, D. and Vormwald, M. "Fatigue crack growth acceleration or retardation due to compressive overload excursions", Proceedings of the Sixth International Fatigue Congress, Fatigue 96, Volume 1, 583-588 (1996).

[5] Romeiro, F., Domingos, C. and Freitas, M. "Measurement of fatigue crack closure for negative stress ratio", Advance in in Fatigue Crack Closure Measurement and Analysis: Second Volume, ASTM STP 1343, R. C. McClung and J. C. Newman, Jr. Eds, 321-336 (1999)

[6] Fatigue Crack Growth Computer Program, NASA/FLAGRO user's manual, theory and operation, (1995).

[7] Newman, J. C. Jr, "A crack opening stress equation for fatigue crack growth" International Journal of Fracture. Volume 24, 131-135 (1984).

[8] Pommier, S. and Bompard, Ph. "Bauschinger effect of alloys and plasticity-induced crack closure: a finite element analysis", Fatigue and Fracture of Engineering Materials and Structures, Volume 23, 129-139 (2000).