Proceedings of PVP2008
2008 ASME Pressure Vessels and Piping Division Conference
July 27-31, 2008, Chicago, Illinois, USA

PVP2008-61384

EFFECTS OF A SINGLE OVERLOAD EVENT ON THE FATIGUE CRACK GROWTH RATE OF A LOW ALLOYED ROTOR STEEL

J.C. Le Roux[1] and F. Hasnaoui[2]

[1]EDF R&D, avenue des Renardières – Ecuelles, 77818 Moret-Sur-Loing cédex, FRANCE
[2]EDF R&D, 1 avenue du Général De Gaulle, BP 408, 92141 Clamart cédex, FRANCE

ABSTRACT

The aim of this work is to study the effect of the overload on the fatigue crack growth rate properties of a low alloyed steel used for rotor disk. On one hand, experimental fatigue tests during which a single overload event is applied are performed on CT specimens. Different loading conditions are imposed in order to study the effects of these parameters on the retardation of the fatigue crack due to the overload. On the other hand, two dimensions elastic plastic Finite Element calculations of crack propagation using nodes release method were used to estimate the effects of a single overload event on the fatigue crack growth rate. Different loading conditions, as for the experimental tests, are used in order to study numerically the effects of these parameters on the retardation of the fatigue crack due to the overload. The experimental and numerical results show the decrease of the crack growth rate due to the overload. This decrease depends on different parameters as overload ratio, stress ratio used for the constant amplitude cyclic loading and ΔK at which the overload is applied. From experimental test results, it can be observed that the decrease is as significant as the overload ratio is high, and as the ΔK at which overload is applied and stress ratio are low. Numerical results show similarities with experimental results, for instance the decrease of the fatigue crack growth is linked to the increase of the overload ratio or to the decrease to the ΔK at which overload is applied. Differences are also observed i.e. the increase of the stress ratio seems to increase the effect of the overload in the numerical calculations in contrary of the experimental results. By comparing to the numerical results, the quality of the results obtained from simplified models has been assessed in regard of the overload effect. A modified Kim and al. model seems to be representative of the different effects of the overload on the fatigue crack growth rate. The future work to be done consists to improve the comparison between experimental and numerical studies.

NOMENCLATURE

K : stress intensity factor
K_{OL} : stress intensity factor corresponding to overload
ΔK : stress intensity factor range for constant amplitude cyclic loading
ΔK_{eff} : effective stress intensity factor range for constant amplitude cyclic loading
R : stress ratio for constant amplitude cyclic loading
F_{max} : maximum load for constant amplitude cyclic loading
F_{min} : minimum load for constant amplitude cyclic loading
F_{OL} : load corresponding to overload
%OL : overload ration given by $(F_{OL}-F_{max})/F_{max}$
OLR : overload ration given by $(F_{OL}-F_{min})/F_{max}-F_{min})$
da/dN : fatigue crack growth rate
$(da/dN)_{OL}$: fatigue crack growth rate after the overload
a_{OL} : crack length corresponding to overload
a_d : crack length corresponding to the end of the overload effect
a_{min} : crack length corresponding to the maximum overload effect (and to the minimum $(da/dN)_{OL}$)
σ_{yy} : normal stress to the crack plane
Z : monotonic plastic zone due to constant amplitude cyclic loading
Z_{OL} : monotonic plastic zone due to overload
Z_{OLc} : length of the compressive zone in which σ_{yy} is negative and almost constant (after overload)
$Z_{OL}num$: Z_{OL} determined by numerical calculation
$Z_{OL}an$: Z_{OL} determined by analytical calculation
$Z_{OLc}num$: Z_{OLc} determined by numerical calculation
$Z_{OLc}an$: Z_{OLc} determined by analytical calculation
Nd : number of cycles of delay due to overload

INTRODUCTION

Several short fatigue cracks appeared in rotor disk in nuclear power plant for last years. In order to prevent the propagation of these cracks, the material in the area of the crack is removed. The risk of the reappearance of such a crack is not unlikely. So, we have to think about the propagation of such a crack in a rotor disk material. Indeed, the material is submitted to the cyclic loading due to the blade vibrations and sometimes to overloads because of the overspeed of the rotor. The objective of this work is to study the effects of a single overload event, within otherwise constant amplitude cycles, on the fatigue crack growth rate of a 20CrNiMo8 low alloyed steel used for rotor disk. On one hand, fatigue crack growth rate tests with a single overload event were performed on CT specimens, with different experimental conditions. On the other hand, two dimensions elastic plastic Finite Element (F.E.) calculations of crack propagation using nodes release method were used to estimate the effects of a single overload event on the fatigue crack growth rate.

EXPERIMENTAL STUDY

Material data and specimens

The material used for the experimental study is a low alloyed steel 20CrNiMo8. It comes from a rotor disk produced from two different melts whose chemical composition is given in the table 1.

	C	Si	Mn	S	P
Specified value	0.18 0.25	0.10 0.40	0.25 0.80	0.035 max	0.035 max
Melt 16910 (60%)	0.235	0.115	0.635	0.010	0.010
Melt 33836 (40%)	0.215	0.265	0.665	0.010	0.010
	Ni	Cr	Mo	V	
Specified value	0.9 1.1	1.2 2	05 0.8	0.05 max	
Melt 16910 (60%)	1.04	1.77	0.635	0.025	
Melt 33836 (40%)	0.9	1.68	0.610	0.020	

Table 1 : chemical composition of the two melts used for the rotor disk from where the CT specimens were taken

Yield strength and ultimate strength are respectively equal to 668 and 775 MPa at room temperature.
CT specimens were used to carry the fatigue crack growth rate tests. As the rotor disk hasn't submitted a stress-relief heat treatment, the CT specimens were thermally treated as shown in the figure 1.
The CT specimens dimensions are W = 50 mm and B = 25 mm in accordance to AFNOR 03-404 French standard [1].

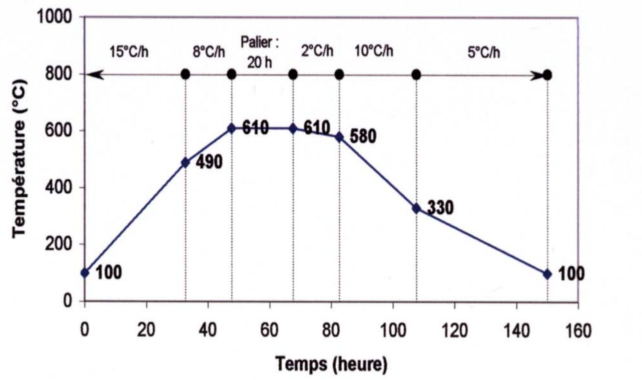

Figure 1 : thermal treatment of the CT specimens before fatigue tests

Experimental equipment

Fatigue crack growth rate tests with a single overload event were performed on a servo-hydraulic 100 kN MTS machine. The machine was controlled via "Fatigue Crack Growth" 4.5B MTS software. Such software allows to perform fatigue tests and to determine results according ASTM E647 standard. During all the test stages, the crack length was measured by the compliance method via a capacitive COD clip gage extensometer.

Test procedure and test parameters

The fatigue tests were performed with a constant amplitude sinusoidal loading and the application of a single overload event at room temperature and in air. For each test, four stages can be distinguished. The first stage (stage 1) consists of precracking the specimen at stress ratio R = –1, at 20 Hz and at room temperature. The initial value of the crack length is 10 mm. After the precracking, the crack length is either 12,5 mm or 15 mm. During the precracking, the K_{max} value decreases from 20 to 9 MPa $m^{1/2}$. The second stage (stage 2) consists of cracking the specimen at constant amplitude cyclic loading so that the crack length at the end of the stage reaches 17 mm. The third stage (stage 3) corresponds to the application of the overload from 0 kN to the desired value. The increase and decrease of the load is obtained in 20 seconds. The fourth stage (stage 4) consists of cracking the specimen at constant amplitude cyclic loading after the overload application in order to measure the effect of the overload on the fatigue crack growth rate of the low alloyed steel. During stage 4, the cyclic load amplitude is the same as in the second stage. When the fourth stage is over (i.e. crack length reaches a value sufficiently high so that effects of overload can be studied), the specimen is broken at –96℃ in order to measure the fatigue crack lengths corresponding to the different stages. The second and the fourth stages are realized at 5 Hz and at room temperature.
The other parameters data given for each fatigue test in the table 2 are the stress ratio R, the maximum Force F_{max} (corresponding to the stages 2 and 4), the overload force F_{OL} (corresponding to the stage 3), the overload ratio given by %OL or by OLR. The stress intensity factor ranges corresponding to the end of the stage 2 and the beginning of the stage 4 are also given. To

obtain these values, we assumed that crack doesn't propagate during the stage 3.

Specimen number	R	F_{max} before OL (ΔK)	F_{OL} (%OL ; OLR)	F_{max} after OL (ΔK)
4	0,1	20 (20)	40 (1,00 ; 2,11)	20 (20)
5	0,1	15 (15)	40 (1,67 ; 2,85)	15 (15)
6	0,1	15 (15)	40 (1,67 ; 2,85)	15 (15)
12	0,1	15 (15)	30 (1,00 ; 2,11)	15 (15)
13	0,1	15 (15)	20 (0,33 ; 1,37)	15 (15)
14	0,1	10 (10)	20 (1,00 ; 2,11)	10 (10)
7	0,1	15 (15)	60 (3,00 ; 4,33)	15 (15) then 20 (20)
8	0,35	20,7 (15)	55,3 (1,67 ; 3,57)	20,7 (15)
9	0,5	26,9 (15)	71,7 (1,67 ; 4,33)	26,9 (15)
10	0,1	15 (15)	50 (2,33 ; 3,59)	15 (15) then 20 (20)

F_{max} and F_{OL} in kN and ΔK in MPa $m^{1/2}$

Table 2 : parameters for fatigue tests with overload

Experimental results

The experimental results show a decrease of the fatigue crack growth rate and sometimes a stop of the propagation of the crack after the application of the overload. As reported in the literature, this phenomenon is due in part to the plastification of the material in front of the crack tip, so that residual stresses are created and closure of crack lips takes place. The closure effects leads to slowdown of the propagation of the crack and sometimes to their stop.
On the figure 2, the effects of the overload is represented on a fatigue crack growth rate versus stress intensity factor range plot.

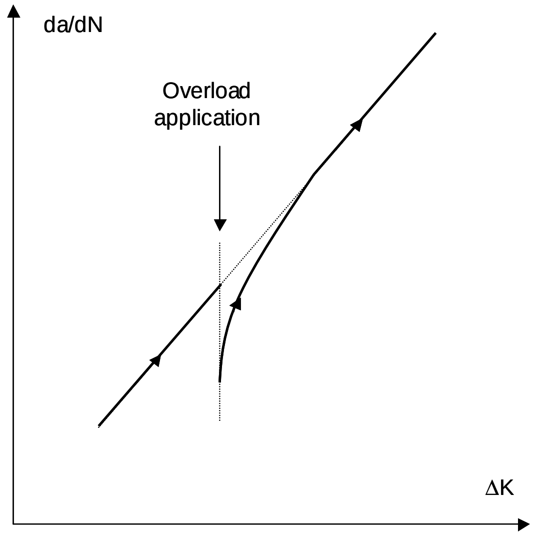

Figure 2 : effect of a single overload event on the fatigue crack growth rate on a da/dN vs ΔK plot

All the tests results are shown on a da/dN vs ΔK plot on the figure 3.

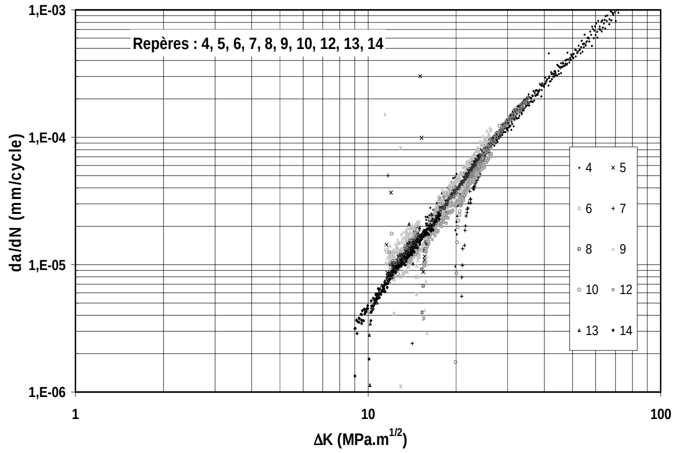

Figure 3 : experimental results on a da/dN vs ΔK plot

the figure 3 shows that the results are gathered around the fictive Paris straight line with a little scattering. It can be observed that some points are under the other data. They correspond to the part of the results which show a lower fatigue crack growth rate than in the nominal regime.
The combination of the loading conditions enable to study the effect of different parameters on the retadartion of the fatigue crack propagation due to the overload application. Indeed, three sets of test can be defined as following :
set 1 includes tests 5, 6, 7, 10 and 12, which are performed at R = 0,1 and ΔK = 15 MPa $m^{1/2}$ (when overload was applied), with different values of %OL,
set 2 includes tests 4, 12 and 14, which are performed at R = 0,1 and %OL = 100% (OLR = 2,11), with different values of ΔK (when overload was applied),
set 3 includes tests 5, 6, 8 and 9, which are performed at ΔK = 15 MPa $m^{1/2}$ (when overload was applied) and %OL = 167%, with different values of R.
The test results of each set are reported on the same plot. For instance the results of the tests 5, 6, 7, 10 and 12 are reported on the figure 4 on a crack length versus number of cycles (after overload) plot.

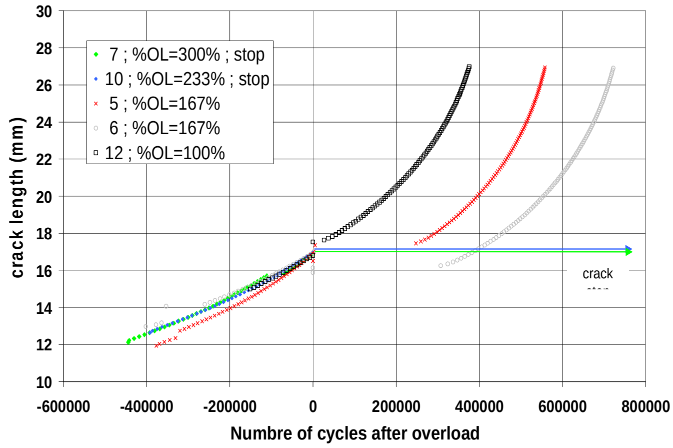

Figure 4 : effect of %OL on the decrease of the fatigue crack growth rate on a "a vs N cycles" plot (tests 5, 6, 7, 10 and 12)

The figure 4 shows the decrease of the fatigue crack growth rate due to the overload application for each test of set 1, except for test 12. It also shows that the decrease is as significant as the %OL is high. For instance, the overload seems to be not effective for the test 12 for which %OL is the lower value of the set 1 (100%) and the crack didn't restart after the overload for tests 7 and 10, for which %OL is the higher value of the set 1 (233 and 300%).
the results of the tests 4, 12 and 14 are reported on the figure 5 on a crack length versus number of cycles (after overload) plot.

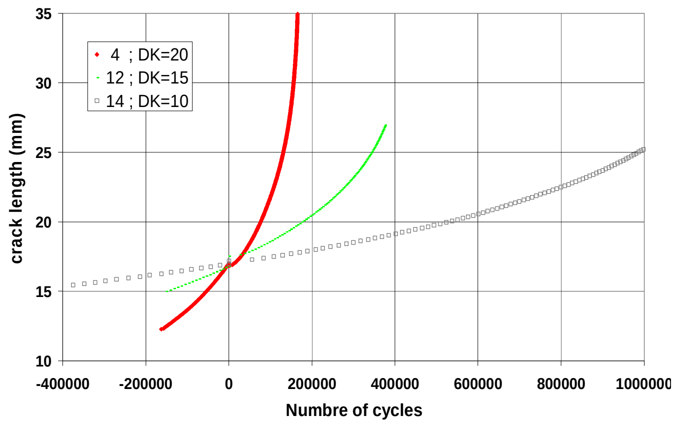

Figure 5 : effect of ΔK on the decrease of the fatigue crack growth rate due to a single overload application on a "a vs N cycles" plot (tests 4, 12 and 14)

The figure 5 shows that for %OL = 100%, the overload has no effect on the fatigue crack growth rate, whatever the value of ΔK between 10 and 20 MPa $m^{1/2}$ is. Other results (obtained by Politecnico Di Milano in a contract with EDF) from fatigue tests with single overload application at OLR = 2,85 show that as the ΔK at which the overload is applied decreases, the delay in crack propagation increases.
the results of the tests 5, 6, 8 and 9 are reported on the figure 6 on a "a vs N cycles" plot.

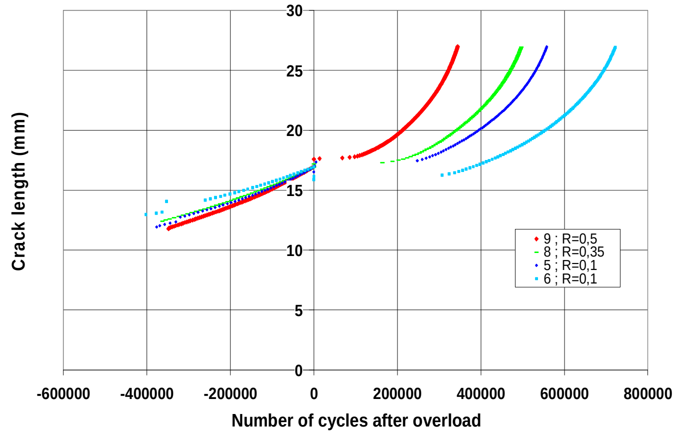

Figure 6 : effect of R on the decrease of the fatigue crack growth rate due to a single overload application on a "a vs N cycles" plot (tests 5, 6, 8 and 9)

The figure 6 shows the decrease of the fatigue crack growth rate due to the overload application for each test of set 3. It also shows that its decrease is as significant as the stress ratio R is low. For instance, the number of cycles of delay due to overload is higher for test 5, for which R = 0,1 than for test 9, for which R = 0,5.

NUMERICAL STUDY

This part of the paper deals with the numerical study of the effects of a single overload event, within otherwise constant amplitude cycles, on the fatigue crack growth rate of a 20CrNiMo8 low alloyed steel used for rotor disk manufacturing. To achieve this objective, we performed two dimensions elastic plastic F.E. calculations of crack propagation using nodes release method with Code_Aster© [2]. The modelling of the calculations is presented. Then, we analyse numerical calculations results through the analysis of the stress field in the front of the crack tip and also the effective stress intensity factor values. They are then used to determine the delay retardation due to the overload application. Effects of the parameters as stress ratio, overload ratio and ΔK at which overload is applied are eventually discussed.

Modelling of the crack propagation

Calculations were made in plane stress conditions but also in plane strain condition on a quadratic F.E. model built according to CT specimen dimension.

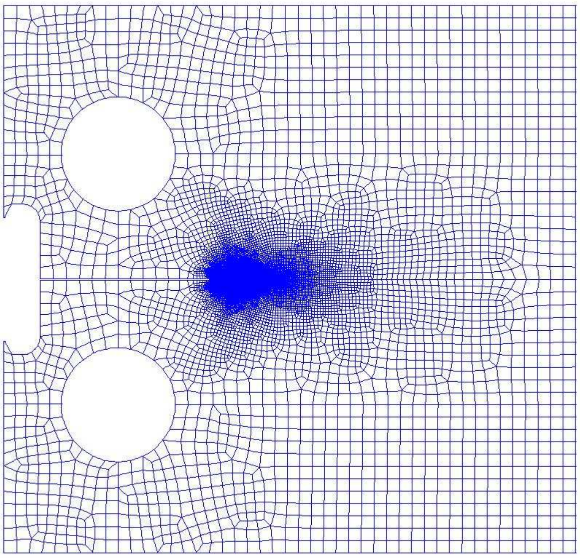

Figure 7 : view of the 2D F.E. mesh

The crack propagation is achieved by releasing progressively nodes that constitute the crack lips. This releasing leads to a 34µm crack propagation. The contact between the faces of the crack is not taken into account, so that crack faces interpenetrate when crack closure is effective. In this case, K is considered equal to 0. A linear cinematic hardening is used as elastic plastic cyclic behaviour of the 20CrNiMo8 material. The stress intensity factors are calculated via the crack tip opening displacement method. As for experimental part, several calculations are performed to study the effect of the parameters as stress ratio, overload ratio and ΔK Base line (ΔK at which overload is applied) on the fatigue crack growth rate.

Qualitative numerical analysis

The normal stress to the crack plane σ_{yy} is calculated in front of the crack tip at 4 different moments. The first and the second ones correspond to the application of respectively the maximum and the minimum forces just before the overload application (blue curves). The third one corresponds to the application of the overload and the fourth one to the minimum force just after the overload application (pink curve). The results of these calculations are reported on the figure 8.

An identical behaviour is obtain for each numerical test condition than those shown on the figure 8. Just after the overload application, in an area just after the crack tip, the material is under compression and σ_{yy} is almost constant. This area is called compressive zone (Z_{OLc}). The stress σ_{yy} then increases until a maximum value. The distance between this point (for which crack length is called a_d) and the overload application point (for which crack length is called a_{OL}) corresponds to the length of the monotonic plastic zone (Z_{OL}) due to overload. When the crack is in this monotonic plastic zone, the propagation is delayed because of the closure effect. When the crack gets out of this zone, the fatigue crack growth rate is as if the overload never happened.

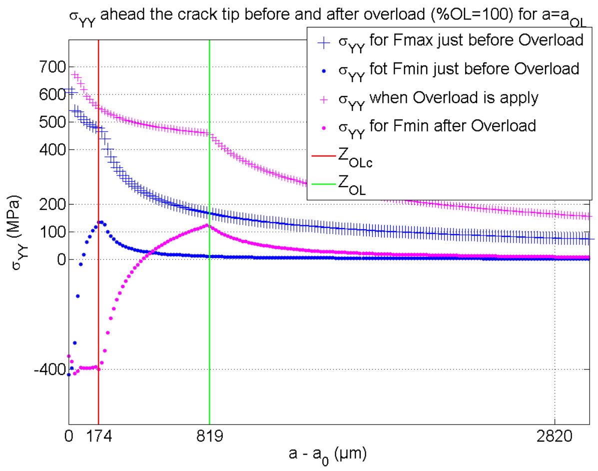

Figure 8 : σ_{yy} in front of the crack tip, before, at and after the overload application

This phenomenon can also be observed on the figure 9 which shows the evolution of the effective stress intensity factor ΔK_{eff} vs the crack length.

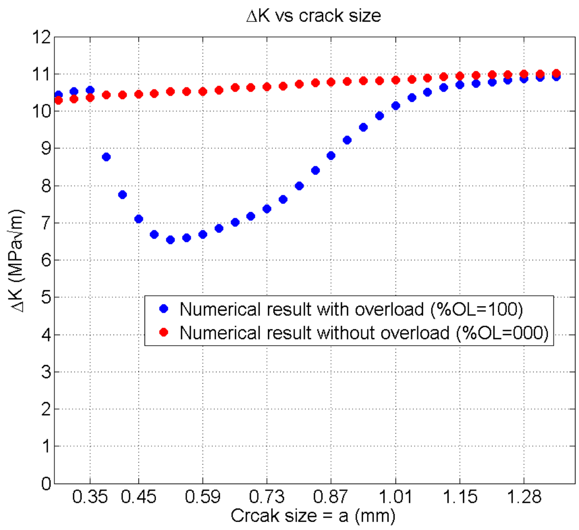

Figure 9: evolution of the effective stress intensity factor range ΔK_{eff} versus crack length

We can observe that ΔK_{eff} decreases as soon as the crack penetrates the monotonic plastic zone due to the overload to reach a minimum value (for which crack length is called a_{min}) and then increases until it gets out of the plastic zone. When crack length is higher than a_d, ΔK_{eff} calculated with or without overload are the same.

Loading parameters

In order to study the effects of overload ratio, stress ratio and ΔK base line on the fatigue crack growth rate, several numerical tests have been performed with different loading conditions. The loading conditions for each numerical test are reported in the table 3.

Test numb	K_{max}	K_{min}	K_{OL}	R	%OL	OLR
1	12	0	24	0	100%	2
2	12	0	21	0	75%	1.75
3	12	0	18	0	50%	1.5
4	12	0	15	0	25%	1.25
5	12	0	12	0	0%	1
10	12	3	24	0.25	100%	2.33
11	12	3	12	0.25	0%	1
12	12	3	21	0.25	75%	2
14	16	4	32	0.25	100%	2.33
15	16	4	28	0.25	75%	2
17	16	4	16	0.25	0%	1
18	12	6	24	0.5	100%	3
19	12	6	12	0.5	0%	1
22	24	12	48	0.5	100%	3
25	24	12	24	0.5	0%	1
26	9	0	18	0	100%	2
27	10	0	20	0	100%	2
28	9	0	9	0	0%	1
29	10	0	10	0	0%	1
36	9	0	13.5	0	50%	1.5
37	10	0	15	0	50%	1.5

K_{max}, K_{min} and ΔK in MPa $m^{1/2}$

Table 3 : loading conditions of the numerical tests

Six types of tests have been performed :
- tests with ΔK =12, R=0 and %OL variable,
- tests with %OL =100%, R=0 and ΔK variable,
- tests with K_{max} =12, %OL =100% and R variable,
- tests with K_{max} =12, OLR=2 and R variable,
- tests with ΔK=12, %OL =100% and R variable,
- tests with ΔK=12, OLR=2 and R variable,

Quantitative numerical results

For each test, Z_{OL} and Z_{OLc} are studied thanks to the analysis of the stress normal to crack plane in front of the crack. The effective stress intensity factor is also calculated for each crack length in order to determine the characteristic values " a_{min} " and "a_d". We observe that the value "a_{min} - a_{OL}" is equal to the length of the compressive zone (called from now Z_{Olc}num) and the value "a_d - a_{OL} " is equal to the length of the monotonic plastic zone due to overload (called from now Z_{OL}num). Z_{Olc}num can also be compared to the analytical values of the length of the compressive zone given by : Z_{OLc}an = $1/\pi((K_{OL}-K_{min})/2\sigma_e)^2$. In the same way, Z_{OL}num can be compared to the analytical value of the length of the monotonic plastic zone due to overload given by : Z_{OL}an = $1/\pi(K_{OL}/\sigma_e)^2$
From our numerical results, Z_{OLc}num and Z_{OL}num have been compared respectively to Z_{OLc}an and Z_{OL}an for all the tests. The results of this comparison is shown on the figures 10 and 11 which give respectively the value of Z_{Olc}num/ Z_{Olc}an and the value of Z_{OL}num/ Z_{OL}an versus the number of the test.

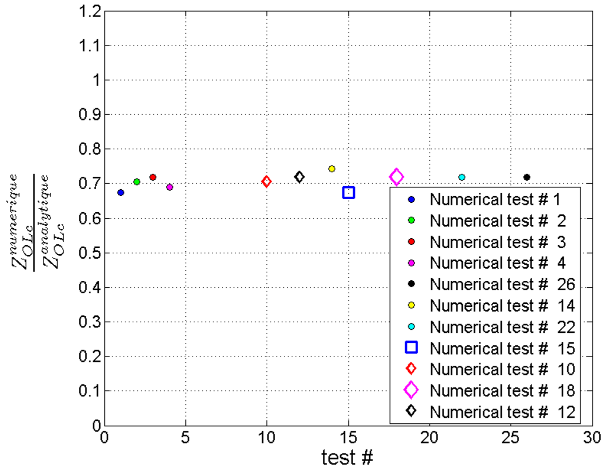

Figure 10 : Comparison of the analytically and numerically determined values of the length of the compressive zone due to overload (Z_{OLc}num/Z_{OLc}an)

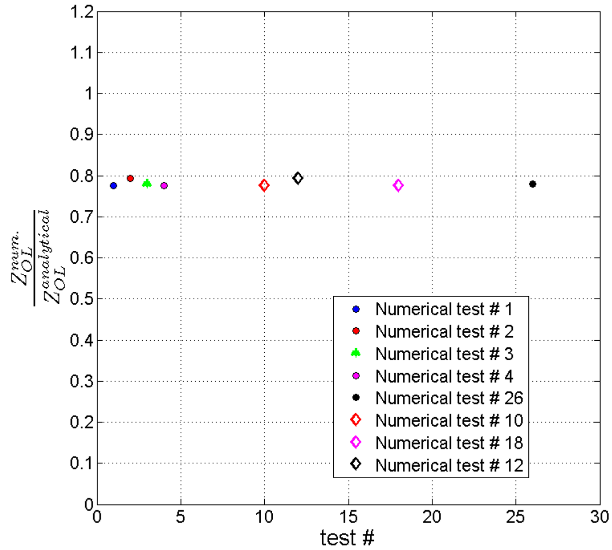

Figure 11 : comparison of the values of the length of the monotonic plastic zone due to overload analytically and numerically determined (Z_{OL}num/Z_{OL}an)

We can see that Z_{OLc}num = 0,7 Z_{OLc}an from the figure 10 and Z_{OL}num = 0,77 Z_{OL}an from the figure 11. The coefficients 0,7 and 0,77 depend on the cyclic behaviour of the material used for the simulations. For a perfectly plastic material, this coefficient is equal to 1, what is in accordance with literature results.

Effects of loading parameters

In order to determine quantitatively the effects of the different loading parameters on the fatigue crack growth rate, we estimated the delay retardation due to the overload application on the crack propagation for each numerical test. The number of delay cycles (Nd) is the difference between the number of cycles at which the steady state is achieved and the number of cycle that would occur for the same crack length at constant amplitude baseline loading. The calculation of the number of cycles corresponding to a crack growth is obtained by integrating the crack growth rate. This last quantity is obtained by using the Paris law (da/dN =

$2{,}2.10^{-8}(\Delta K)^{2{,}576}$) from the ΔK_{eff} which is calculated as shown on the figure 9. It is assumed that nominal ΔK is almost constant (the crack growth length is low). The figure 12 shows the crack length evolution versus the number of cycles with and without overload and the calculation of the number of delay cycles.

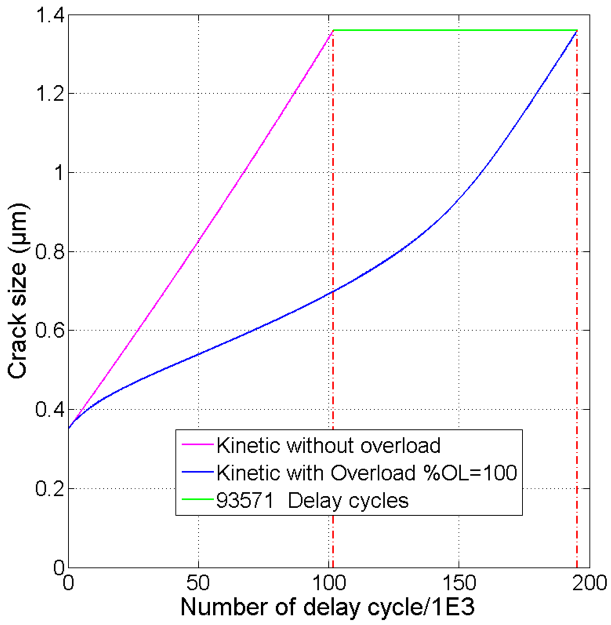

Figure 12 : calculation of the number of cycles of delay due to overload

The numbers of delay cycles for tests 1, 2, 3 and 4 are reported on the below.
The comparison between these different values show us the effect of %OL on delay cycles.

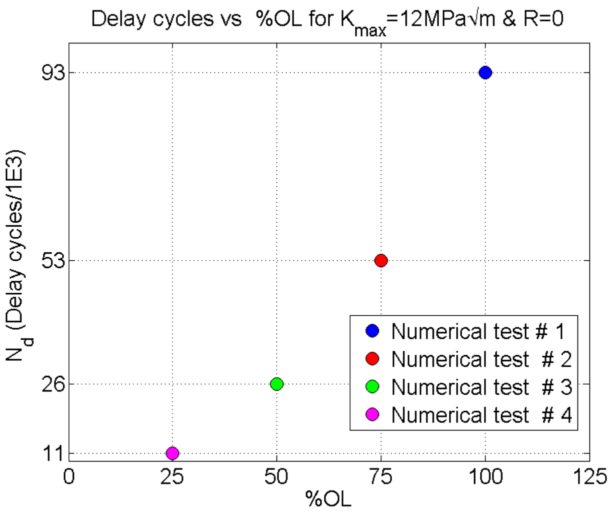

Figure 13 : number of delay cycles (Nd) due to overload versus overload ratio %OL

It is obvious regarding the figure 13 that the delay due to overload application increases when overload ratio %OL increases. These results are obtained for R = 0 and ΔK = 12 MPa $m^{1/2}$.

The numbers of delay cycles for tests 1, 26 and 27 are reported on the figure 14. The numbers of delay cycles for tests 3, 36 and 37 are reported on the figure 15.

The figures 14 and 15, obtained for R = 0 and respectively for %OL = 100% and %OL = 50% emphasize the role of the ΔK (i.e. K_{max} because R = 0) at which overload is applied.

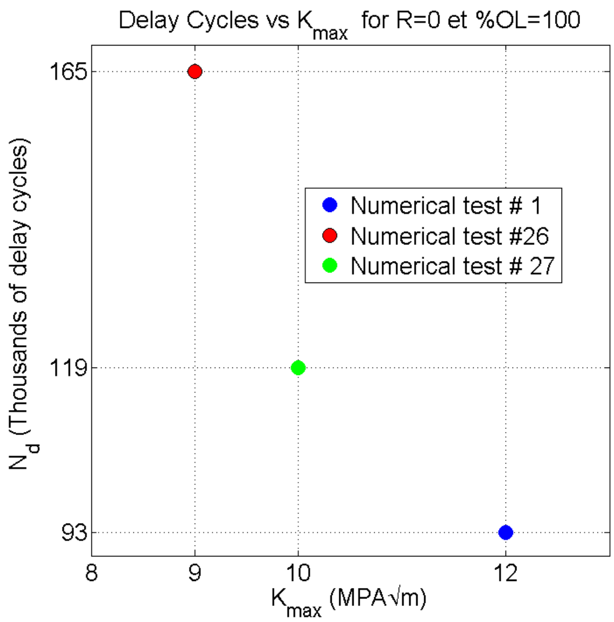

Figure 14 : number of delay cycles due to overload versus K_{max} for R=0, %OL=100

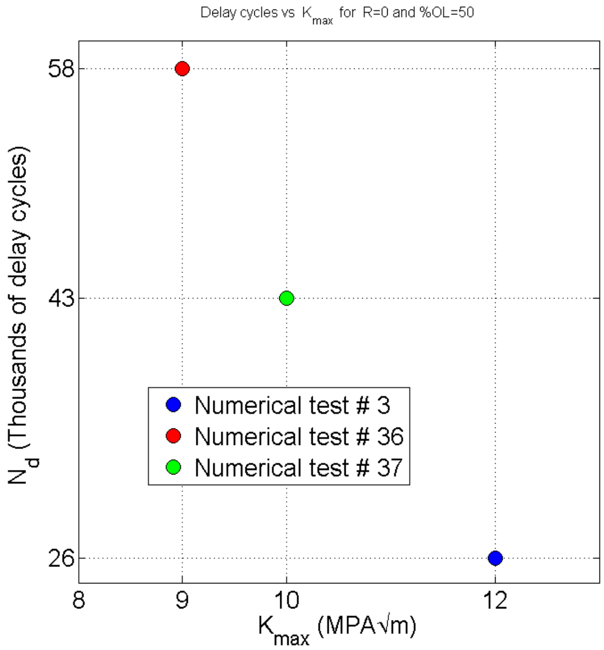

Figure 15 : number of delay cycles due to overload versus K_{max} for R=0, %OL=50

The delay due to overload decreases as ΔK increases.

The numbers of delay cycles for tests 1, 10 and 18 are reported on the figure 16. The numbers of cycles of delay for tests 1 and 12 are reported on the figure 17. These figures 16 and 17, obtained for K_{max} =12 MPa $m^{1/2}$ and respectively for %OL = 100% and for OLR = 2 emphasize the role of the stress ratio R.

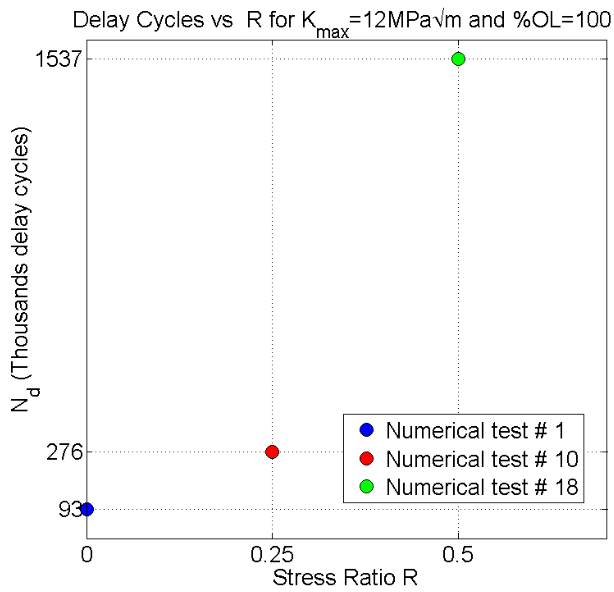

Figure 16 : number of delay cycles due to overload versus stress ratio R for %OL=100 and K_{max} =12MPa√m

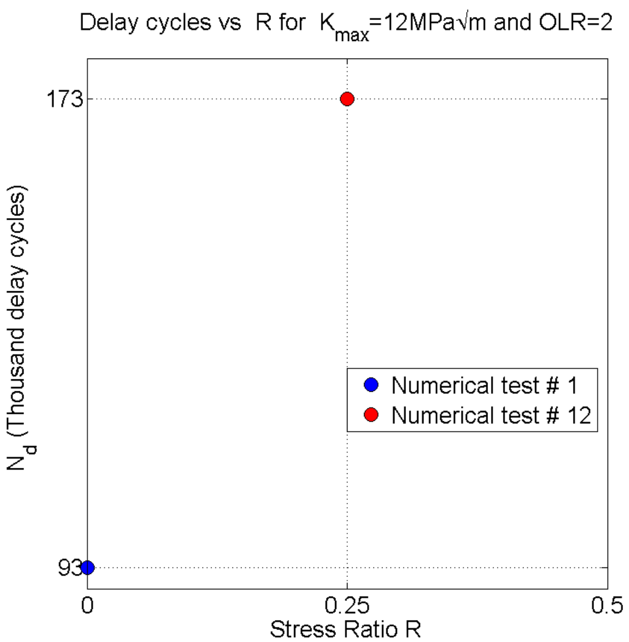

Figure 17 : number of delay cycles due to overload versus stress ratio R for OLR=2 and K_{max}=12MPa√m

The delay due to overload increases as R increases.

SIMPLIFIED MODELLING

Two models have been tested in order to predict the overload effects. The first one is the Kim and al. model [3]. The second one is the modified Wheeler model [4].

Kim and al. model

It was developed from experimental results obtained from fatigue with single overload tests on aluminium alloy. The model describes the fatigue crack growth after the overload application $(da/dN)_{OL}$ as a function of the nominal fatigue crack growth (da/dN) (without overload) and a delay coefficient D as following :

$(da/dN)_{OL} = (da/dN) \times D$

D is a function of the parameter Dmin which is equal to $(da/dN)_{OL}min$ / (da/dN) and which depends only of the overload ratio %OL. D also depends on a_{OL}, a_{min} and a_d which are respectively the crack lengths corresponding to the overload application, the minimum crack growth rate and the end of the overload effect.

In the Kim and al. model, D is defined as following :

$D = (Dmin - 1) \times (a - a_{OL}) / (a_{min} - a_{OL}) + 1$

when $a_{OL} < a < a_{min}$ and

$D = Dmin + (1\text{-}Dmin) \times (1\text{-}((a_d - a) / (a_d - a_{min}))^2)^{1/2}$

when $a_{min} < a < a_d$ and where a is the crack length.

In the case our 20CrNiMo8 steel, Dmin was determined from the four numerical tests 1, 2, 3 and 4. The linear regression of Dmin gives the following result :

Dmin = 0,85 – 0,0012 × %OL (%OL in percent)

From this model, number of cycles of delay was determined with the same method as described in part "Effects of loading parameters" for different loading conditions. The Kim and al. model underestimates the number of cycles of delay in comparison to the results obtained from the numerical tests. This can be explained by the differences of the evolution of the ΔK_{eff} versus the crack length between the two approaches as shown on the figure 18.

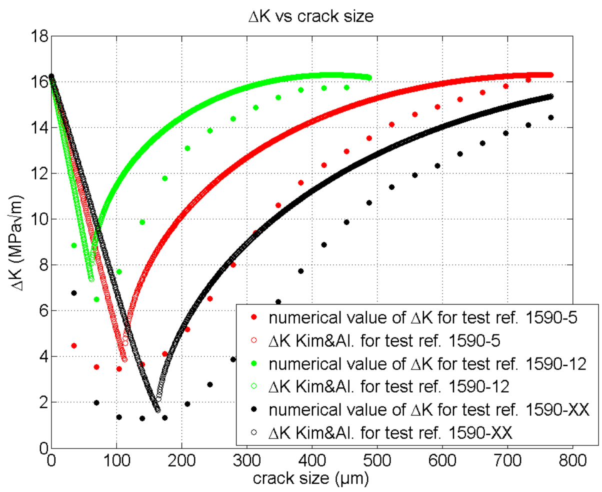

Figure 18 : evolution of ΔK_{eff} versus crack length from F.E. calculations and Kim and al. model.

The formulation of the Kim and al. model can be changed in order to better fit to the elastic plastic F.E. results and to give better estimation of the number of cycles of delay.

Modified Wheeler model

In this model [5], ΔK_{eff} is calculated from nominal ΔK, from Z and Z_{OL}, which are the monotonic plastic zones due to respectively the cyclic constant amplitude loading and the overload, from a and a_{OL}, which are the crack length and the one at which overload was applied and from a coefficient γ which depends on the material as following :

$\Delta K_{eff} = \Delta K \times (Z/(Z_{OL} + a - a_{OL}))^{\gamma}$

It is remarkable that for Wheeler model, fatigue crack growth rate is minimum just after the application of the overload. The coefficient γ was calculated from the numerical tests 1, 2, 3 and 4. The linear regression gives γ = 0,256.

For other loading conditions (tests 26, 27, 36 and 37), ΔK_{eff} min was calculated with Wheeler model and compared to F.E. calculations. The results from the model differ with numerical analysis more than 50% in some cases. We conclude that Wheeler model is not reliable for our overload effect issue.

DISCUSSION

There is several experimental evidence supporting the role of plasticity-induced crack closure in influencing retardation effects. Furthermore, compressive residual stresses are considered as playing a significant role on the retardation effect due to overload application [6]. Although some events of retardation are inconsistent with these mechanisms [7], we consider below that compressive residual stresses and plasticity-induced crack closure are the main explanation of the retardation effects due to a single tensile overload.

Comparison between experimental and F.E. results.

The most of the conclusions in regards of the effects of the loading parameters on the decrease of the fatigue crack propagation due to overload are in accordance between our experimental and numerical studies. Indeed, overload effect is affecting the behaviour of the material in the same way for both studies i.e. a decrease of the fatigue crack growth rate after the overload application and until the crack gets out of the monotonic plastic zone generated by the overload. Moreover, increasing overload ratio and decreasing ΔK at which overload is applied increases the delay of the crack propagation. In regard to the considered mechanisms, these results are partly suitable. Indeed, overload ratio increase produces a larger stretch in the wake of the fatigue crack tip which leads to an increase of the crack closure effect. It also enlarges compressive stresses zone ahead the crack tip which retards the post-overload crack growth. It is more difficult to have reliable conclusion on the effect of the ΔK value on the retardation phenomenon on the base of the mechanisms described above. Indeed, when ΔK decreases, the crack closure may be more efficient to retard or to stop the crack propagation, because of the decrease of ΔK_{eff} (decrease of the K_{max}). But in the same time, when ΔK value is decreased at constant %OL, K_{OL} is decreased, so that overload should have less influence on the crack growth.

Conclusions on the effect of the stress ratio are not so clear. In one hand, experimental results show a decrease of the effect of the overload when R increases. In the other hand, elastic plastic F.E. calculations show the decrease of the overload effect as stress ratio R decreases. Conditions of the numerical calculations have to be taken into account. Actually, the effect of the stress ratio is studied by comparing tests performed at constant K_{max}, so that ΔK decreases as R increases. So, the comparison between experimental and numerical results are not completely suitable. The numerical tests at constant ΔK and %OL and variable R (tests 1, 14 and 22) have to be analyse in the same way as the previous ones to conclude correctly. Regarding the mechanisms, the effect of the increase of the stress ratio is difficult to analyse, because it leads to an increase of F_{OL} for constant ΔK (in experimental tests) and %OL. But in the same time F_{max} and F_{min} are also increased so that both of them can be higher than the opening stress, which leads to an increase of the ΔK_{eff}.

Simplified modelling

Wheeler model is not appropriate to predict the effect of the overload on the fatigue crack growth rate for 20CrNiMo8 low alloyed rotor steel. Nevertheless, Kim and al. model seems to give good results in terms of the prediction of the Dmin. However, for our case, it is insufficient to predict the number of cycles of delay. A modified model can be proposed to better fit the evolution of the ΔK_{eff} versus the crack length so that number of cycles of delay is nearer from real value.

CONCLUSION

In conclusion, the results obtained firstly with experimental tests and secondly with numerical F.E. calculations show the retardation effect due a single overload event on a fatigue crack growth of a 20CrNiMo8 low alloyed steel. Effects of %OL and ΔK are similar in experimental and numerical studies i.e. increasing %OL and decreasing ΔK at which overload is applied increases the retardation effect of the crack propagation. Conclusions on the effect of the stress ratio are not so clear and further numerical conditions have to be tested in order to progress in the understanding of the effect of the stress ratio on the retardation of the crack growth due to a single overload event.

Plasticity-induced crack closure and compressive stresses zone are ones of the mechanisms that can explain the retardation effect of an overload on the fatigue crack propagation. These mechanisms can easily explain the observed influence of the parameter %OL on the retardation effect. It is more difficult to explain the influence of the parameters as R and ΔK at which overload is applied from them.

ACKNOWLEDGEMENT

The authors thank Denis Chollet from EDF R&D for performing the experimental fatigue tests.

REFERENCES

[1] : A03-404 AFNOR standard
"Produits métalliques. Pratique des essais de vitesse de propagation de fissure en fatigue", juin 1991.
[2] : www.code-aster.org
[3] : Shin C.S. and Hsu S.H.
"On the mechanisms and behaviour of overload retardation in AISI 304 Stainless Steel", International Journal of Fatigue, Vol. 15, No 3, pp 181-192, 1993.
[4] : Skorupa M.
"Load interaction effects during fatigue crack growth under variable amplitude loading – a literature review. Part II : qualitative interpretation", Fatigue and Fracture of Engineering Materials and Structures, Vol. 22, No 10, pp 905-926, 1999.
[5] Wheeler, O.E., "Spectrum Loading and Crack growth" J. of Basic Engin. Pp181-186, 1972.

[6] Bathias C. et Baïlon J.P., "La fatigue des matériaux et des structures", Hermès, 1997.
[7] Suresh S., "Fatigue of Materials", Cambridge University Press, 1998.