Structural mechanics behaviors for computational simulations

Summarized:

The behavior of the material is an input datum impossible to circumvent in most mechanical studies. In a computational simulation this behavior is taken into account via a more or less complex model, supposed to reproduce in a sufficiently precise way the behavior of the actual material. The parameters controlling the model will have been adjusted as a preliminary from experimental data.

Very models being a representation simplified and inaccurate of reality, it is essential to make sure that the choices of formulation as well as the selected set of parameters is relevant for the group of the field of requests characterizing the study.

As soon as one leaves the simple cases where one can be satisfied with a linear elastic behavior or a plastic behavior with isotropic hardening, the choice of a model of behavior and its retiming for a given material are a long and delicate process, which requires to have relevant experimental data which it is not always easy to collect.

This document is complementary to [U2.04.03] which gives advice to an user wishing to carry out computations with nonlinear behaviors of elastoplastic type or élasto-visco-plastic to choose a model adapted to the modelizations considered.

Contents

1 Some recalls on the structural mechanics behavior

In mechanics, one can gather under the term "constitutive law" the models which govern the relation between the local states of stress and strain by possibly taking into account the former states.

Before speaking about constitutive laws, it seems useful to us to quickly point out the principal phenomena which one can meet in terms of behavior of the materials, by focussing more particularly on the behavior of the metallic materials.

In order to look further into the subject, the reader will be able to refer to various works referring in the field, in particular [biberon2] and [biberon3].

1.1 Elasticity and plasticity

the simplest constitutive law is the linear elasticity which corresponds to the capacity of the material to regain its shape of origin when one removes the request the constitutive law which represents linear elasticity corresponds to a relation of proportionality between the stresses and the strains. For a large number of materials, one will be able to consider elasticity as isotropic (the proportionality factor is same whatever the direction of request). However certain materials (monocrystals, textured materials) show elastic characteristics different according to the direction from the request.

Certain materials such as elastomers have a nonlinear elastic behavior. In this case, the stresses and the strains are not connected any more by a relation of proportionality, however the material regains its initial shape when he is not requested.
For most materials (which the metallic materials) one observes a linear elastic behavior for the moderate requests. When one continues to increase the loading one creates an irreversible plastic strain gradually and one loses the relation of linearity between stress and strain.

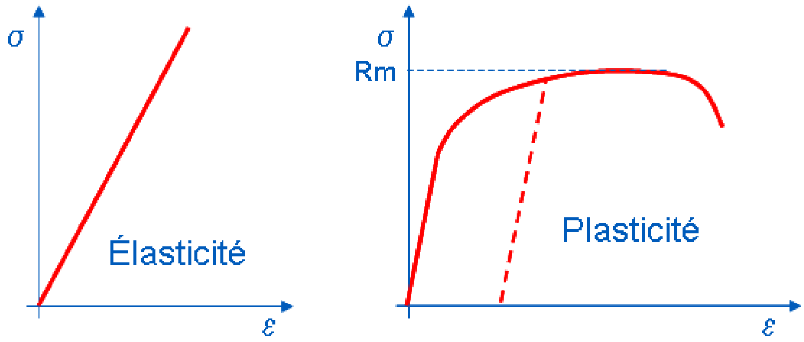

Figure 1.1-1 : Behaviors elastic and plastic

1.2 Influences temperature

When one mechanically requests the same material at various levels of temperature, one observes an evolution of its response as well in the elastic domain as in the plastic range. Generally, when the temperature increases, the total deflection observed is more important for the same level of stress.

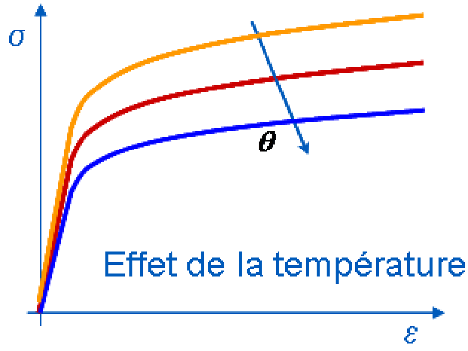

Figure 1.2-1 : Influence temperature

1.3 Viscosity

If one requests the same material with different loading rates one generally obtains different mechanical responses in the plastic range. The sensitivity to the rate loading translates the viscous character of the material.

Viscosity appears in different ways according to the stress type applied. With a monotonic loading growing one will be interested in the hardening modulus according to the rate loading. One can also apply a level of strain to the material, then to observe the progressive decrease of the stress with constant strain. One speaks then about relaxation. One can also impose a level of stress and observe a progressive increase in the strain with constant stress. One speaks then about creep.

It will be noted that viscosity is generally a thermically activated mechanism. It will be all the more important as the material is with a high temperature. One can sometimes belong to the more complex dependences to the temperature. It is for example the case of the austenitic stainless steels which have a significant viscosity to room temperature. This viscosity decreases when the temperature grows and becomes practically null in the neighborhoods of $350°C$ then it reappears and grows quickly beyond $450°C$.

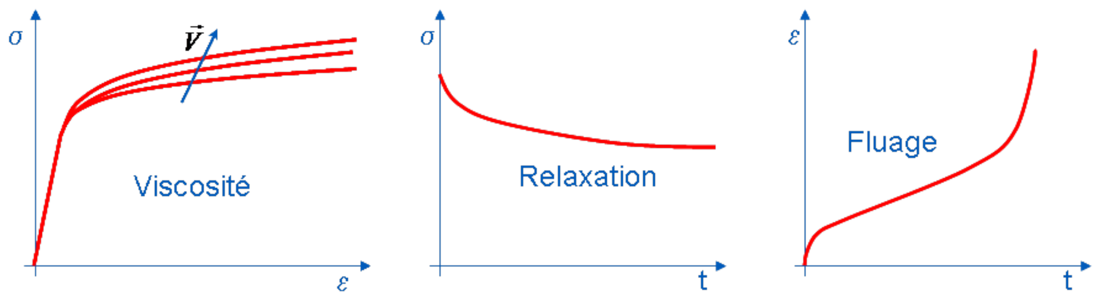

Figure 1.3-1 : Manifestation of viscosity according to the nature of the request

1.4 Behavior cyclic

the phenomena described until now are observable with monotonic loadings. When the request applied is cyclic and that the level of request applied is sufficient to generate a plastic strain of the material, one notes an evolution of the mechanical response to the wire of the cycles. According to the material considered this evolution can be various natures.

Under a cyclic request with an amplitude of constant stress one observes an accumulation of strain at the time as of first cycles. If the amplitude of stress is sufficiently high, one continues to accumulate strain with each cycle. One speaks then about progressive strain which can lead to the fast fracture of the material.

If the amplitude of pressure applied is more moderate one observes a stabilization of the cyclic response. According to the material (and the amplitude of loading) stabilization can be of two types. If the stabilized cycle present of plasticity, one speaks about accommodation of the material. If the stabilized cycle is completely elastic, one speaks then about adaptation.

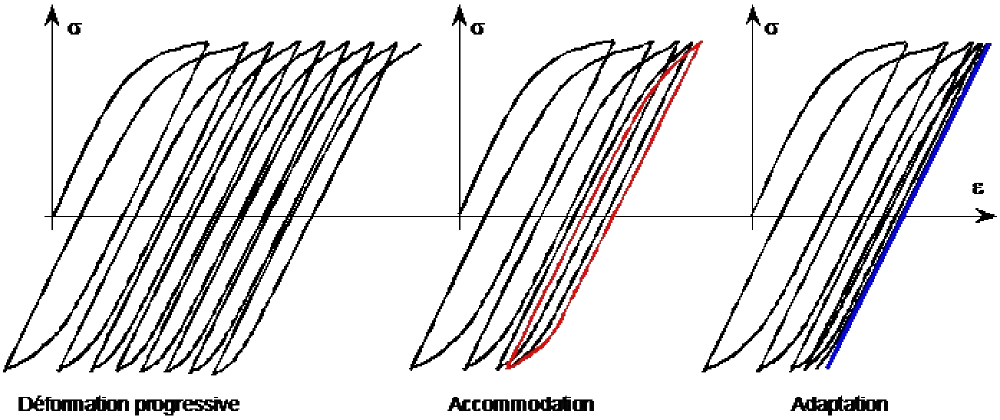

Figure 1.4-1 : Stabilization of the cyclic response of the material

Under cyclic loading, one generally observes an evolution of the envelope of the way of loading to the wire of the cycles because of an office plurality of hardening. One can classify the materials in two categories:

1. Lenitive materials when the amplitude of stress decrease for a loading with amplitude of constant strain, or when the amplitude of strain increases for a loading with amplitude of constant stress.
2. The hardening materials when the amplitude of stress increases with the wire of the cycles for a loading with amplitude of constant strain or whose amplitude of strain decrease for a loading with amplitude of constant stress.

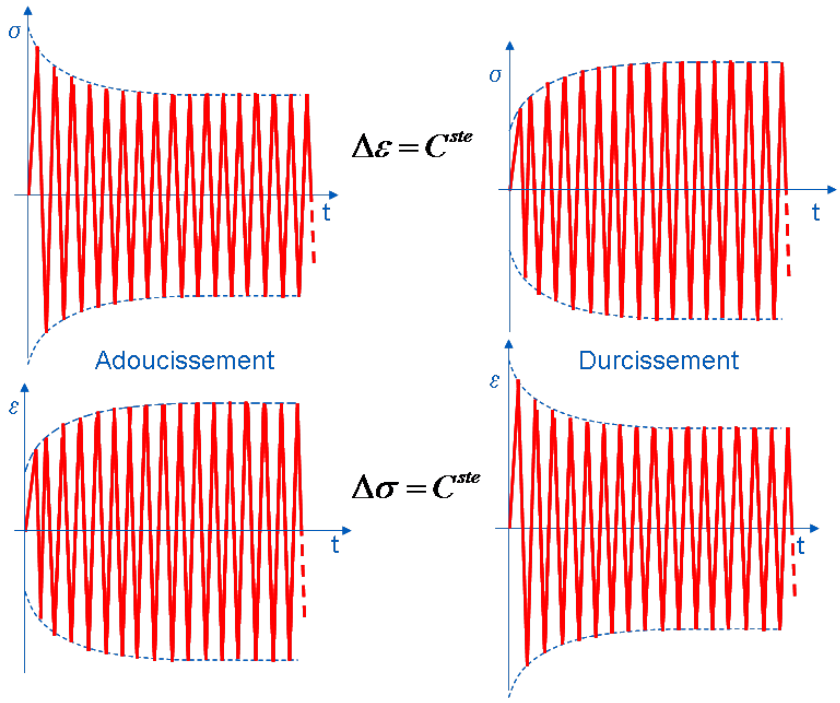

Figure 1.4-2 : Hardening and cyclic softening

When the amplitude of loading is constant, the phenomena of hardening or softening tend to diminish with the office plurality of the cycles to reach a stabilization of the response of the material.

If the material has viscosity, the response of the material with a cyclic loading will be dependant the velocity of request.

1.5 Static restoration

Certain materials also have a sensitivity to time in the case of a loading with plasticization followed by an unloading then of a handing-over in load. If one leaves the material at rest a certain time before making the second loading, one observes sometimes a phenomenon of restoration.

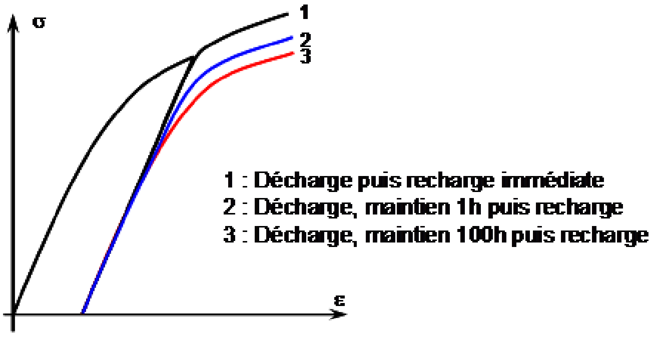

Figure 1.5-1 : The phenomenon of restoration

If recharging is carried out immediately after the discharge, one observes an elastic behavior until reaching the maximum level of stress before discharge, then the response curve of the material is in the prolongation of the initial curve before discharge.

If the material is sensitive to the restoration, and if one leaves the material at rest before reloading it, one observes a response of the material which will be intermediate between the initial response of the material and the response obtained during an immediate refill. It is thus noted that the material at rest gradually loses the memory of hardening accumulated during the first loading.

1.6 Ratchet effect

On certain metallic materials, and more particularly the crystalline structure alloys $C.F.C.$ (Cubic Centered Face), one observes that the cyclic behavior preserves the memory of the maximum level of strain reached during the life of the material.

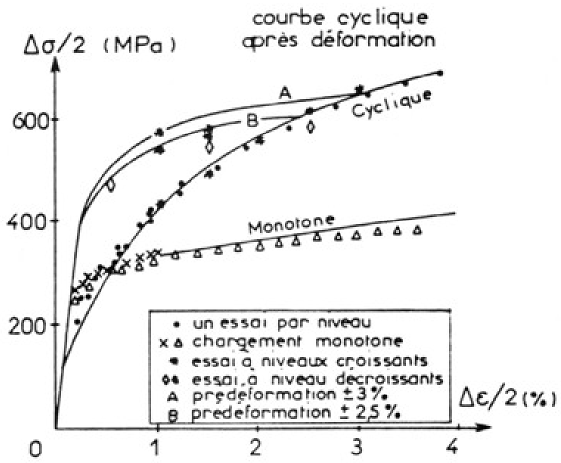

Figure 1.6-1 : The ratchet effect of hardening

Figure 1.6-1 described the evolution of the amplitude of stress according to the amplitude of strain for a significant number of cyclic tests on the same material. When an initially virgin material is requested, one obtains the cyclic curve of consolidation located on the diagram. If one carries out initially a hardening of the material up to a relatively important level of strain then that one cycles with a weaker loading, the response corresponds to a “tough” material more as the two curves show it A and B corresponding on different levels of pre-hardening.

1.7 On-hardening

the mechanical response of the material can sometimes be very different according to whether the loading is uniaxial or that it is multiaxial nonproportional. One speaks then about axial on-hardening multi. This phenomenon is illustrated by the two following figures. One subjects a steel 316L test-tube to a combined loading of tension and alternate torsion (controlled in amplitude of strain) with a phase shift of 90° between the two requests.

The reached levels of stress (represented by the red points on the right part of the figure) are approximately twice higher than those which would be reached on a test-tube requested with a radial or linked loading axial of amplitude of equivalent strain.

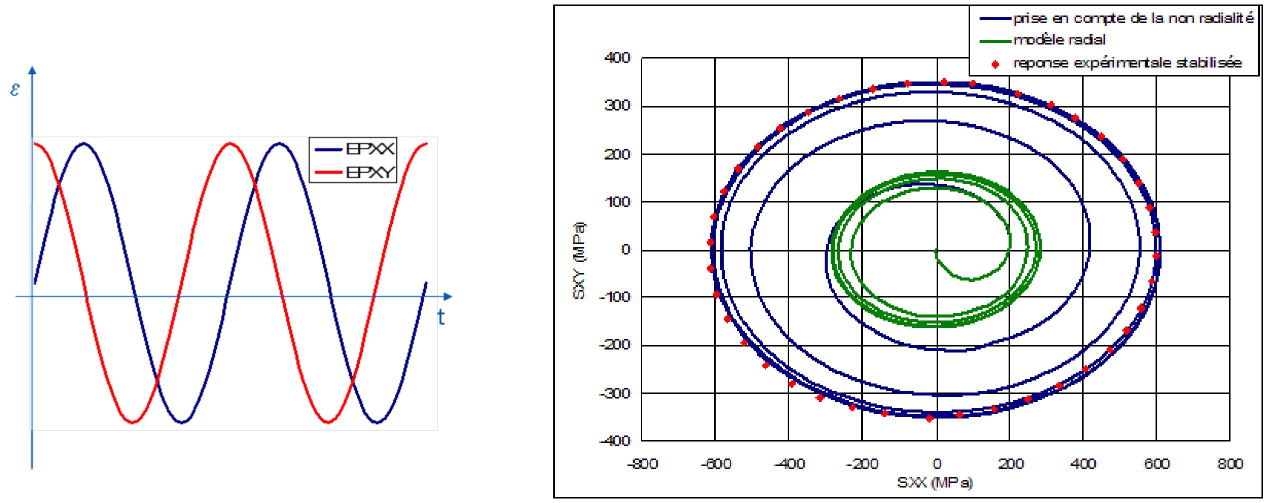

Figure 1.7-1 : Effect of on-hardening under nonradial multiaxial loading

This test was simulated with two different constitutive laws. The blue curve corresponds to a model of behavior able to reproduce the effect of on-hardening. The green curve is obtained with a similar constitutive law in which one withdrew the taking into account of on-hardening. The second formulation predicts amplitudes of stresses definitely lower, which correspond to the response of the material for a radial loading.

1.8 Isotropic hardening and kinematics

When the loading exceeds the elastic limit of the material, we saw previously that plasticization is accompanied by a hardening which modifies the later response of the material in the event of discharge or alternate loading.

If one places oneself within the space of stresses one can define a surface threshold inside which the material remains elastic. When the way of loading reaches this surface, one sees appearing plastic strain and surface threshold adapts so that the point of loading remains on surface as long as there is no discharge. The adaptation of the surface of load can be done according to two distinct modes:

If surface dilates while remaining centered on the origin (which corresponds in a stress state null) one speaks about isotropic hardening (see Figure 1.8-1). Isotropic hardening thus corresponds to a variation of size of the elastic domain.

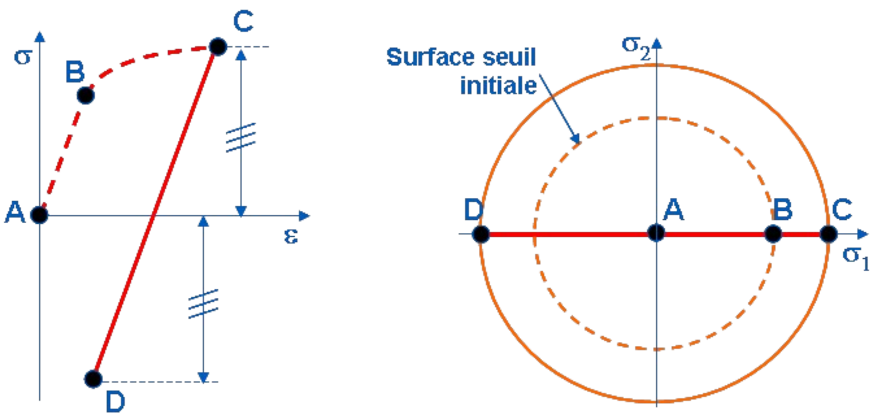

Figure 1.8-1 : Isotropic hardening

For a loading of tension followed by a discharge then of a compression, the material will preserve an elastic behavior up to a level of compression equivalent to the maximum loading reached in tension.

If the surface of load moves to follow the loading one speaks about kinematic hardening (see Figure 1.8-2). The elastic domain preserves a constant size and is relocated to follow the loading. In the case of an alternate loading of traction and compression the elastic domain will correspond to the double of the initial elastic limit (in absence of residual stress in the virgin material).

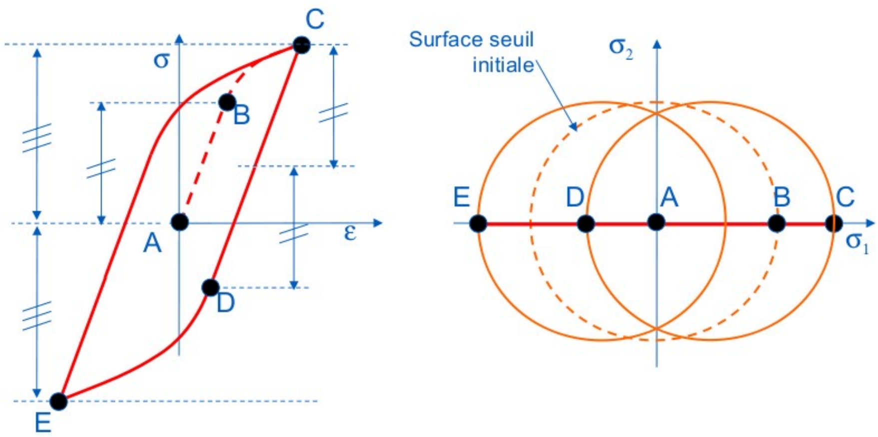

Figure 1.8-2 : Kinematic hardening

the behavior observed on the actual materials generally corresponds to a combination of kinematic hardening and isotropic.

2 Taken into account of the structural mechanics behavior in computational simulations

In many cases an isotropic elastic constitutive law is sufficient, for example for a study of design for which one is generally satisfied to check that the maximum stress does not exceed a value threshold (elastic limit, threshold of endurance in fatigue, etc). The only parameters of behavior to be defined are the Young modulus E and the Poisson's ratio ν .

For the studies anisothermals, it is enough to replace the scalar parameters E and ν by tabulated functions in temperature.

When it is necessary to take into account the plastic behavior of the material, the simplest solution is to directly use an experimental uniaxial curve of tension which one will have beforehand tabulated in the form of an evolution of the stress according to the strain. In the computer code Code_Aster of the formulations such as `VMIS_ISOT_TRAC` during the resolution allow to generalize the uniaxial curve with ways of multiaxial loadings.

This kind of model has the advantage of implementation a very simple insofar as one frees oneself from any stage of identification of the parameters of a constitutive law since an experimental curve of tension directly is used. It is necessary however to keep in mind that these models implicitly integrate the assumption of a purely isotropic behavior of the material.

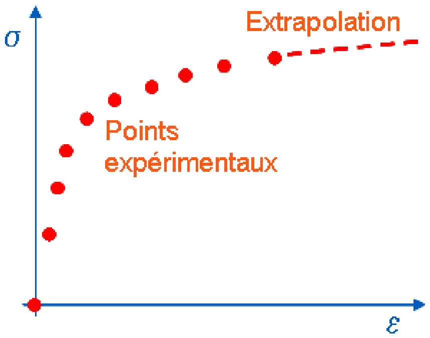

Figure 2-1 : Use of a curve of tension as behavior models

Although the actual materials generally present a share of kinematic hardening, the approximation by a purely isotropic behavior is not necessarily penalizing, provided the way of loading in any point of studied structure observes certain conditions specified hereafter.

In order to highlight the limits of the isotropic assumption of behavior, we consider the borderline case of a material whose real behavior in hardening is purely kinematical and we consider a material point subjected to a uniaxial loading growing then decreasing. As long as the way of loading in any point of structure remains monotonous, the assumption of isotropy does not have any incidence. If a moderate local discharge is obtained, the model remains relevant. However, if the discharge is accentuated, the model an elastic response until a compressive stress equivalent to the maximum stress of tension reached will predict previously (the response of the model is represented by a curve in continuous feature on the figure). The real response of the material is represented in dotted feature. If the actual material is purely kinematical, it is noted that the entry in plasticity in compression occurs much earlier than than envisages isotropic behavior the model, and than the difference between the calculated stress and the real stress can be significant.

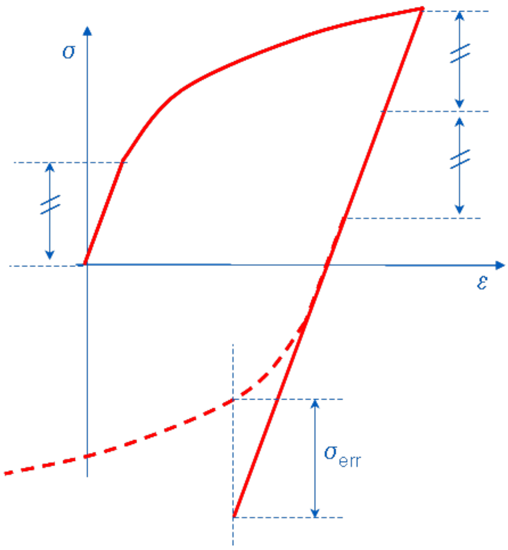

Figure 2-2 : Difference between isotropic behavior and real behavior

the illustration presented here corresponds to a very unfavourable situation, in particular owing to the fact that we suppose a material whose real behavior is purely kinematical, but it is important in any study using this kind of behavior to be vigilant with respect to this kind of error. It should be also underlined that a weak decrease of the total loading can result in a discharge much more important into certain points of structure. It is thus desirable to make a checking on the group of the stress field throughout simulation.

Simulations anisothermals are relatively simple with this kind of setting in data. One provides to the code computer several curves of tension corresponding to different temperatures and the code deals with the interpolation in temperature between the various curves.

If the study to be realized requires to take into account a behavior more complex than those which we have just approached in the beginning of this chapter, it is necessary to use a constitutive law leaning on a mathematical formulation (generally in the form of differential equation).

Several stages are then necessary before carrying out computational simulation itself:

1) The choice of the formulation will have to be carried out in coherence with the physical phenomena which one wishes to take into account.
2) One collects the relevant experimental data for the chock of the model with for purpose covering the field of request as well as possible undergone by structure (while supplementing by complementary tests if necessary).
3) One carries out then the identification of the parameters of the model so that the numerical response is possible nearest experimental results.

It is frequent to avoid all the process of identification when one has of a model and a set of parameters obtained in a comparable study on the same material or resulting from a thesis or an article.

In this case, it is important to keep in mind that, whatever its complexity, a model of behavior proposes only one simplified and thus imperfect reproduction of the reaction of the material. It is usable only on one limited field of mechanical request, which generally corresponds to the beach of request covered by the experimental data used for its identification. The re-use of a formulation and preexistent parameters can thus prove to be risky if one of also does not have accurate information as for the field of validity of the model which one wishes to use.

As illustration one compares on figure 2-3 the ways of loadings experimental and simulated for cyclic loadings at various levels of amplitude. The constitutive law used was identified on a beach of amplitude of total deflection understood enters $\pm 0,2\%$ and $\pm 0,7\%$ (with tests with intermediate loadings with $\pm 0,3$ and $\pm 0,5\%$). One can thus consider that this beach of amplitude corresponds *a priori* to the field of validity of the model in terms of amplitude of strain.
The test charged was carried out under an amplitude of $\pm 0,15\%$. This level is close to the limit of the field of validity and the constitutive law seems relevant in spite of a light extrapolation.
The test with $\pm 0,4\%$ is located in the field of validity. The interpolation between the results with $\pm 0,3$ and $\pm 0,5\%$ used for the identification proves to be satisfactory.

For the two tests with $\pm 1\%$ and $\pm 1,2\%$ one notes that the extrapolation of the model towards amplitudes of loading definitely higher than the limit of the field of validity led to a significant undervaluation of the amplitude of simulated stress.

It will be retained that the knowledge (and the respect) of the field of validity of the model put in work are essential ingredients as for the quality of result of a computational simulation. In the event of absence of accurate information on the field of validity of “recycled” model, it is strongly recommended to confront the model with some quite selected experimental results before using it in a simulation.

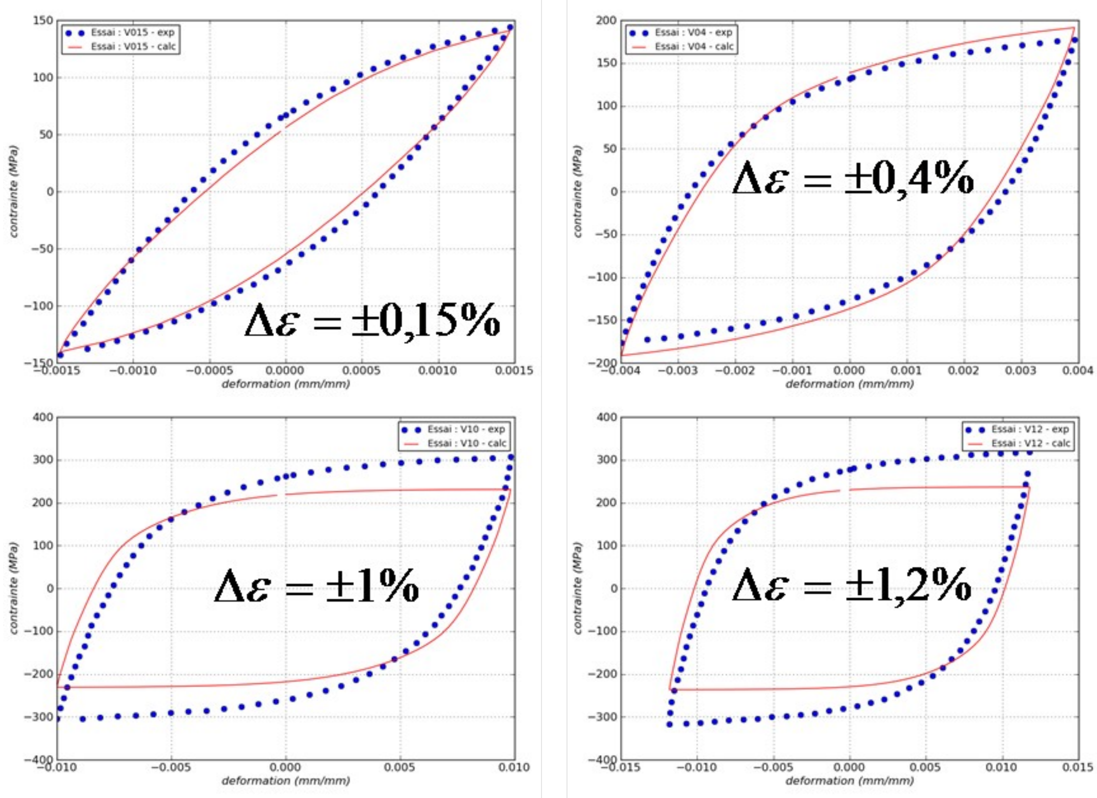

Figure 2-4 : Estimate of the robustness of a constitutive law in the event of extrapolation out of its field of validity.

For simulations anisothermals, several strategies are possible.

Simplest consists in having an isothermal constitutive law for which one identifies sets of parameters for several levels of temperature. During simulation, the computer code will realize in each point of integration a linear interpolation in temperature of each parameter of the model then will integrate the behavior on the basis as of interpolated parameters. This solution is completely satisfactory, subject to making sure that the evolution of each parameters according to the temperature is reasonably regular.

A more elegant alternative on the thermodynamic level consists in integrating the effects of the temperature directly in the formulation of the constitutive law. This approach can prove a little more complex, but it in particular makes it possible to propose an interpolation finer (and not necessarily linear) of the behavior between the experimental data available to constant temperature.

In a general way, it is important during a simulation anisothermal to make sure that the beach of covered temperature does not comprise change of mechanism of strain for the material considered (or of phase change). If that proves to be the case, the change of mechanism will have to be taken into account in the model of behavior selected.

Other parameters can influence the structural mechanics behavior of a material, such as the water content (for certain polymers or the concretes) or the irradiation of which the effect on the behavior with very strong amount leads to swelling, an activation of creep and a hardening of steel. The influence of these parameters is generally integrated directly into the formulation of specific constitutive laws.

3 Bibliography

1. CURTIT F.: “Assessment of the constitutive laws material used in the studies of R & D and engineering relating to the principal components of park EDF” H-T24-2012-03041-FR

2.Jean LEMAITRE and Jean-Louis CHABOCHE; “Mechanical of the solid materials”; Editions DUNOD

3.Dominique FRANCOIS, Andre PINEAU and Andre ZAOUI; “Structural mechanics behavior of the materials”; Edition HERMES

4.[U2.04.03] “Choice of the behavior élasto- (visco) - plastic”

4 History of the versions of the document

Version Aster	Author (S) or contributor (S), organization	Description of the modifications
11.3	F. CURTIT EDF/R & D	initial Version resulting from document H-T24-2012-03041-FR