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FATIGUE INITIATION OF CRACK UNDER MODE III AND MIXED MODE I + III LOADS IN A 9CR STEEL

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ABSTRACT

To contribute to the improvement of knowledge of the behavior of 9Cr-1Mo steel, particularly on the topic of fatigue life prediction, cyclic tests of fracture mechanics have been practiced on two types of notched specimens at the CEA, submited to simple or combined loadings, in order to determine experimentaly the number of cycles to obtain the initiation of a crack. These results are confronted with the evaluations obtained by using a simplified rule of the French design code, RCC-MR, the σ_d method for the prediction of the initiation of a crack at the tip of a geometrical singularity.

Keywords: 9Cr steel– intiation – Fatigue – Mixed mode – High temperature

1. INTRODUCTION

Within the framework of Generation IV studies, 9 Cr-1Mo steel is considered to be a potential material for the construction of vessels and internal components of High Temperature Gas-cooled Reactors.

Reactors are assembled structures made up of a great number of welded junctions. The realization of these weldings can lead to geometrical singularities similar to notches. That can occur, for example, when a part of the unit is accessible only from one side of the assembly, and when the weldment is made only by this side.

During the life of nuclear power plant, such components can particularly be subjected to fatigue loading, at elevated temperature, thus leading to a risk of rupture. The French design code, RCC-MR, in its Appendix A16, describes rules to asses crack like defects. Crack initiation is the first stage considered. The σ_d rule deals with this subject and is used for its analysis.

The objective of this study is to examine the ability of the σ_d rule to determine the number of cycles to obtain the initiation of a crack under single and combined cyclic loadings, for 9 Cr-1Mo steel specimens.

For this purpose, cyclic tests of fracture mechanics have been practiced on notched specimens. Simple loadings in mode I or III (Figure 1) or in mixed mode (I + III) have been applied. The goal was to determine experimentaly the number of cycles to obtain the initiation of a crack, and then to compare these results to the prediction of the rule.

2. EXPERIMENTATION

Samples were taken into a 9Cr-1Mo steel plate, thickness 30 mm. Its chemical composition is indicated in table 1.

Two types of specimens were used : Standardized CT specimens, thickness 25 mm (Figure 2) and axisymmetric notched specimens. The Figure 3 schematically presents the geometry of this second type of specimen. The radius R of the specimen is 10 mm, the depth of the notch is 5 mm, and the radius of the machined tip of the notch is lower than 100 µm.

All the tests were carried out at 550°C.

2.1 Tests on axisymmetric notched specimens

The test bench used for this campaign permits to simultaneously apply variable loadings of tension, with imposed force, and of torsion, with imposed momentum, along or around the axis of the specimen by means of two electric stepper motors. Loadings only in torsion (mode III) or in tension and torsion proportionaly combined (mode I+ III) were imposed.

Two load sensors are used respectively for the measurement of the axial effort and the momentum imposed. The machine also has axial and angular incremental position sensors.

An Electric potential drop (EPD), in the vicinity of the notch, is used to detect the crack initiation. It is obtained by the injection of an electrical current in the specimen.

After the test, the measurement of the crack area, by summation of several sectors having same angle, makes it possible to calculate an equivalent radius and to determine an averaged crack growth Δa (Figure 4). From this value and with the measurement of the variation of EPD at the end of the test, a calibration curve ΔEPD (Δa) is built (Figure 5).

The initiation of a crack is defined by its growth. The retained value of the criterion is 100 µm. The corresponding number of cycles is determined by using the representation ΔEPD (Nr), where Nr is the current number of the cycles.

2.2 Tests on CT specimens

The realization of the tests is done according to the methodology described in the previous paragraph.

A servo-hydrolic test bench equipped with load and displacement sensors is used. A measurement of EDP is placed near the notch tip to detect the crack initiation (Figure 6). Each crack growth at the end of the test, (Δa), is calculated by using eleven measurements practiced at equal distance one from the other, along the edge of the crack. Then a calibration curve ΔEDP (Δa) is built (Figure 7). It makes it possible to determine, for each test, the experimental number of cycles to initiation for a crack growth of 100 µm.

3. RESULTS OF THE TESTS

3.1 Tests on axisymmetric notched specimens

For the axisymetric notched specimen, the A16 Appendix of the RCC-MR [1] proposes the following formulations of the stress intensity factors according to the applied loadings.

For the loading of tension :

$K_I = F_N.\sigma.\sqrt{\pi.a}$ with $\sigma = \frac{N}{\pi.R^2}$ where N is the applied load

and $F_N = \frac{1}{2}.\left(1+\frac{1}{2}.x+\frac{3}{8}.x^2-0{,}363.x^3+0{,}731.x^4\right).\frac{1}{x^{1.5}}$, $x = \frac{R-a}{R}$

For the loading of torsion :

$K_{III} = F_T.\tau.\sqrt{\pi.a}$ with $\tau = \frac{2.T}{\pi.R^3}$ where T indicates the momentum

and $F_T = \frac{3}{8}.\left(1+\frac{1}{2}.x+\frac{3}{8}.x^2+\frac{5}{16}.x^3+\frac{35}{128}.x^4+0{,}208.x^5\right).\frac{1}{x^{2.5}}$

The tables 2 and 3 respectively present the results for the tests in mode III and mixed mode I+III.

3.2 Tests on CT specimens

The stress intensity factor for CT specimen (ASTM E 399-81) is expressed by :

$K_I = \frac{F}{B\sqrt{W}} f(\frac{a}{W})$ where F is the load applied

$$f(x) := (2+x)\cdot\frac{0.886+4.64x-13.32x^2+14.72x^3-5.6x^4}{(1-x)^{1.5}}$$ with x=a/W

Table 4 presents the results of the tests practiced on CT specimens.

4 INTERPRETATION

4.1 σ_d Method

This method is based on the use of the mechanical characteristics determined with smooth specimens and on the distance d, which is specific to the material. The principle is to consider a small smooth specimen located at a distance d of the notch tip (figure 8) and to carcaterize its rupture.

a) The first stage consists in calculating the elastic stresses at the distance d of the notch tip, by using the Creager's formulas (1966) which types are:

$$\sigma_{jk} = \frac{K_i}{\sqrt{2\pi d}} f_{ijk}(\theta, \rho, d) ,$$

where ρ is the radius of the notch tip and θ the angle mesaured from the plane of symmetry of the notch .

In the plane of the crack (the θ angle is considered as null), and by neglecting the influence of the radius of the notch tip, the Creager's formulas lead to the following expressions of the stresses tensor at the distance d:

In mode I, in plane strains: $\frac{K_I}{\sqrt{2\pi d}}\begin{pmatrix}1 & 0 & 0\\ 0 & 1 & 0\\ 0 & 0 & 2\nu\end{pmatrix}$, where ν is the Poisson's ratio.

In mode III: $\frac{K_{III}}{\sqrt{2\pi d}}\begin{pmatrix}0 & 0 & 0\\ 0 & 0 & 1\\ 0 & 1 & 0\end{pmatrix}$,

b) The equivalent elastic stress range $\overline{\Delta\sigma_{de}}$ is calculated during the second stage. Its expression is :

$\max_{t,t'}\left[\overline{\sigma_{de}(t) - \sigma_{de}(t')}\right]$, where $\overline{\sigma_{de}(t,t')}$ represents the greatest principal stress found in the difference of the tensors of the elastic stresses $\sigma_{de}(t) - \sigma_{de}(t')$ taken at two different moments.

In the following stages, the equivalent elastoplastic stress range is determined (figure 9).

c) The method initially requires the calculation of the equivalent elastic strain range $\Delta\varepsilon_1$ associated to $\overline{\Delta\sigma_{de}}$:

$$\Delta\varepsilon_1 = \frac{2(1+\nu)\overline{\Delta\sigma_{de}}}{3E}$$

d) Then, one determines the increase in plastic strain range $\Delta\varepsilon_2$ due to the primary stresses range. In general, one can neglect them because these stresses are lower than the yield stress. In this paragraph this increase will be systematically neglected.

e) The elastoplastic strain range is calculated according to the Neuber's method.

The hardening cyclic curve of the material is used and is expressed in the form of a Ramberg-Osgood's law :

$$\Delta\varepsilon = \frac{2(1+\nu).\Delta\sigma}{3E} + \left(\frac{\Delta\sigma}{K}\right)^{\frac{1}{m}}$$

One determines the point of co-ordinates ($\Delta\varepsilon$,$\Delta\sigma$), intersection of the hardening cyclic curve and the hyperbola $\Delta\sigma.\Delta\varepsilon = \Delta\sigma_e.\Delta\varepsilon$ = constant. Then one defines plastic increase $\Delta\varepsilon_3$, such as $\Delta\varepsilon = \Delta\varepsilon_1 + \Delta\varepsilon_2 + \Delta\varepsilon_3$.

f) The increase of plastic strain $\Delta\varepsilon_4$ due to the triaxiality at the crack tip must be taken into account through the contribution

$\Delta\varepsilon_4 = \frac{2(1+\nu)\overline{\Delta\sigma_{de}}}{3E}(K_\nu - 1)$, where E is the Young modulus. The value of the coefficient K_ν is detailed in the RCC-MR.

g) The number of cycles to initiation is deducted by using the best-fit fatigue curve of the material. The design curve (A3.18S.64), is deduced from the best-fit fatigue curve ($\Delta\varepsilon$, Nr) by taking the minimal envelope of the two curves ($\Delta\varepsilon$/2, Nr) and ($\Delta\varepsilon$, Nr/20). The opposite operation can be carried out to find the best-fit curve to initiation from the codified data.

Tables 2 and 3 respectively present the results for the tests in mode III and mixed mode I+III, by using the characteristic distance d of the 9Cr-1Mo steel.which is equal to 36µm

The calculations overpredict the experimental number of cycles to the initiation, on average, roughly by a factor 3. Figure 10 permits to visualize these first results. One notes, on this figure, that the overprediction is more important for the tests in mode III.

Table 4 respectively presents the results of the tests practiced on CT specimen.

The prediction of these tests underestimate, on average, the number of cycles to the initiation roughly by a factor 0,5.

4.2 Modifications of the method - Relation with J

A) In this paragraph the plastic increase $\Delta\varepsilon_2$ due to the primary stresses range is taken into account, if this one is not null. It is calculated by using an equivalent reference stress $\sigma_{ref.}$ in the zone of the notch. This stress characterizes the plasticity in this zone. It is given by integrating the elastoplastic behavior law in the section of the notch by considering the normal stress constant in this section and the strain resulting from the imposed momentum proportional to the radius.

B) The possible extended plasticity around the vicinity of the notch can also be taken into account by analogy with the J integral.

The elastic part of J is given by $J_{el} = (K_{eq})^2/E$.

The A16 appendix of the RCC-MR indicates how to determine the elastoplastic value of J by using the refernce stress concept :

$$\frac{J}{J_{el}} = \frac{E.\varepsilon_{ref}}{\sigma_{ref}}$$

An effectif stress intensity factor ΔK_{eff} can then be determined :

$$\Delta K_{eff} = (E.J)^{1/2} = \Delta K.\left(\frac{E.\varepsilon_{ref}}{\sigma_{ref}}\right)^{1/2}$$

The same reference stress as for the calculation of $\Delta\varepsilon_2$ is used.

C) Moreover, the equivalent stress intensity factor K_{eq} is deduced from the following expression :

$$K_{eq}^2 = K_I^{\,2} + K_{II}^{\,2} + \frac{1}{1-\nu} K_{III}^{\,2},$$

in which the contribution of K_{III} is affected by the coefficient $\frac{1}{\sqrt{1-\nu}}$.

D) In practice, using the proposed formula, the value of the variation ΔK_{III} must be multiplied by $\frac{1}{\sqrt{1-\nu}}$, for the calculation of the equivalent $\overline{\Delta\sigma_{de}}$. In addition, the value of $\overline{\Delta\sigma_{de}}$ must be multiplied by $.\sqrt{\frac{E.\varepsilon_{ref}}{\sigma_{ref}}}.$, before evaluating the elastoplastic strain range according to the methodology developed previously.

For the determination of $\Delta\varepsilon_3$, in the stage "e", Neuber's method must be replaced by solving the equation

$$\frac{\Delta\sigma.\Delta\varepsilon}{\Delta\sigma_e.\Delta\varepsilon_e} = \frac{E.\varepsilon_{ref}}{\sigma_{ref}}$$

Figure 11 permits us to visualize the predictions obtained by taking into account these modifications. The predictions overestimate, on average, the number of cycles to initiation roughly by a factor 1.6. These modifications do not have a significant effect on the predictions of the tests on CT.

The ratios between the predicted number of cycles to initiation and the experimental one are similar to the dispersions generally observed for the fatigue tests practiced on smooth specimens.

5 CONCLUSIONS

Cyclic tests were carried out on various notched specimens sampled out of a 9Cr-1Mo steel plate to determine the number of cycles to obtain the initiation of a crack. Specimens were submitted to mode I, III and I+III loadings.

These tests were analyzed with the rule σ_d of the RCC-MR. The ratios observed between the predictions and the experimental values are on average about 0.5 to 3, following the type of specimen. Taking into account the simplicity of the method, they remain acceptable and of the same order as the dispersions observed for the fatigue tests.

By analogy with the integral J, and taking into account plasticity through a reference stress, simple modifications of the σ_d method are proposed. It consists in the introduction of an effective value of the stress intensity factor. These modifications improve the predictions.

REFERENCES

[1] RCC-MR, "Design and Construction Rules for Mechanical Components of FBR Nuclear Islands ", ed 2002, publ. AFCEN

[2] Creager, (1966), "The Elastic Stress Field Near Tip Off Blunt Ace", Thesis Lehigh University

Table 1 : 9CR-1Mo plate chemical composition (Wt %)

C	**Mn**	**P**	**S**	**Si**	**Cu**	**Ni**	**Cr**	**Mo**	**Al**	
0.086	0.363	0.017	0.0010	0.324	0.068	0.149	8.910	0.917	0.018	
Nb	**V**	**N_2**	**Sn**	**Zr**	**Ti**	**As**	**W**	**B**	**Sb**	**O_2**
0.08	0.198	0.0411	0.005	0.001	0.002	0.0122	0.010	0.0010	0.0006	0.0018

Table 2 : Tests on axisymmetric notched specimen under torsion loading - Results and predictions

Test Number	ΔM (Nm)	ΔK_{III} ($MPa\sqrt{m}$)	Number of cycles to crack initiation	Calculated number of cycles
LISN-03-133	42.5	10.2	3000	6916
LISN-03-135	46.2	11	1000	4245
LISN-03-134	48.5	11.6	790	3391
LISN-03-218	50	12	2800	2975
LISN-03-132	54.5	13	560	2056
LISN-03-216	55.6	13.3	540	1924

Table 3 : Tests on axisymmetric notched specimen under mixed mode loading - Results and predictions

Test Number	ΔF (kN)	ΔK_I (Mpa $m^{0.5}$)	ΔM (Nm)	ΔK_{III} ($MPa\sqrt{m}$)	Number of cycles to crack initiation	Calculated number of cycles
LISN-04-092	900	0.68	52.9	12.66	440	1966
LISN-04-093	17200	13.04	3	0.72	700	1995
LISN-04-094	6600	5	39	9.33	600	1890
LISN-04-095	10200	7.73	28.5	6.82	950	1977
LISN-04-096	13100	9.93	20.7	4.95	2200	1933
LISN-04-097	9440	7.16	42.3	10.12	850	1972
LISN-04-098	6600	5	20.6	4.93	400	4400
LISN-04-099	3050	2.31	29.7	7.1	1600	8144
LISN-04-100	16400	12.44	8.7	2.08	13000	16720
LISN-04-101	12600	9.55	5	1.2	1600	17640

Table 4 : Tests on CT Results and predictions

Test Number	ΔF (kN)	ΔK_I ($MPa\sqrt{m}$)	Number of cycles to crack initiation	Calculated number of cycles
LISN-05-001	11.0	14,3	3400	1560
LISN-05-002	12.4	16,1	2000	1111
LISN-05-003	14,0	18,2	1150	790
LISN-05-004	11.7	15,2	2250	1310
LISN-05-005	10,0	13,0	4500	2070

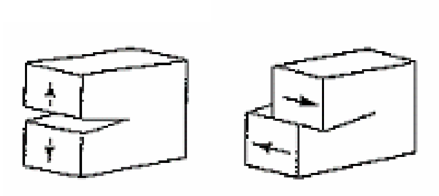

Figure 1 : Crack loadings.

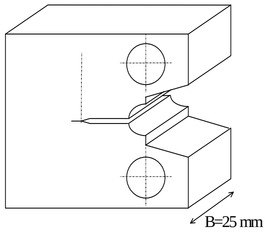

Figure 2 : CT 25 specimen (Compact Tension)

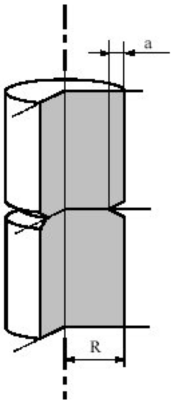

Figure 3 : Axisymmetric notched specimen

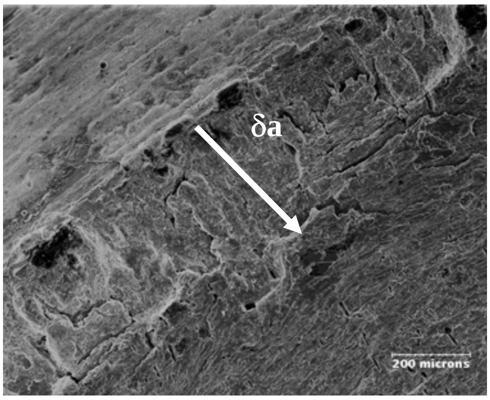

Figure 4: Fractography of a crack growth on axisymmetric notched specimen (torsion loading)

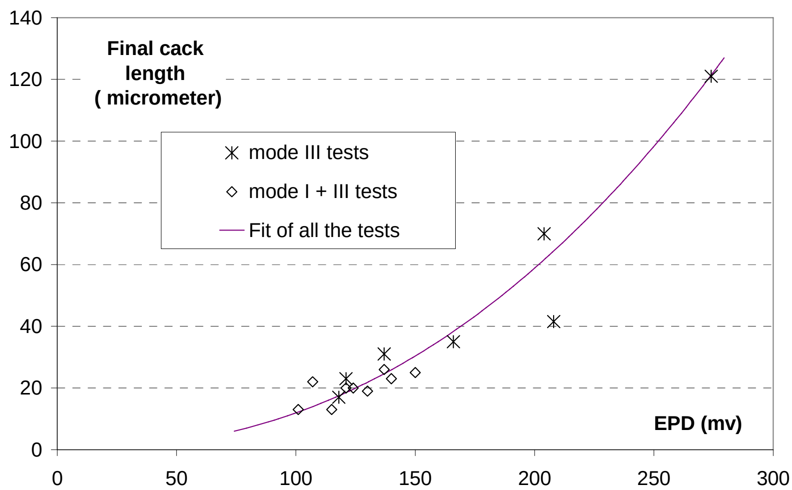

Figure 5 : Axisymmetric notched specimens - Crack growth versus the variation of electric potential drop

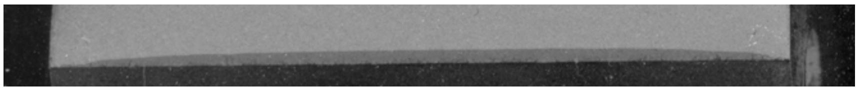

Figure 6 : CT specimen- Crack growth at the notch tip.

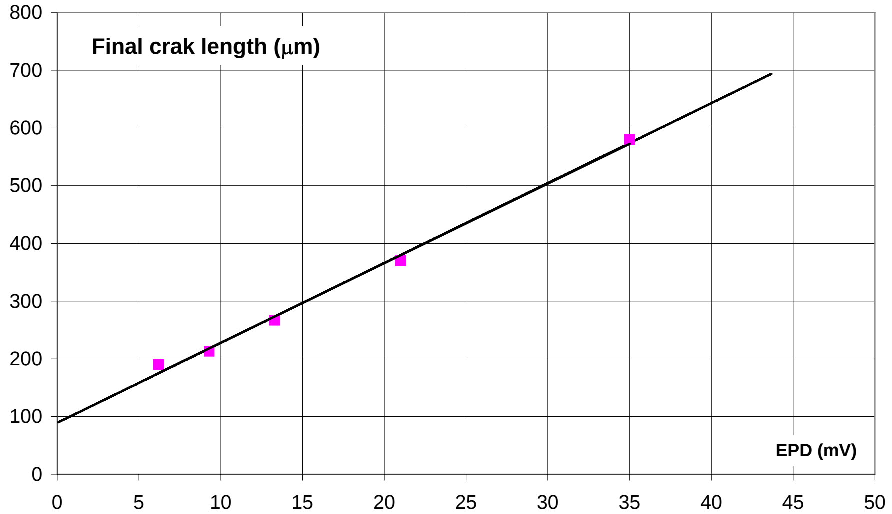

Figure 7 : CT specimens- Crack growth versus the variation of electric potential drop

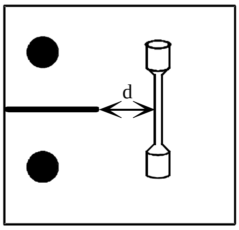

Figure 8 : Principle of the σd method

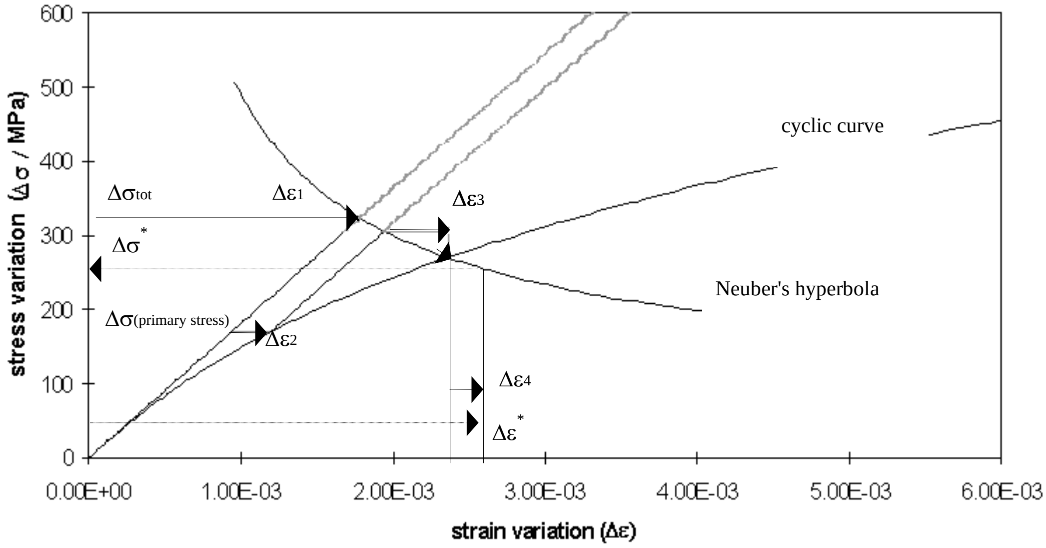

Figure 9 : Determination of the elastoplastic strain variation

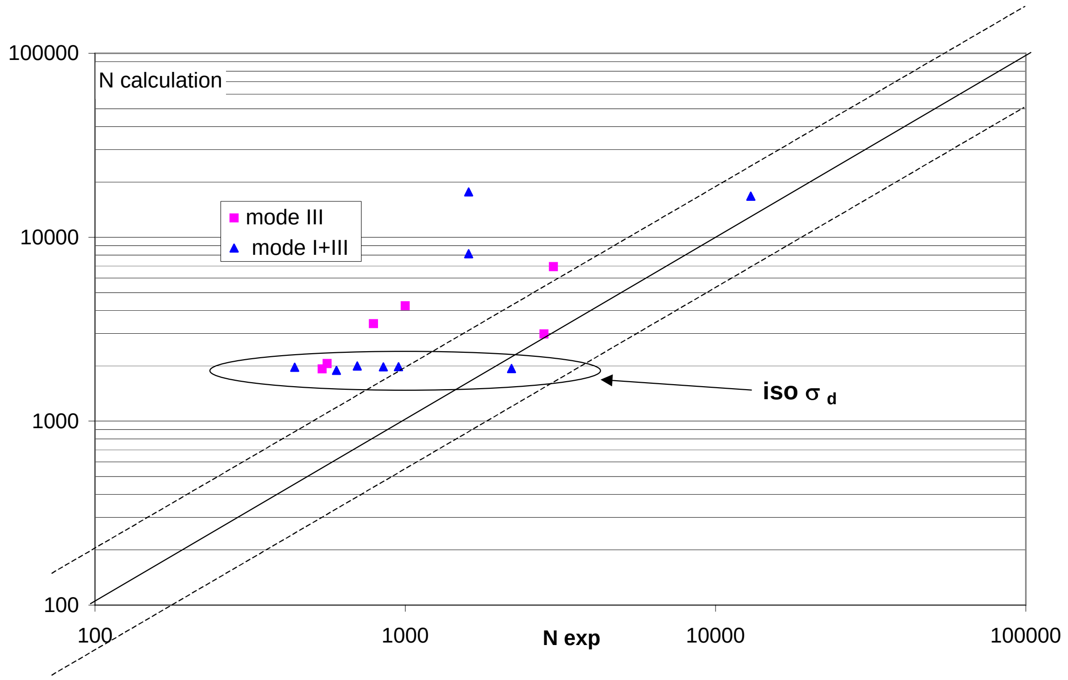

Figure 10 : Prediction of the number of cycles to initiation of the tests on axisymmetric notched specimen with the σ_d rule

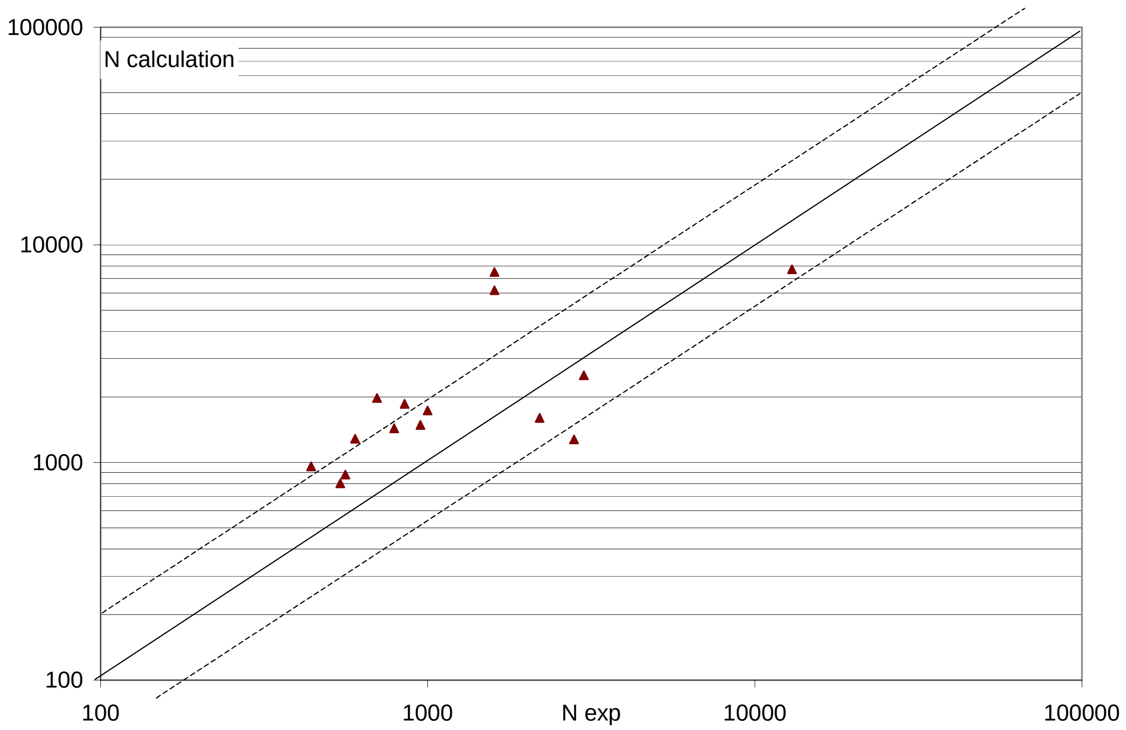

Figure 11 : Prediction of the number of cycles to initiation of the tests on axisymmetric notched specimen with the modified rule