SMiRT-12 / K. Kussmaul (Editor)

L03/1

CALIBRATION OF THE PARAMETERS OF THE NONLINEAR KINEMATIC ELASTOPLASTIC MODEL FROM MECHANICAL TESTS

C. Migne, A. Pellissier-Tanon and E. Thomas-Solgadi

Framatome, Paris-la-Défense, France

ABSTRACT

This paper presents the approach followed to calibrate the parameters of the nonlinear kinematic model for the A316 steels at 20°C and 320°C, in order to use it for progressive deformation analysis.
The basis of the calibration is to reproduce the monotonic and cyclic stress strain curves of the material and experimental values of progressive elongation of thin cylinders subjected to a constant tensile stress and an alternate torsion.

1. INTRODUCTION

For a few transients undergone by class 1 pipings of the Frensh 900 MWe and 1300 MWe PWR series, some conditions of §B3600 for class 1 pipings of the RCC-M code can not be fulfilled as explained in [1]. Numerical analysis has been chosen as an alternative approach to verify acceptable conditions, because valuable constitutive models had been checked for LMFBR analysis [2] and were available on industrial computer codes. The general conditions and criteria for the progressive deformation analysis are explained in [1].
The nonlinear kinematic model chosen for this study is an elastoplastic version of the more general viscoplastic models proposed by LEMAITRE J. and CHABOCHE J.L. [3] [4], which was available on the SYSTUS computer code [5].

2. CONTEXT OF THE ANALYSIS

This analysis follows two previous analyses in which a calibration of the nonlinear kinematic model had been performed, on the one hand on the cyclic stress strain curve only, on the other hand on the monotonic stress strain curve only.

Application of these two calibrations to predict the behavior of the thin cylinders under constant tensile stress and alternate torsion brackets loosely the experimental progressive deformation curves (see figure 1). The model calibrated on the cyclic stress strain curve displays the observed trend of continuous slow down of the elongation rate leading to a stop of the deformation, but the limit elongation value is much lower than the experimental limit value. The model calibrated on the monotonic stress strain curve gives elongation values which are close to the experimental values after one cycle, but overestimates after a few cycles the progressive deformation without showing a trend towards reaching a limit value.

These first experiments have revealed that a rather good reproduction of the thin cylinders progressive deformation tests should be obtained with a model incorporating the features of cyclic strain hardening in a way which creates a transition from a behavior calibrated on the monotonic curve towards a limit state calibrated on the cyclic stress strain curve. These features were existing in the nonlinear kinematic hardening model programmed in the SYSTUS computer code [5] and described below.

3. MECHANICAL REFERENCE TESTS

The monotonic and cyclic behavior curves for austenitic Z3-CND-17-12 (A316) steels are presented in figure 2 at 20°C and in figure 3 at 320°C, where σ is the stress, ε^p the plastic strain. An example of the programs through which these data have been gathered can be found in [6]. The principle of the progressive elongation tests, which have been performed at Commissariat à l'Energie Atomique, DMT, Saclay, France, are presented in [7]. Figure 4.a gives an example of an elongation-twist record, and figure 4.b gives an example of the progressive elongation diagram.

To perform the calibration of the kinematic hardening model, as described below, the following tests have been selected within the CEA DMT program :

Temp. (°C)	Test N°	$\frac{P}{R_e}$	$\frac{\Delta Q}{R_e}$	$\frac{\Delta Q}{P}$	Limit value of elongation ε_1 (%)	Number of cycles to limit value
20	41	0.93	1.	1.07	3.15	>1000
	45	0.91	2.	2.20	4.86	>1000
	46	0.66	4.	6.06	3.82	>1000
320	4	0.69	4.69	6.79	2.63	100
	3	0.97	2.42	2.49	2.80	40
	18	0.97	6.50	6.70	7.05	500
	15	0.50	6.50	13.05	1.90	200

P is the axial stress, ΔQ is the shear stress range corresponding to the torsion in elastic condition, R_e is the experimental average yield stress at 0.2% of plastic deformation.

4. DESCRIPTION OF THE NONLINEAR KINEMATIC ELASTOPLASTIC MODEL

4.1. Equations of the model

A detailed description of the model equations is contained in reference [3] [4], with explanations of its mechanical bases.
The basic equations are those of kinematic hardening, the kinematic hardening variable tensor $\underline{X}$ being defined by its rate :

$$\dot{\underline{X}} = \frac{2}{3} C \, \dot{\underline{\varepsilon}}^p - \gamma \, \underline{X} \, \dot{P} \quad \text{with} \quad \dot{P} = \left[\frac{2}{3} \, \dot{\underline{\varepsilon}}^p : \dot{\underline{\varepsilon}}^p \right]^{1/2} \tag{1}$$

$\dot{P}$ is the strain hardening scalar variable.

C and γ are the material behavior characteristics.

The yield condition is : $J(\underline{\sigma} - \underline{X}) - k = 0$

k being the yield stress in uniaxial tension loading.

Its expression in monotonic uniaxial tension is :

$$\sigma(\varepsilon^p) = X(\varepsilon^p) + k \ , \quad \dot{\varepsilon}^p>0 : \quad \dot{X} = (C - \gamma X)\dot{\varepsilon}^p \quad , \quad \dot{\varepsilon}^p<0 : \quad \dot{X} = (C + \gamma X)\dot{\varepsilon}^p \qquad (2)$$

The (X,ε^p) curve has an horizontal assymptote for $X = C/\gamma$ when $\dot{\varepsilon}^p>0$ and for $X = -C/\gamma$ when $\dot{\varepsilon}^p<0$. C is the slope at the origin. At the extremal point of a cyclic loading (see figure 5), inversion of the sign of $\dot{\varepsilon}^p$ causes a same inversion of the sign of $\dot{X}$ with a ruth increase of its absolute value. This feature creates an active tendency to cancel the shakedown state reached at point A, which promotes occurrence of progressive deformation.

4.2. Application to alternate cyclic loading

Application of this model to the stabilized conditions of strain or stress controlled alternate cyclic loading leads to :

$$\varepsilon^p{}_a = \frac{\Delta\varepsilon^p}{2} = \frac{1}{2\gamma} \ln\left(\frac{C + \gamma X_a}{C - \gamma X_a}\right) \quad ; \quad X_a = \frac{C}{\gamma}\,\frac{\exp(2\gamma\varepsilon^p{}_a) - 1}{\exp(2\gamma\varepsilon^p{}_a) + 1} \qquad (3)$$

where $X_a = \sigma_a - \sigma_y$ and $\varepsilon^p{}_a = \varepsilon_a - \sigma_a/E$
σ_a and ε_a are the cyclic stress strain curve parameters.

The curve described by equation (3) has the same horizontal assymptote and slope at origin than the tensile curve, but its shape is different. Actually, the cyclic curve for A316 steels does not display the horizontal assymptote. In order to represent this curve with the nonlinear kinematic model, it is necessary to turn to an adaptation of the model with two kinematic hardening variables. Studies [3] and [4] explain that the multiplication of the number of the internal variables is a necessary condition to account for cyclic stress hardening effects.

In uniaxial tension, with $\dot{\varepsilon}^p>0$

$$X = X_1 + X_2 = \frac{C_1}{\gamma_1}\left[1 - \exp(-\gamma_1\varepsilon^p)\right] + \frac{C_2}{\gamma_2}\left[1 - \exp(-\gamma_2\varepsilon^p)\right] \qquad (4)$$

Equation (3) of the cyclic stress strain curve becomes

$$X_a = \frac{C_1}{\gamma_1}\,\frac{\exp(2\gamma_1\varepsilon^p{}_a) - 1}{\exp(2\gamma_1\varepsilon^p{}_a) + 1} + \frac{C_2}{\gamma_2}\,\frac{\exp(2\gamma_2\varepsilon^p{}_a) - 1}{\exp(2\gamma_2\varepsilon^p{}_a) + 1} \qquad (5)$$

Relations (4) and (5) have the same boundary conditions :

$$\frac{dX}{d\varepsilon^p} = \frac{dX_a}{d\varepsilon^p_a} = C_1 + C_2 \qquad \text{when } \varepsilon^p=0$$

$$X \text{ and } X_a \rightarrow \frac{C_1}{\gamma_1} + \frac{C_2}{\gamma_2} \qquad \text{when } \varepsilon^p \text{ and } \varepsilon^p_a \rightarrow +\infty$$

Thus $C = C_1 + C_2$ is the slope at the origin ($\sigma=\sigma_y$, $\varepsilon^p=0$) for the two curves.

4.3. Introduction of the cyclic hardening in the model

This has been done by making the material characteristics γ_1 and γ_2 to depend on the plastic stored up deformation p by the following relation :

$$\gamma_i = \gamma_i^\circ(a + (1-a)\exp(-bp)) \qquad i=1,2 \qquad (6)$$

where a and b are material behavior characteristics. When $p \rightarrow \infty$, $\gamma_i \rightarrow a.\gamma_i^\circ$ and γ_i° is γ_i value when p=0.

A feature of this model is that the number of cycles to reach the limit state of strain hardening should decrease when the amplitude of the cyclic loading increases. Examination of the results of the reference tests at 320°C shows that this is not the case and that the number of cycles to reach the limit state tends to increase with the value of the limit strain ε_1 as shown in figure 6. The physical behavior is therefore more complex that what the chosen model can describe.
But this model can be used safely for engineering application if the parameter b controling the kinetic of strain hardening is calibrated on tests presenting larger cyclic loadings than those which can occur on the structure which will be analyzed. The range of the loading parameter values P/R_e, $\Delta Q/R_e$ and $\Delta Q/P$ of the tests selected to perform the calibration bound correctly the values expected for the applications described in [1].

5. CALIBRATION OF THE PARAMETERS OF THE MODEL

5.1. Organization of the calibration

The model which is described above includes the six parameters :

C_1, C_2 — constant during the analysis,

γ_1°, γ_2° — γ_i values when the plastic deformation is nil which have to be calibrated on the monotonic curve,

$a = \dfrac{\gamma_i}{\gamma_i^\circ}$ — $a\gamma_i^\circ$ being the γ_i values when the plastic deformation is infinite, a has to be calibrated on the cyclic curve (i=1,2),

b — which determine the progressive deformation stabilization rate.

The principle of the calibration is :

- in a first stage, to calibrate the five parameters (C_1, C_2, γ_1°, γ_2°, a) on the monotonic and cyclic stress strain curves. At this stage, it is possible to obtain several solution values.

- in a second stage, to search for the conditions to satisfy in order to be able to reach a progressive deformation limit state in the numerical simulation of the tests. At this stage, only one solution is kept.

- in a third stage, to search for the b parameter value which will allow to represent at best the experimental progressive elongation values on the thin cylinders subjected to constant axial stress and alternate torsion.

5.2. First stage : calibration on monotonic and cyclic stress strain curves

The parameters taking a part in the calibration, as described below, are represented in figure 7.
The range of interest is limited to ε^p no much larger than 1.5%.
The calibration method is based on the numerical representation of the monotonic and cyclic behavior curves according to equations (4) and (5), by forcing it to pass through the experimental point ε^p=1.5% and trying to minimize the distance between experimental and numerical curves at point ε^p=0.5%.

In practice, $C=C_1+C_2$ is given by the tangent from origin (ε^p=0, X=0) of monotonic and cyclic behavior curves. In order to be able to draw a common tangent from the origin to the monotonic and cyclic (X, ε^p) curves, the yield stress k of the model had to be fixed to the value 0.7xR_e. The tangents have been drawn on the (σ, ε^p) monotonic and cyclic curves in figures 2 and 3.
A set of arbitrary values are chosen for C_1 and γ_1°, and, for each set, γ_2° and a parameters values are optimized in order to minimize the deviation with the experimental stresses X(ε^p=0.5%) and X_a($\varepsilon^p{}_a$=0.5%) (see figure 7).

Solutions of the described method verify the condition : a<1, and by convention :

$$r = \frac{C_1}{\gamma_1^\circ} \Big/ \frac{C_2}{\gamma_2^\circ}, \quad r > 1$$

Several sets of values could be found giving a rather similar overall level of accuracy, but with variations of the local differences between the models and the experiments.

5.3. Second stage : calibration to reach a limit state of progressive deformation

The next stage consists in simulating the specimens behavior with elastoplastic cyclic calculations using the sets of parameters already calibrated on the cyclic stress strain material curve in order to obtain a progressive deformation stop.
A monotonic uniaxial tension and an alternate cyclic torsion loading is applied on a two-dimensional linear mesh element, using equation (5) and the four parameters : C_1, C_2, $\gamma_1=a.\gamma_1^\circ$, $\gamma_2=a.\gamma_2^\circ$.

After doing one calculation with each set of parameters determinated in the first stage, there was only one set of values which permitted to reach a limit value of elongation. It is the one corresponding to the largest value of r.

These parameters, given in the table below, will be completed with the parameter b in the third stage of calibration.

Temp. (°C)	C_1 (MPa)	$\gamma_1 = a.\gamma_1^o$	C_2 (MPa)	$\gamma_2 = a.\gamma_2^o$	Calculation cycles number	C_1/γ_1^o / C_2/γ_2^o
20	10800	0.102	61200	280.5	300	246
320	9450	0.240	53550	193.8	100	142.4

The calculated monotonic and cyclic stress strain curves at 320°C are compared to the reference curves in figure 8.

5.4. Third stage : calibration to represent tests tubes behavior under a monotonic uniaxial tension and an alternate cyclic torsion loading

The parameter b makes it possible to adjuste the numerical plastic deformation curve and the experimental reference specimen curve : the progressive deformation slows down and stop faster when the b value is larger.

Elastoplastic cyclic calculations, using the parameters which are calibrated on the monotonic and cyclic stress strain curves, show that the best and safe adjustements on the reference progressive elongation curves are obtained for the following six parameters values :

Temp. (°C)	C_1 (MPa)	C_2 (MPa)	γ_1^o	γ_2^o	a	b	cycles number	Figures
20	10800	61200	21	58000	0.004836	16	300	9
320	9450	53550	67	54000	0.003590	40	100	10

With these parameter values, the numerical plastic deformation curves are conservative as shown in figures 9 and 10, except for the test N°18 at 320°C which gives the largest limit strain of 7%. This calibration has been chosen for the application described in [1], for which limit strains lower than 3.5% were expected.

6. CONCLUSION

This work shows that the nonlinear kinematic hardening model is able to account for the features of progressive deformation undergone by A316 steel components.

The calibration of the six parameters of the model has been undertaken by an approach fitted to industrial application in which the experimental references had been taken on simple mechanical tests performed at the two extreme temperatures of the range of interest 20°C and 320°C :

- the monotonic tension curve,
- the cyclic stress strain curve,
- the progressive elongation values recorded on tests tubes under an uniaxial tension loading and an alternate torsion deformation.

The model, thus calibrated, has been used to analyze the behavior of nozzles of the main primary circuit of the 900 MWe PWR serie, as presented in [1]. Experimental tests of cracked structures subjected to constant mechanical loads and thermal loads are underway to provide a more elaborate basis for the validation of the model [1].

REFERENCES

[1] PELLISSIER TANON A. and al, alternative Methods for primary Piping Analysis induced by operating Experience, SMIRT12, paper DF09/1.

[2] RIOU B. and al, Validation of viscoplastic Model and Life Assesment on a Mock-up representative of LMFBR Structures, SMIRT11, paper E06/2.

[3] LEMAITRE J., CHABOCHE J.L., Mécanique des Matériaux Solides, 1985, Bordas Ed., Paris.

[4] CHABOCHE J.L., constitutive Equations for cyclic Plasticity and cyclic Viscoplasticity, Int. J of Plasticity, 1989, 247-269.

[5] SYSTUS Users Manual, Chapter A3.3.1.8, Ed. by Framasoft+CSI, Paris.

[6] PELLISSIER TANON A., BERNARD J.L., AMZALLAG E., RABBE P., an Evaluation of the Resistance of 316SS against progressive Deformation, low Cycle Fatigue and Life Prediction, ASTM STP 770, 1982, 69-80.

[7] ROCHE R.L., MOULIN D., LEBEY J., practical Analysis of Ratcheting, Nucl. Eng. Des., 71, 1982, 51-56.

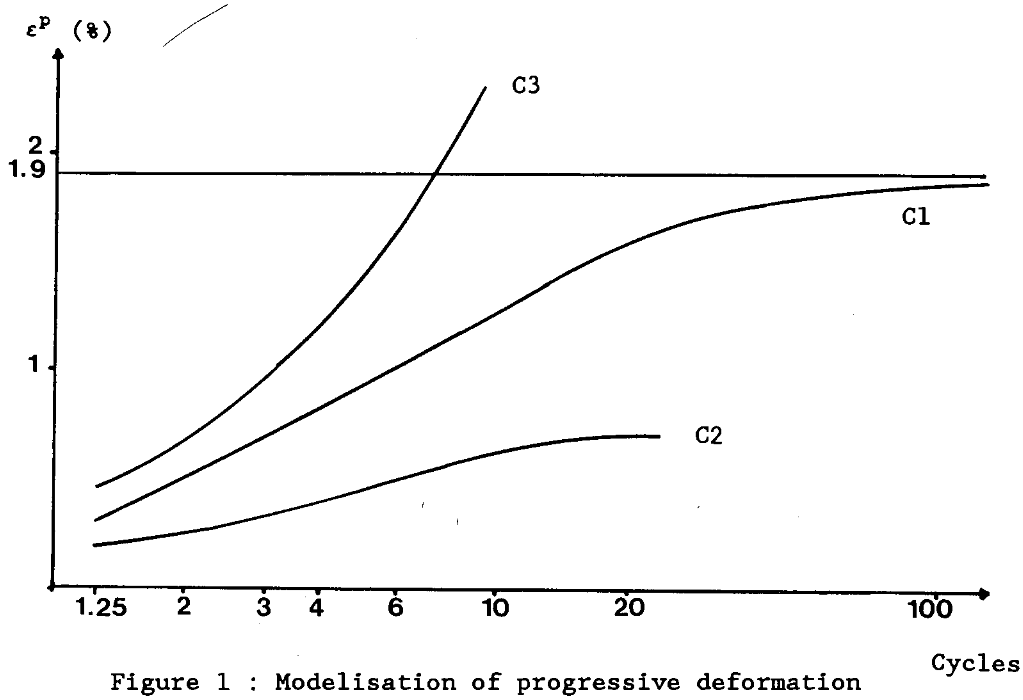


Figure 1 : Modelisation of progressive deformation with nonlinear kinematic hardening model calibrated on the monotonic or the cyclic stress strain curve.

C1 : experimental curve

C2 : calculation with the model calibrated on the cyclic curve

C3 : calculation with the model calibrated on the monotonic curve

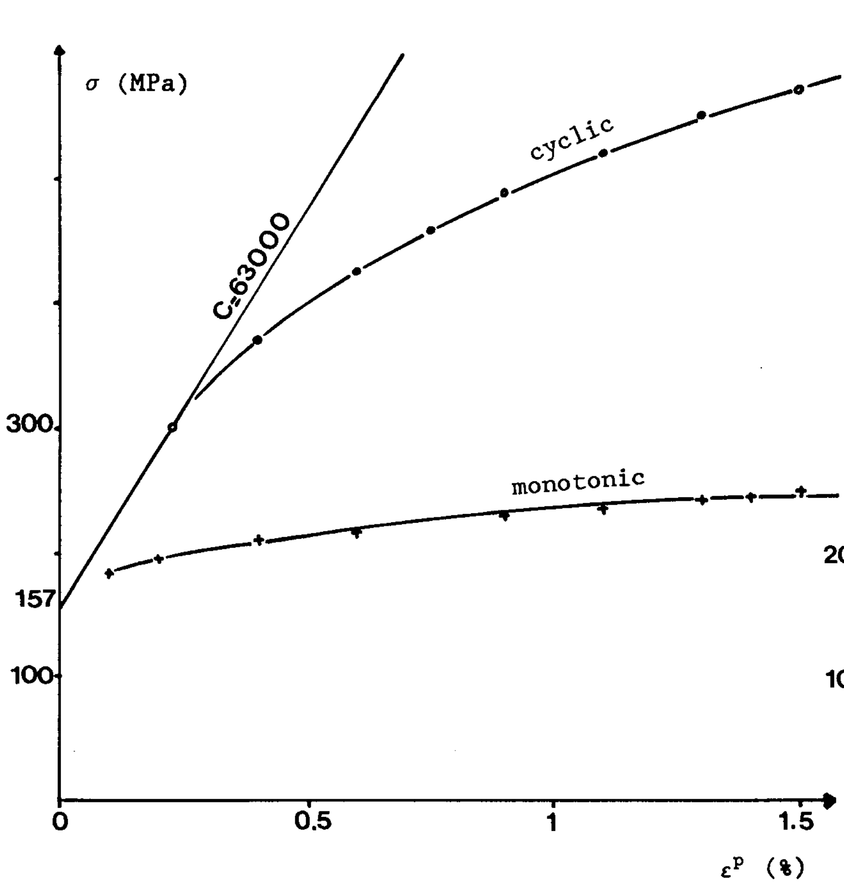


Figure 3 :
Reference curves for Z3-CND-1712 (A316) at 320°C.

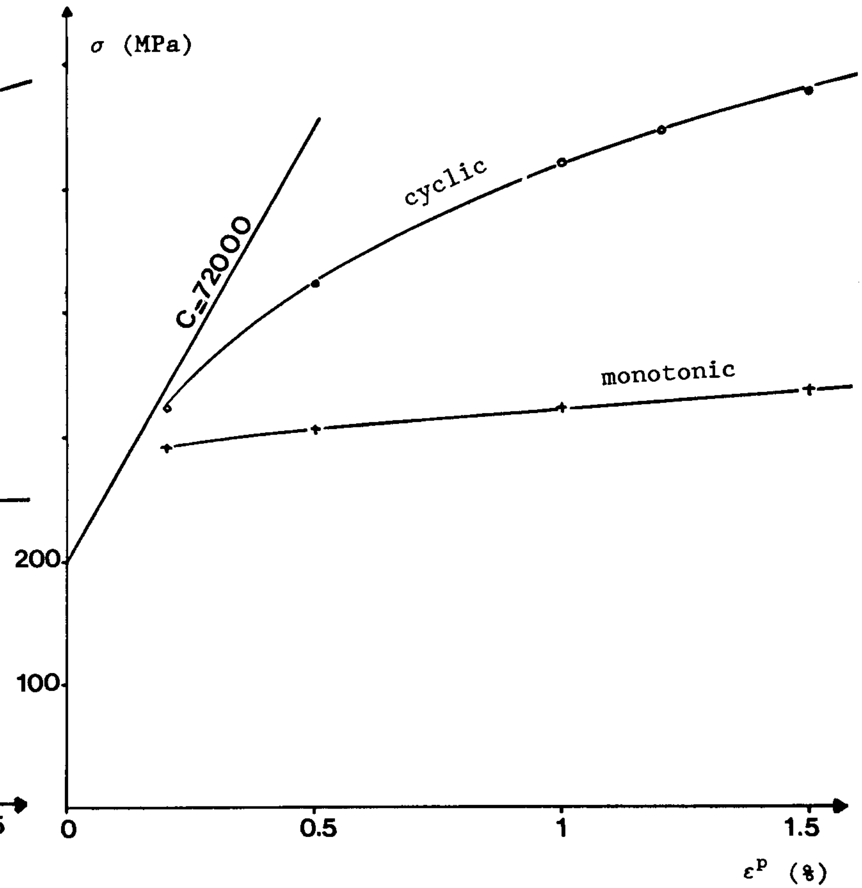


Figure 2 :
Reference curves for Z3-CND-1712 (A316) at 20°C.

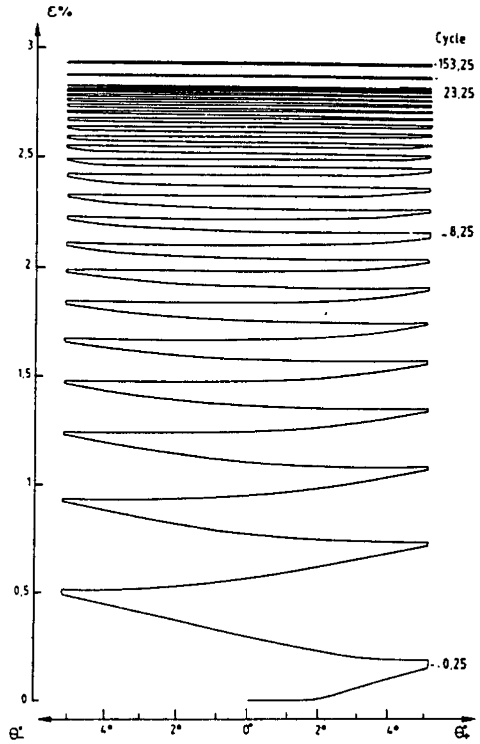


Figure 4.a :
Axial elongation twist diagram.

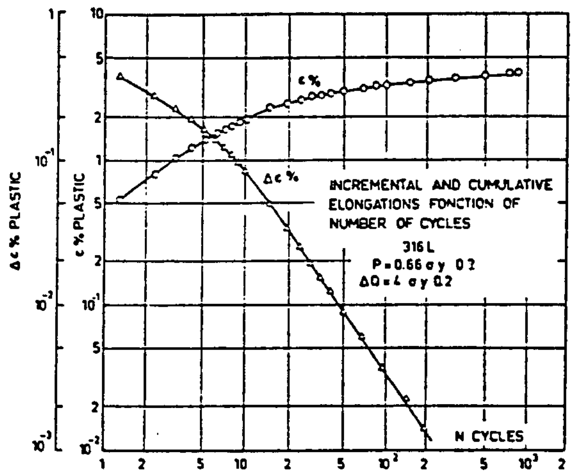


Figure 4.b :

Axial elongation as a function of the number of cycles

Figure 4 :
Progressive deformation diagram of thin tube under constant axial load and imposed torsion.

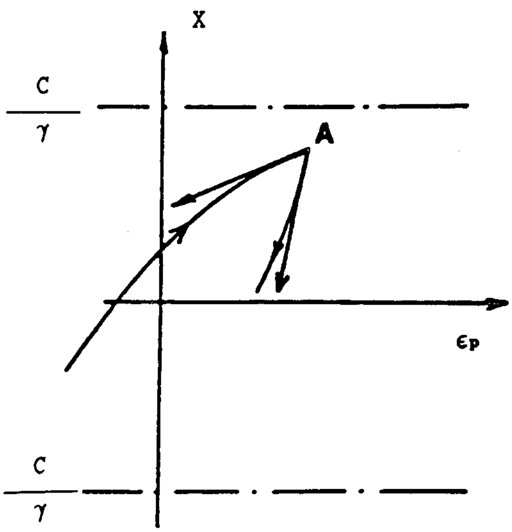


Figure 5 :
Nonlinear kinematic model.

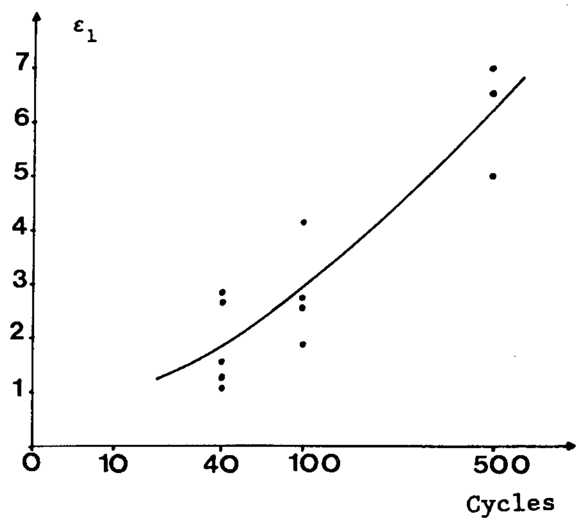


Figure 6 :
Limit strain of reference tests.

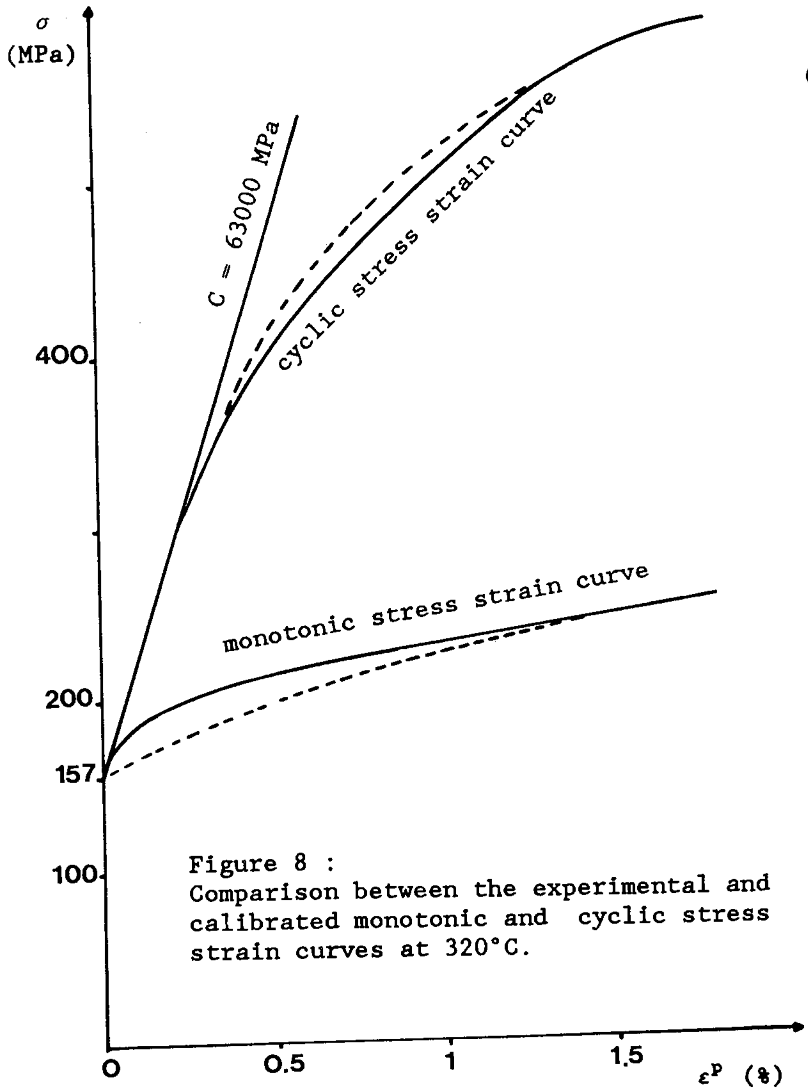


Figure 8 :
Comparison between the experimental and calibrated monotonic and cyclic stress strain curves at 320°C.

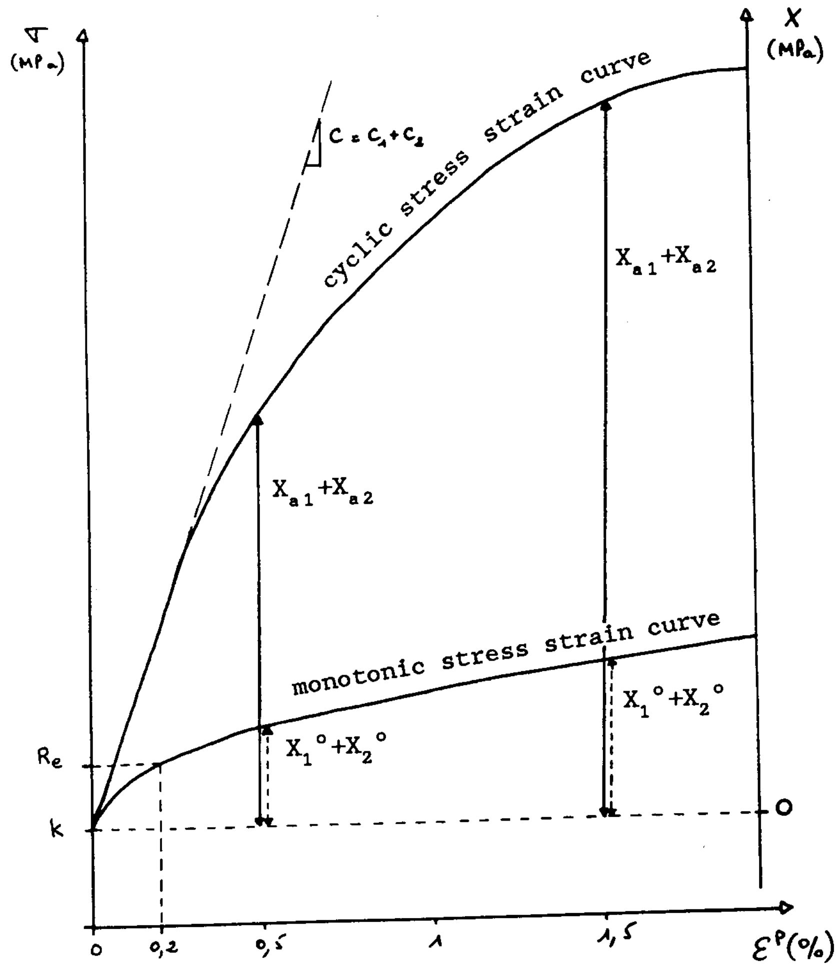


Figure 7 : Parameters for the monotonic and cyclic stress strain curves.

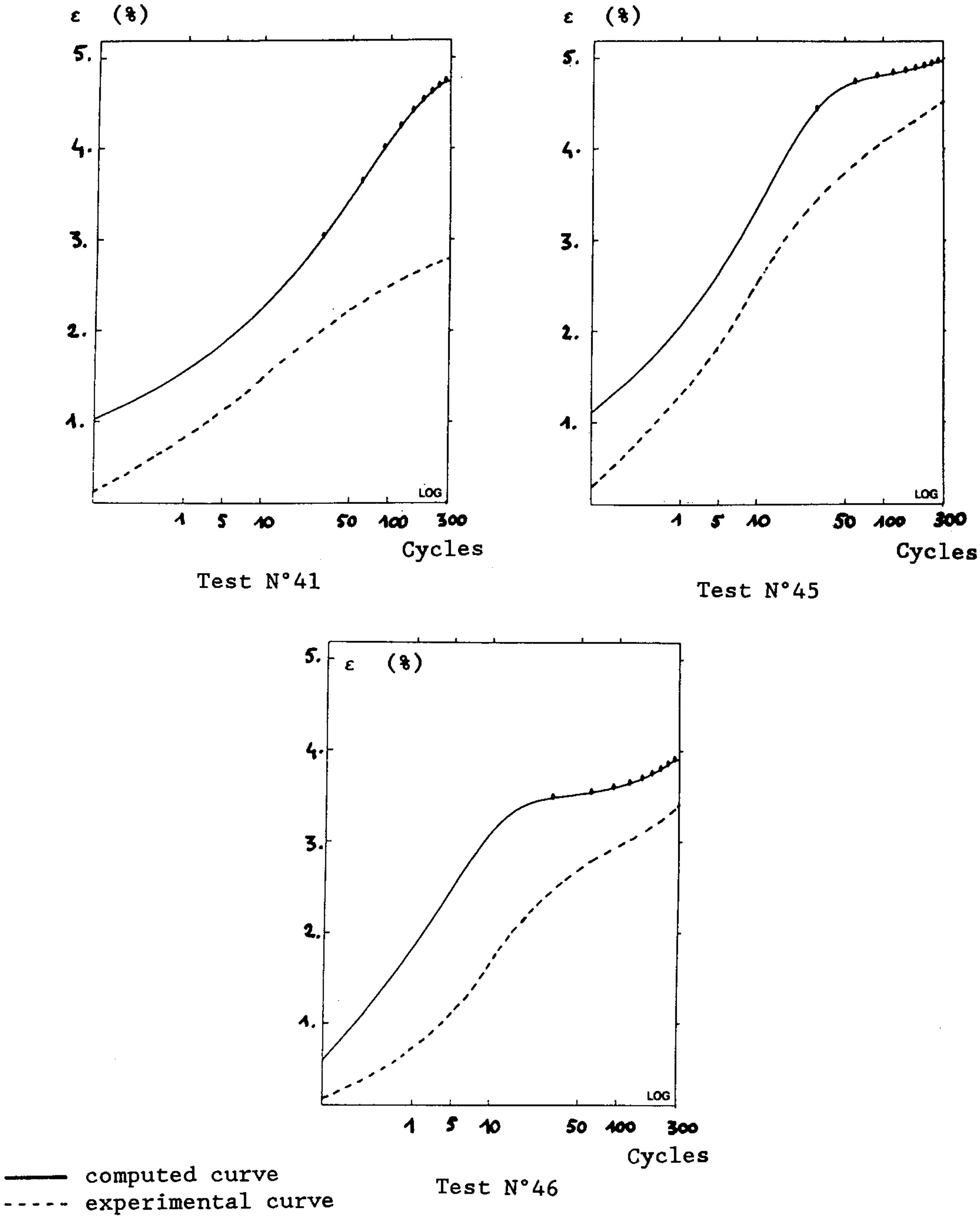
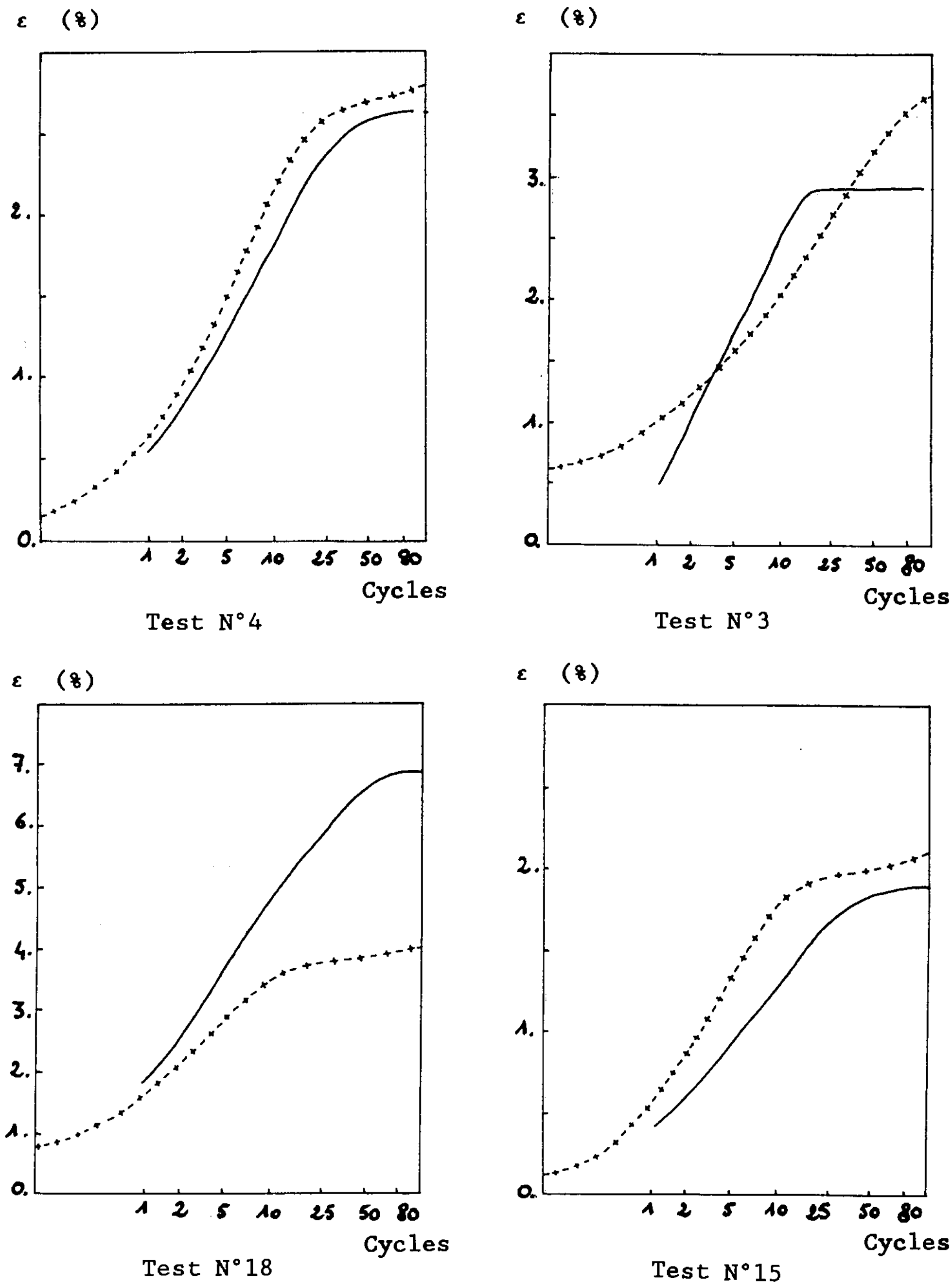


Figure 9 :
Comparison of the computed progressive elongation diagram to the experimental results on the thin tubes at 20°C.



——— experimental curve
-+-+- computed curve

Figure 10 :
Comparison of the computed progressive elongation diagram to the experimental results on the thin tubes at 320°C.