MODELIZATION OF THE STRAIN MEMORY EFFECT ON THE CYCLIC HARDENING OF 316 STAINLESS STEEL

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ABSTRACT

Life predictions in structures undergoing cyclic loads use the calculated stabilized stress-strain loops, for which plastic flow is introduced through cyclic constitutive equations. The paper deals with the description of strain history effects observed in some materials, especially in the 316 Stainless steel. The main results of this study can be summarized as follows :

- a special cyclic test with increasing and decreasing strain levels indicates a complex cyclic hardening behaviour and some strain history effects at room temperature,
- a new internal variable keeping memory of the maximum plastic strain range is introduced, which gives a fairly good description of the observed effects,
- two modelizations are proposed for the 316L, on the basis of several non-linear kinematic and isotropic internal variables associated to the strain memory variable,
- a practical identification procedure is discussed which leads to the determination of the whole set of coefficients from one special cyclic test only,
- the proposed formulation, with the obtained coefficients, describes very well a lot of test results, monotonic tension curve, cyclic hardening with stabilization, cyclic stress-strain curve, persistent cyclic hardening after stabilization under a smaller strain range, memory of the cyclic hardening under a prior higher strain range inducing larger stress ranges, simulation of the incremental step tests and their dependancy on the maximum strain range,
- systematic application of the Neuber's rule for plane stress notched specimens demonstrates the importance of the strain memory effect in order to correctly predict the stabilized local stress-strain curves. Finite element calculations are possible for plane strain or axisymmetric notched specimens and will be used to generalize the Neuber's rule.

1. INTRODUCTION

With the present degree of refinement in computer techniques, stress and strain calculation in structures is now a useful step in order to improve the design, especially in the gas turbine components or in the nuclear plant industries. When low Cycle Fatigue or cyclic ratchetting have to be predicted, an important need is the correct definition of the cyclic plastic flow rules : in fact, more sophisticated are the computer techniques, better has to be the macroscopic description of the material behaviour, the results of the analysis beeing always dependent on the inputs.

In several stainless steels a complex cyclic inelastic behaviour has been observed, showing some unusual strain history effects. This study deals with the modelization of such complex phenomena on the example of A316 L at room temperature.

In the past twenty years large improvements have been done in the description of material straining with constitutive equations, including isotropic as well as kinematic hardening parameters [1] [2] . The introduction of such internal variables can be justified through general thermodynamical frameworks [3] [4] but, when identification of macroscopic processes is needed, we choose the following strategy :

- the simplest constitutive equations are used as long as they give a sufficiently good description,
- when a poor modelization is observed (even with an optimized choice of coefficients) we consider that a new macroscopic process is identified and look after new internal variables or new flow equations with more degrees of freedom.

2. CLASSICAL FORMULATION

The most common internal variables, whose introduction is thermodynamically consistant, are the isotropic and the kinematic ones :

- the isotropic internal variable can be the cumulated plastic strain p (or the cumulated plastic work) and is associated on a microscopic scale with the density of dislocations,
- the kinematic one is a tensorial variable associated with the strain incompatibilities from one grain to another.

In the classical time independent plasticity, using the associated flow rule theory, one postulates the existence of a yield surface in the stress space [1][3] : plastic flow takes place only when the stress state stays on the surface. Usually the size **R** of the yield surface is associated with the isotropic variable and its center is defined by an internal stress $\underset{\sim}{X}$ (or friction stress) namely the kinematic stress. Then the surface can be written :

$$f = J(\underset{\sim}{\sigma}-\underset{\sim}{X}) - R(p) \leqslant 0 \qquad (1)$$

$J(\underset{\sim}{\sigma}-\underset{\sim}{X})$ denotes a distance in stress space : for example the Von Mises criterium corresponds to :

$$J(\underset{\sim}{\sigma}-\underset{\sim}{X}) = \sqrt{\tfrac{3}{2}(\underset{\sim}{\sigma}'-\underset{\sim}{X}'):(\underset{\sim}{\sigma}'-\underset{\sim}{X}')} = \sqrt{\tfrac{3}{2}(\sigma'_{ij}-X'_{ij})(\sigma'_{ij}-X'_{ij})} \qquad (2)$$

where $\underset{\sim}{\sigma}'$ and $\underset{\sim}{X}'$ are the stress and kinematic stress deviators.

The most common kinematic rule is the linear one due to Prager [5] : unfortunatly this rule gives rise to a linear hardening [6] especially when the stabilized cycles are considered [7] . Generalisations like the Mroz's model [2] imply piecewise stress strain curves and some specific properties (such as the Masing rule) which are not always exhibited by the material.

A practical way to describe a non-linear kinematic hardening, giving rise to a correct modelization of cyclic loops, consists in introducing an evanescent memory of the plastic strain path as initially proposed by Armstrong and Frederick [8] and recently developed by Marquis [9] for an aluminium alloy and an austenitic stainless steel. This non-linear kinematic effect appears in the internal stress equation :

$$\dot{\underset{\sim}{X}} = C(\tfrac{2}{3}\, a\, \dot{\underset{\sim}{\varepsilon}}_p - \underset{\sim}{X}\, \dot{p}) \qquad (3)$$

where the first term corresponds to the Prager's linear rule and the second one to the evanescent strain memory, the cumulated plastic length beeing defined for example by : $\dot{p} = \sqrt{\tfrac{2}{3}\, \dot{\underset{\sim}{\varepsilon}}_p : \dot{\underset{\sim}{\varepsilon}}_p}$

A very good continuous description of cyclic loading of materials obeying to a combination of isotropic and kinematic rules can be obtained under the following generalization :

$$X = \sum_k X^k \qquad \dot{X}^k = C_k \left(\frac{2}{3} a_k \dot{\varepsilon}_p - X^k \dot{p} \right) \tag{4}$$

$$R = \sum_k R^k \qquad \dot{R}^k = b_k (B_k - R^k) \dot{p} \tag{5}$$

subjected to the initial conditions : $X^k(0) = 0 \qquad R^k(0) = R^k_0 \qquad p(0) = 0$ (6)

In that case the plastic strain rate follows by the classical normality hypothesis :

$$\dot{\varepsilon}_p = \dot{p} \frac{\partial f}{\partial \sigma} = \frac{3}{2} \dot{p} \frac{\sigma' - X'}{J(\sigma - X)} = \sqrt{\frac{3}{2}} \dot{p}\, n \tag{7}$$

where the plastic multiplier $\dot{p}$ is obtained by the conditions relating to occurence of plastic flow only if $f = \dot{f} = 0$:

$$\dot{p} = H(f) \frac{\left\langle \sqrt{\frac{3}{2}}\, \dot{\sigma} : n \right\rangle}{\sum_k C_k \left(a_k - \sqrt{\frac{3}{2}}\, X^k : n \right) + \sum_k b_k (B_k - R^k)} \tag{8}$$

The function H is defined by $H(f) = 1$ if $f = 0$, $H(f) = 0$ if $f < 0$ and we states : $\langle u \rangle = u\, H(u)$.

Under tension-compression loading the denominator of eq. (8) represents the actual plastic tangent modulus : thus, identification of constants a_k, C_k, b_k, B_k can be done from a number of hysteresis loops. One important advantage of this formulation lies in the explicit integrability in the one-dimensional case :

$$X^k = \nu a_k + (X^k_0 - \nu a_k) \exp(-\nu C_k (\varepsilon_p - \varepsilon_{p_0})) \qquad R^k = B_k + (R^k_0 - B_k) \exp(-\nu b_k (\varepsilon_p - \varepsilon_{p_0})) \tag{9}$$

for each half cycle where the initial conditions are $\varepsilon_p = \varepsilon_{p_0}$, $X^k = X^k_0$, $R^k = R^k_0$ and with $\nu = Sign(\dot{\varepsilon}_p)$.
Under this particular case the yield function can be written from (1) :

$$f = |\sigma - X| - R \tag{10}$$

Let us consider now the conditions for cyclic stabilization : this is possible only when a sufficient plastic strain cumulation ($p \to \infty$) leads to the saturated values for the isotropic variables ; and when the kinematic ones are alternating, that is (Note) :

$$R^k_0 = B_k \qquad X^k_0 = - a_k\, Th\left(\frac{C_k}{2} \Delta\varepsilon_p \right) \tag{11}$$

where $\Delta\varepsilon_p$ denotes the stabilized plastic strain range. We recognizes here that stabilized cyclic stress-strain loops are independent of the prior loading path : this is an usual property for most of the classical plastic flow theories.

Note that a similar formulation, with one non-linear kinematic stress gives a very good modelization of the high temperature cyclic viscoplastic behaviour [10] .

3. CYCLIC STRAINING ON 316L AT ROOM TEMPERATURE

At low temperature, when viscoplastic phenomena are neglected, the material characterization is generally done in tension-compression under two states : the initial one for which the monotonic tension curve gives an indication on the hardening and the stabilized conditions after cyclic hardening (or softening). In this last case the usual tests are periodic and allow to the cyclic hardening curve, with one result by specimen (see figure 3).

In order to limit the necessary number of specimens, several special cyclic loadings can be defined [12] such as the increasing strain level test or the incremental testing method : unfortunately this last one leads to different cyclic hardening curves (depending on maximum strain range), especially for the considered steel [13] . In this study the first type has been choosen and allows to a rapid identification of the plastic behaviour (see figure 1) : one test only gives indications on the monotonic hardening (until 1% for example), on the cyclic hardening (number of cycles to reach stabilization and stabilized stress-strain loops) for several increasing strain levels. Moreover this unique test shows also two effects which cannot be described by the classical isotropic and kinematic variables :

Note : cyclic stabilization without ratchetting leads always to zero mean stress conditions, which is in good accordance with the generally observed results under cyclic straining [11] .

1 - after cyclic hardening and loop stabilization under small amplitudes, the stabilization for a larger cyclic strain range needs always ten cycles or more (fig. 1a) : although the behaviour was already stabilized, more hardening can be observed under the larger strain ranges.

2 - after a large cyclic straining a smaller strain range shows an history effect : the stabilized loop corresponds to a much higher stress range than in usual cycling without prior straining (see fig. 1b). Moreover this stress range seems independent of the mean strain as long as the strain path is contained in the prior largest one.

Several other tests (constant strain range $\Delta\mathcal{E} = 0{,}6\%$, but varying mean strain) indicate that the hardening essentially depends on the largest plastic strain range. This is also confirmed by the incremental step tests which show hardening curves depending on the maximum strain range (figure 4).

4. A NEW INTERNAL VARIABLE DESCRIBING THE STRAIN HISTORY EFFECT

In the classical formulation the only variable allowing to cyclic hardening description is the cumulated plastic strain p (isotropic variable) because of its irreversibility within each cycle. Consequently the first cyclic stabilization implies saturation of the response to this cyclic strain accumulation : after that stage no more hardening can be described, the only evolution phenomena beeing induced by the reversed kinematic hardening variable. Moreover this last type of internal variable always gives stabilized stress-strain loops independent on the initial conditions.

These two remarks, associated with observations reported above, allow us to conclude on the need of a new internal variable, keeping memory of the previous largest plastic strain range. This can be done by the concept of a new index function F defined by an hypersphere in the plastic strain space. For example we can choose :

$$F = I(\varepsilon_p - \alpha) - q = \sqrt{\tfrac{2}{3}(\varepsilon_p - \alpha):(\varepsilon_p - \alpha)} \tag{12}$$

and suppose that evolution of the internal variables α and q is only possible if F=0. The width q of the surface F gives the memory of the largest plastic strain range by the following equations :

$$\dot{\alpha} = \tfrac{1}{2} H(F)\,(\dot{\varepsilon}_p : n^*)\,n^* \qquad \dot{q} = \tfrac{1}{2}\,\eta\, H(F)\,\dot{p} \tag{13}$$

where n^* is the unit normal to the hypersphere at point ε_p: $n^* = \sqrt{\tfrac{2}{3}}\,(\varepsilon_p - \alpha)/I(\varepsilon_p - \alpha)$

The restriction $F=\dot{F}=0$ for evolution of this hypersphere leads to the determination of coefficient η :

$$\eta = n : n^* \tag{14}$$

which corresponds to the scalar product of unit normals to the yield surface and to the strain memory surface (Note). Under tensile compressive loading we have $\eta=1$, and one can see that q represents the half maximum plastic strain range.

Now, introduction of this memory in the cyclic constitutive eq. (4) to (8) is possible, by a dependency between the coefficient B_k of eq. (5) and q. For the sake of simplicity, limiting to two isotropic variables, we can suppose the following equations :

$$X = \sum_k X^k \qquad \dot{X}^k = C_k\left(\tfrac{2}{3} a_k\,\dot{\varepsilon}_p - X^k\,\dot{p}\right) \tag{15}$$

$$R = R + R^* \qquad \dot{R} = b\,(Q - R)\,\dot{p} \qquad \dot{R}^* = -b^*\,R^*\,\dot{p} \tag{16}$$

$$\dot{Q} = 2\mu\,(A - Q)\,\dot{q} = \mu\,\eta\,H(F)\,(A - Q)\,\dot{p} \tag{17}$$

Finally the plastic strain memory appears only through the presence of the index function F, which evolution is given by (13). The variable represents the actual asymptotic value for the isotropic hardening R (under periodic cycling) and keeps memory of the largest strain range because on its irreversibility. The second isotropic variable R^* can be added in order to describe a prehardened initial state. The initial conditions for the internal variables can be choosen as :

$$X^k(0) = \alpha(0) = q(0) = 0 \qquad Q(0) = Q_0 \qquad R(0) = R_0 \quad R^*(0) = R^*_0 \tag{18}$$

Note : a negative normal product corresponds to an unloading in the sense of this new index function ($\dot{F} < 0$). Evolution of the memory is possible only if $n : n^* > 0$.

Application to the 316L stainless steel is considered under two cases : modelization with two kinematic variables only (X_1 and X_2) and one isotropic ($R^* \equiv 0$) which needs nine coefficients and a better modelization with three kinematic and two isotropic variables using thirteen coefficients.

In order to obtain the best choice of coefficients in each case, automatic identification procedures could be used but we discuss here on a manual technique taking advantage of some possible disconnections. The only test necessary to completely determine the model is the increasing level test showed on figure 1.

- We use firstly the five stabilized loops, for which one can suppose that $R \# Q = Q_i$, Q_i beeing constant within each loop i. The measured difference between the maximum stress and the current one can be associated with the calculated response from eq. (9) to (11) :

$$\sigma_{Mi} - \sigma = \sum_k a_k \left[Th\left(C_k \frac{\Delta \varepsilon_{pi}}{2}\right)\left(1 + \exp(-C_k \varepsilon_p)\right) + \exp(-C_k \varepsilon_p) - 1 \right] \tag{19}$$

For the model 2 three kinematic variables are used (k= 1, 2, 3) but we can associate the first with the very small strains giving rise to a smooth elastoplastic transition and choose arbitrarily a_1 = 50 MPa and C_1 = 1200. In the model 1 this small strain kinematic variable is deleted which explain the sharp transition (see fig. 3 or 5).

Similarly the third variable can be associated mainly with the large strains and choosen to give a good fit of relation (19) when the second one is saturated, that is in the large strain area of ± 2.5 and ±3% stabilized loops : a_3= 450 MPa, C_3= 4. The intermediate kinematic effect is then easily determined from the relation (19) : a_2 = 140 MPa, C_2 = 140.

- The second step consists in determining the values Q_i associated with each loops : this is now given by the difference between measured σ and calculated X . This measurements are identified with the response of eq. (17) with initial conditions (18) :

$$Q = A + (Q_o - A)\exp(-\mu \Delta\varepsilon_p) \tag{20}$$

which leads to the choice : A = 485 MPa, μ = 30, Q_o= 110 MPa.

- The third step concerns the rapidity of hardening stabilization in each cyclic loading : the coefficient b in eq. (16) is easily obtained from the difference between the successive measured maximum stresses and their stabilized values : b = 8.

- In the last step we determine the values R_o= 150 MPa, R^*_o= 70 MPa, b^*= 140, which give a good fit of the monotonic tension curve (each other coefficients beeing already fixed).

The nine coefficients of the model 1 have been determined following the same procedure : a_1= 180 MPa, C_1= 280, a_2 = 150 MPa, C_2= 15, μ= 14, A= 685 MPa, Q_o= 135 MPa, b = 5, R_o= 180 MPa. Let us examine now the possibilities of the proposed constitutive equations on the basis of the two determined models :

- By comparison with experimental loops of figure 1, figure 2 shows a very good simulation of the five level test with the model 1. Successive loops as well as the stabilized ones are correctly predicted ; furthermore the ± 1% and ± 1.5% calculations after ± 3% prior cycling give similar results as the experimental ones : the stabilized stress ranges are much more higher than in normal conditions,

- A general comparison can be made on the figure 3 between experimental stress-strain curves and the calculated ones by the two models. The monotonic as well as the stabilized cyclic curves [14][15] shows a fairly good correlation with the model 2. Also the cyclic curves after prior straining to ± 3% or ± 2.5% are predicted, but in each case stabilized stress ranges are overestimated : this is due to a slight partial evanescence of the strain memory, evanescence which is neglected in the present formulation,

- Predictions by the model 1 are slightly less good, especially for the monotonic curve (one coefficient only was identified from this curve : R_o), but the essential differences of the three kind of curves are reproduced,

- An interesting prediction is made in the case of incremental step tests on a similar material (316 in place of 316L). Figure 4 shows the good correlations (model 2), for the difference with the normal cyclic curve as well the dependency to the maximum strain range [13] [14],

- Let us remark on figure 3 and 4 that for small strains the cyclic curve lies under the monotonic one, which implies a small softening effect in that case, especially under stress control.

5. APPLICATION TO STRESS CONCENTRATION PROBLEMS

The observed strain memory effect and the corresponding proposed constitutive equations can influence the results of structural analysis under plastic flow. Illustration is given here for the stress concentration problems under plane stress conditions : in such cases the Neuber's rule gives a sufficiently good approximation of local stress σ and strain ε in each cycle [17] [18] by :

$$(\sigma-\sigma_o)(\varepsilon-\varepsilon_o) = K_t^2\ (\sigma_n - \sigma_{n_o})^2/E \tag{21}$$

where σ_n is the nominal applied stress, K_t the elastic stress concentration factor, E the Young's modulus and σ_o, ε_o , σ_{n_o} are the respective initial values for the half-cycle.

A simplified procedure has been studied which define the strain memory value within the first cycle only (the subsequent ones are contained in the first strain range) : the first loading follows the monotonic curve on figure 5 with the value b = 5 ; the first compressive reversal is also calculated with this value but the stabilization is accelerated in the next two cycles by using b = 1000. Simulation of this procedure under the Neuber rule shows no difference with the normal calculations (b = 5) in the case of reversed loading. However the difference is larger for the repeated loading (see curve I and dashed curve) because on the progressive mean stress relaxation, which increases slightly the maximum strain (see figure 5b).

An interesting remark concerns the effect of strain memory when comparing the predictions (A) with the classical ones by the normal stabilized cyclic curve [18] : especially in the repeated loading case, one observes large differences (figure 5a), which underline well the importance of taking into account the strain memory behaviour in the plastic flow structural analysis.

Several ways can be proposed to generalize Neuber's rule to cases where the highest local stress is not uniaxial (for example plane strain or axisymmetric notched specimens). With the aim of defining and validating the best generalization, the proposed constitutive equations have been introduced in the finite element program developed by Ecole Polytechnique [16] and applied to notched axisymmetric bars loaded in tension-compression. In such cases the iterative scheme works satisfactorily under plastic flow with internal strain memory.

As an example, figure 6 shows the finite element idealization : 195 superelements, each of them made of 4 triangular elements (3 nodes) with central node elimination, giving rise to 838 degrees of freedom. Some calculated plastic zones (plastic strain above 10^{-4}) are indicated : because of the reversed loading, small differences only exists between the monotonic and cyclic zones. Five successive calculated half cycles in the notch tip are indicated on figure 7 in the σ_{zz} , ε_{pzz} diagram. Such calculations are made with the coefficients of model 1 excepted a value b = 25 in order to accelerate the stabilization : another procedure is under study taking into account the first cycle with b = 5 a larger value beeing used in the few next cycles.

This part of the study is still under way : the finite element calculations will be systematically applied to notched plane strain or axisymmetric specimens in order to validate a generalization of Neuber's rule under monotonic as well as cyclic conditions.

6. CONCLUSION

The main objective of this work was to develop Mechanical constitutive equations taking into account several complex phenomena induced by cyclic loading in several stainless steels. As summarized in the abstract, the proposed formulation gives a fairly good description of the 316L cyclic behaviour including the observed strain memory effect.

Some secondary effects have been neglected in this study : 1-a slight evanescence of the strain memory which induces smaller stabilized stress ranges (after larger straining) than predicted by this theory : as well the classical formulation gives a lower bound for the stress range, the present one leads to an upper bound. 2-a possible anisotropy of the stabilized cyclic hardening as observed for example in ref. 11 for annealed OFHC copper : such a behaviour could be described by introduction of anisotropy coefficients in the strain memory index function and in the yield function.

Let us underline that the proposed constitutive equations could be applied to many other materials, showing cyclic hardening as well softening, with or without strain memory effect. 13 practical use of these equations could be developed because on their explicit integrability under several proportional loading conditions : stress control, strain control, stress concentration problems with Neuber's rule. Similar formulations could also be proposed for the high temperature viscoplastic case, including possibility of time recovery as in [10] .

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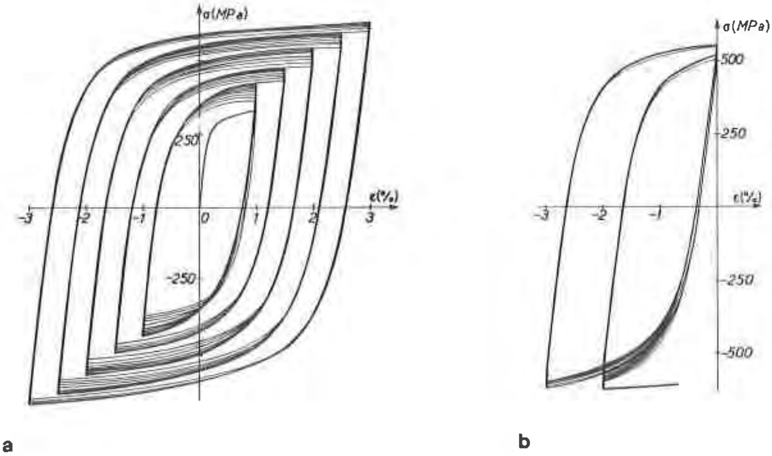

Fig. 1 — Cyclic straining on the 316 L at room temperature. a) increasing level test, b) cycling after ± 3% prior strain.

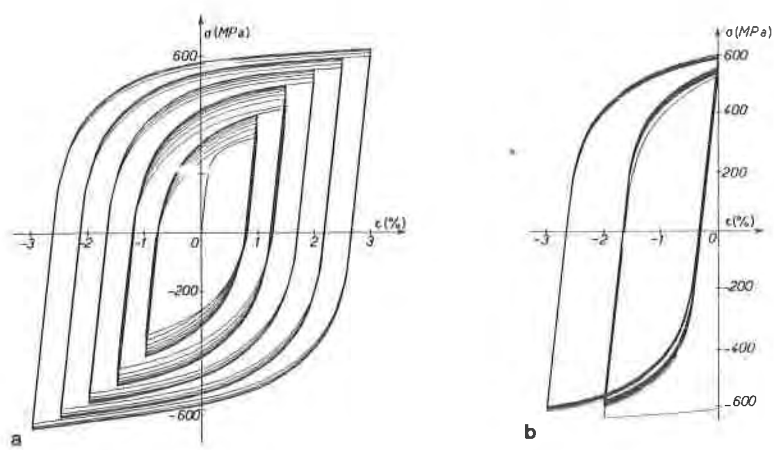

Fig. 2 — Modelization of the cyclic tension-compression of 316 L (model 2) : a) increasing level test, b) cycling after ± 3%.

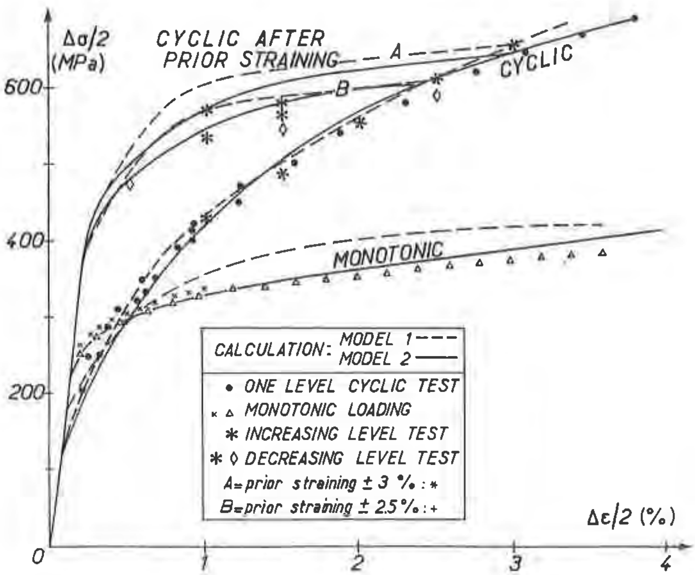

Fig. 3 — Measured and calculated monotonic and cyclic tension curves.

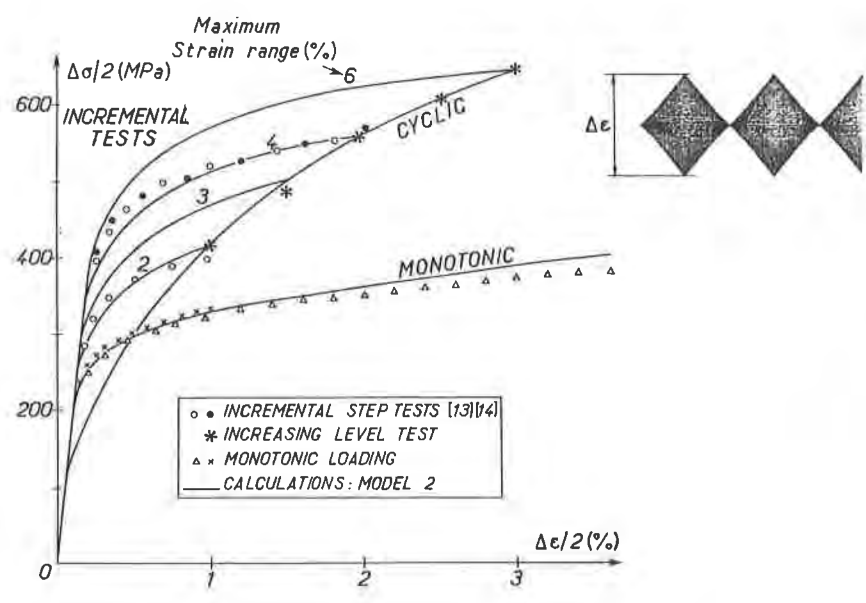

Fig. 4 — Prediction of the incremental step tests on 316 L.

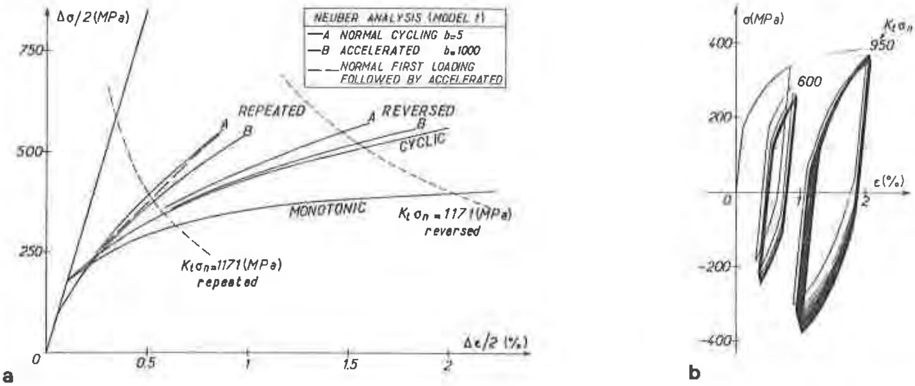

Fig. 5 — Predictions of local behaviour in plane stress by the Neuber rule (model 1) : a) cyclic stress strain curves, b) successive cycles under repeated loading.

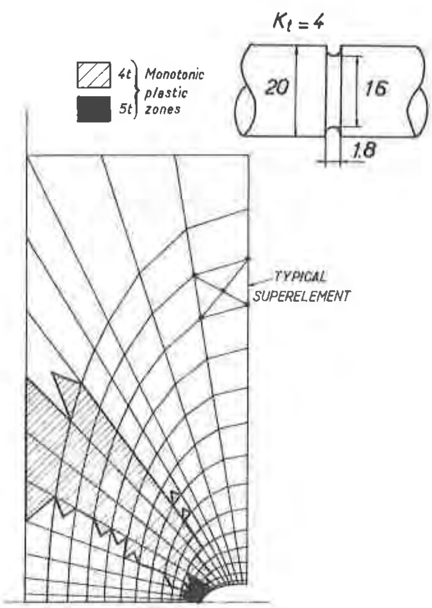

Fig. 6 — Finite element idealization and calculated monotonic-plastic zones for axisymmetric notched specimens (K_t = 4).

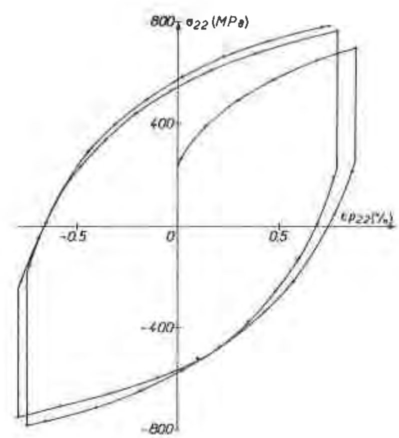

Fig. 7 — Calculated local stress strain loops (K_t = 6, ± 4 tons) with the model 1 (b = 25).