Mechanical behaviors for the digital simulations

Summary:

The behavior of material is an input datum impossible to circumvent in most mechanical studies. In a digital 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 actual material. The parameters controlling the model will have been adjusted as a preliminary starting from experimental data.

Very model being a simplified and inaccurate representation 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 whole 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 behaviour with isotropic work 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 advices to a user wishing to carry out calculations with non-linear behaviors of elastoplastic type or élasto-visco-plastic to choose a law adapted to modelings considered.

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1 Some recalls on the mechanical behavior

In mechanics, one can gather under the term “law of behavior” the models which govern the relation between the local states of constraint and deformation by possibly taking into account the former states.

Before speaking about laws of behavior, it seems useful to us to quickly point out the principal phenomena which one can meet in terms of behavior of materials, by focussing more particularly on the behavior of 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 [bib2] and [bib3].

1.1 Elasticity and plasticity

The simplest law of the behavior is the linear elasticity which corresponds to the capacity of material to regain its shape of origin when one removes the request the law of behavior which represents linear elasticity corresponds to a relation of proportionality between the constraints and the deformations. 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 constraints and the deformations 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 deformation gradually and one loses the relation of linearity between constraint and deformation.

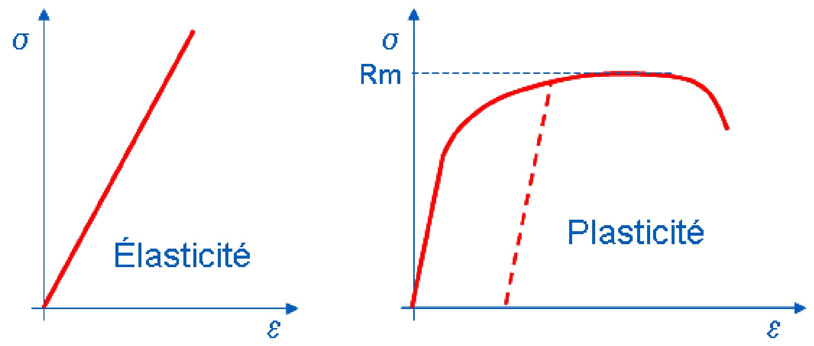


Figure 1.1-1 : Behaviors rubber band and plastic

1.2 Influence of the temperature

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

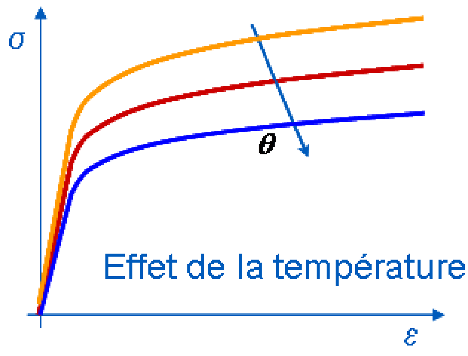


Figure 1.2-1 : Influence of the temperature

1.3 Viscosity

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

Viscosity appears in different ways according to the stress type applied. With a monotonous loading growing one will be interested in the module of work hardening according to the rate loading. One can also apply a level of deformation to material, then to observe the progressive decrease of the constraint with constant deformation. One speaks then about relieving. One can also impose a level of constraint and observe a progressive increase in the deformation with constant constraint. 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 at 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 worthless in the neighbourhoods of $350°C$ then it reappears and grows quickly beyond $450°C$.

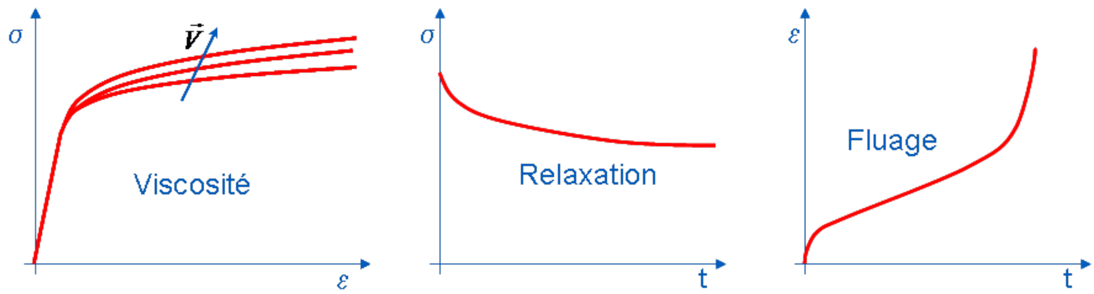


Figure 1.3-1 : Manifestation of viscosity according to the nature of the request

1.4 Cyclic behavior

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

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

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

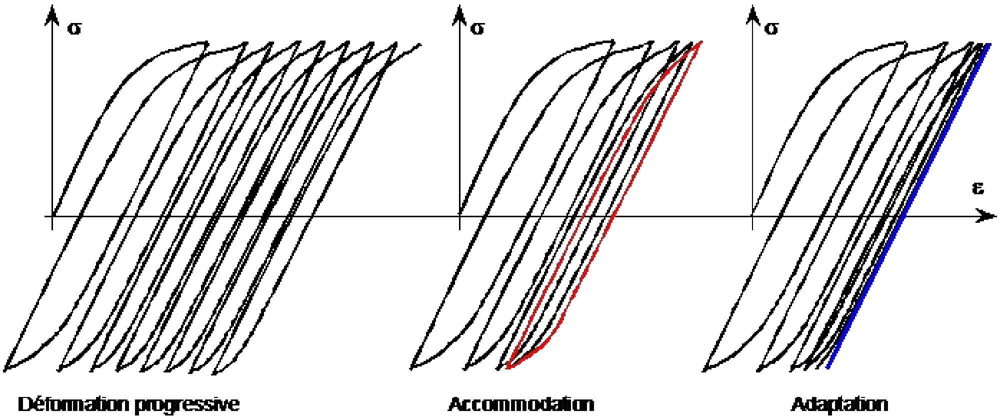


Figure 1.4-1 : Stabilization of the cyclic answer of material

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 work hardening. One can classify materials in two categories:

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

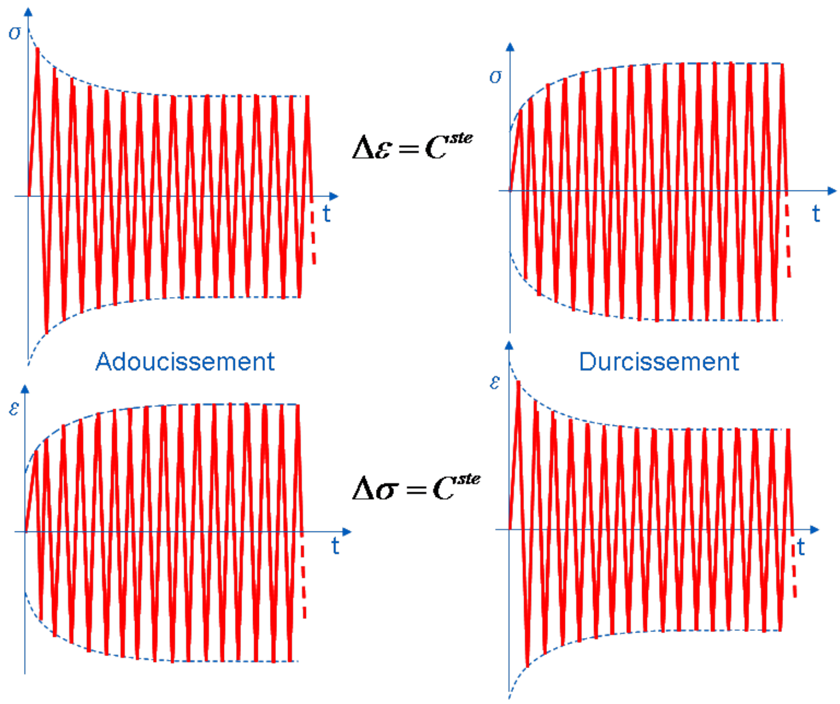


Figure 1.4-2 : Hardening and cyclic softening

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 answer of material.

If the material has viscosity, the response of material to a cyclic loading will be dependent the speed 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 material at rest a certain time before making the second loading, one observes sometimes a phenomenon of restoration.

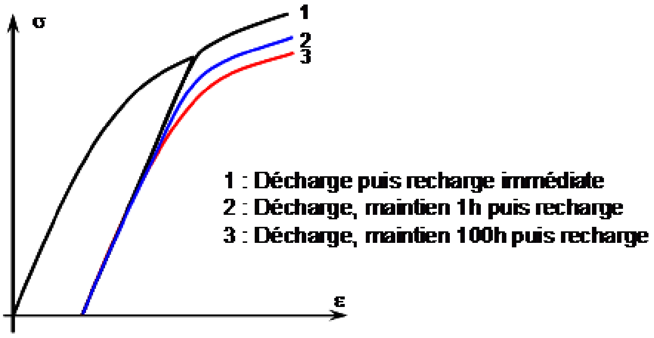


Figure 1.5-1 : The phenomenon of restoration

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

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

1.6 Ratchet effect

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

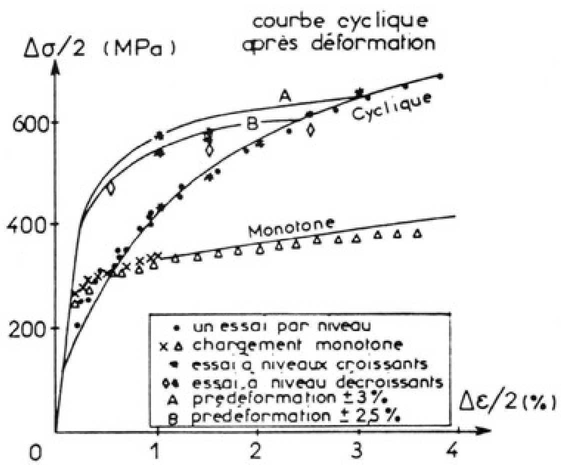


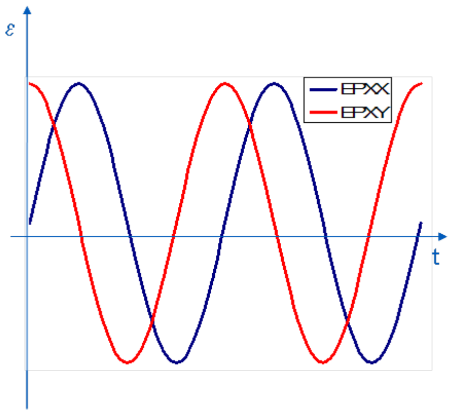
Figure 1.6-1 : The ratchet effect of work hardening

Figure 1.6-1 described the evolution of the amplitude of constraint according to the amplitude of deformation 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 work hardening of material up to a relatively important level of deformation then that one cycles with a weaker loading, the answer corresponds to a “hard” material more as the two curves A and B show it corresponding to different levels of pre-work hardening.

1.7 On-work hardening

The mechanical answer of 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-work hardening multi. This phenomenon is illustrated by the two following figures. One subjects a steel 316L test-tube to a combined loading of traction and alternate torsion (controlled in amplitude of deformation) with a dephasing of 90° between the two requests.

The reached levels of constraint (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 deformation.



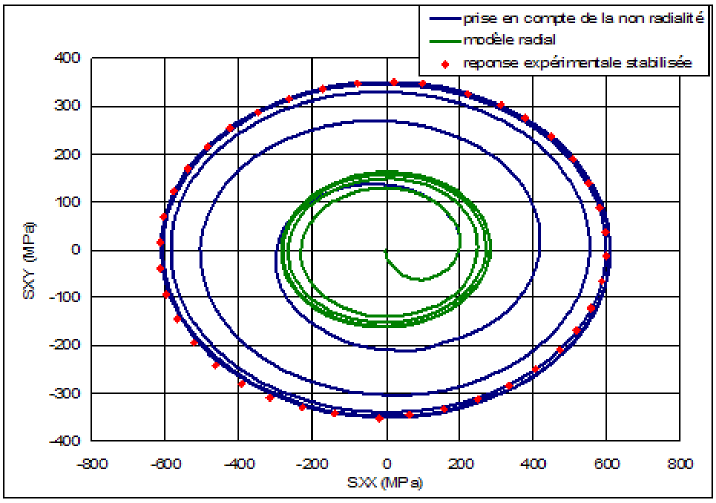


Figure 1.7-1 : Effect of on-work hardening under nonradial multiaxial loading

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

1.8 Isotropic and kinematic work hardening

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

If one places oneself within the space of constraints one can define a surface threshold inside which the material remains elastic. When the way of loading reaches this surface, one sees appearing plastic deformation 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 state of worthless stress) one speaks about isotropic work hardening (see Figure 1.8-1). Isotropic work hardening thus corresponds to a variation of size of the elastic range.

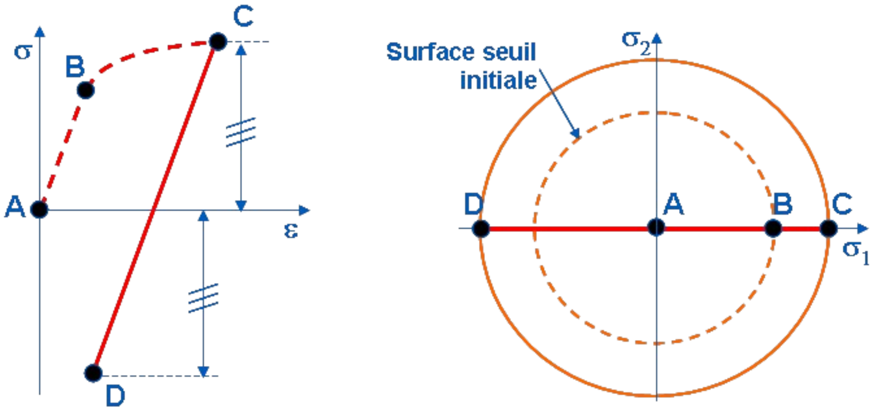


Figure 1.8-1 : Isotropic work hardening

For a loading of traction 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 traction.

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

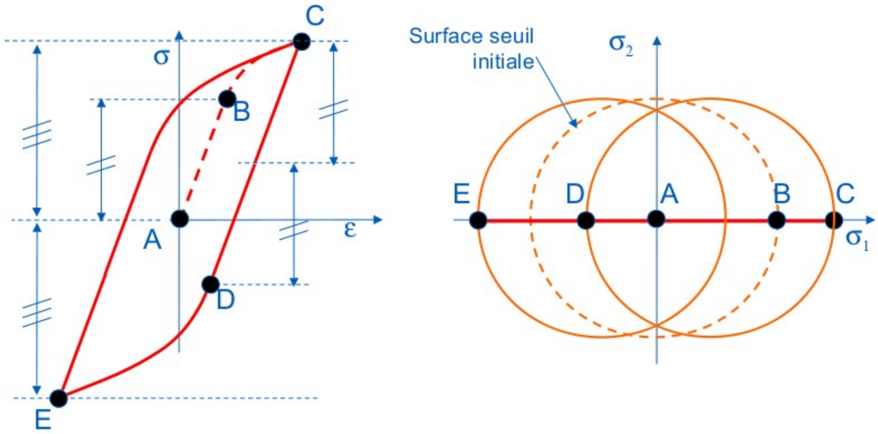


Figure 1.8-2 : Kinematic work hardening

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

2 Taking into account of the mechanical behavior in the digital simulations

In many cases a law of elastic behavior isotropic is sufficient, for example for a study of dimensioning for which one is generally satisfied to check that the maximum constraint does not exceed a value threshold (limit elastic, 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 anisothermes, it is enough to replace the scalar parameters E and ν by functions tabulées in temperature.

When it is necessary to take into account the plastic behavior of material, the simplest solution is to directly use an experimental uniaxial traction diagram which one will have beforehand tabulée in the form of an evolution of the constraint according to the deformation. In code Code_Aster the computer of the formulations such as `VMIS_ISOT_TRAC` allow at the time of the resolution 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 law of behavior since an experimental traction diagram directly is used. It is necessary however to keep in mind that these models implicitly integrate the assumption of a purely isotropic behavior of material.

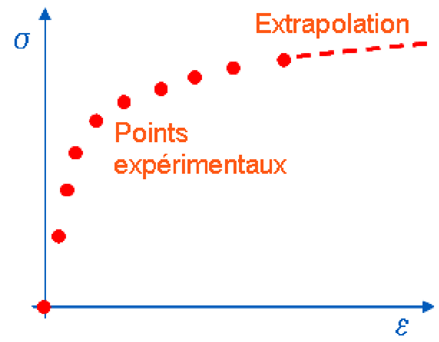


Figure 2-1 : Use of a traction diagram like model of behavior

Although the actual materials generally present a kinematic share of work hardening, the approximation by a purely isotropic behavior is not necessarily penalizing, provided the way of loading in any point of the 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 behaviour in work hardening is purely kinematic 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 the 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 will predict an elastic answer until a compressive stress equivalent to the maximum constraint of traction reached previously (the answer of the model is represented by a curve in continuous feature on the figure). The real answer of material is represented in dotted feature. If the actual material is purely kinematic, it is noted that the entry in plasticity in compression occurs much earlier than than envisages the isotropic model of behavior, and than the difference between the calculated constraint and the real constraint can be significant.

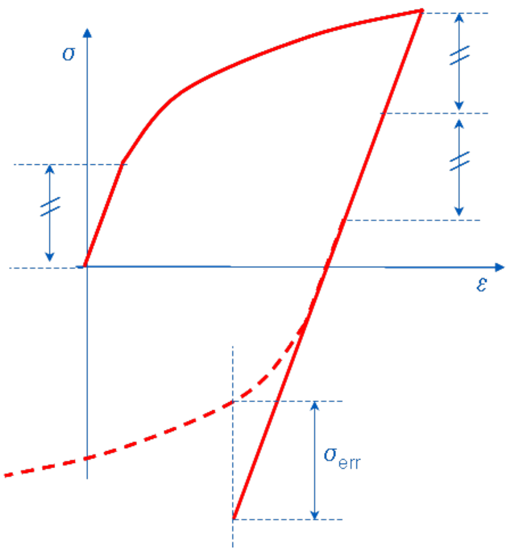


Figure 2-2 : Difference between isotropic behavior and real behavior

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 kinematic, 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 the structure. It is thus desirable to make a checking on the whole of the stress field throughout simulation.

Simulations anisothermes are relatively simple with this kind of setting in data. One provides to the code computer several diagrams traction 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 law of behavior being based on a mathematical formulation (generally in the form of differential equation).

Several stages are then necessary before carrying out the digital 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 objective covering the field of request as well as possible undergone by the structure (while supplementing by complementary tests if necessary).
3) One carries out then the identification of the parameters of the model so that the digital answer is possible nearest experimental results.

It is frequent to avoid all the process of identification when one has of a law and a set of parameters obtained in a comparable study on 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 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 law which one wishes to use.

As illustration one compares knownr la Figure 2-3 ways of loadings experimental and simulated for cyclic loadings at various levels of amplitude. The law of behavior 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 *has* priori with the field of validity of the law in terms of amplitude of deformation.
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 law of behavior seems relevant in spite of a light extrapolation.
The test with $\pm 0{,}4\%$ is located in the field of validity. The interpolation enters the results to $\pm 0{,}3$ 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 constraint.

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

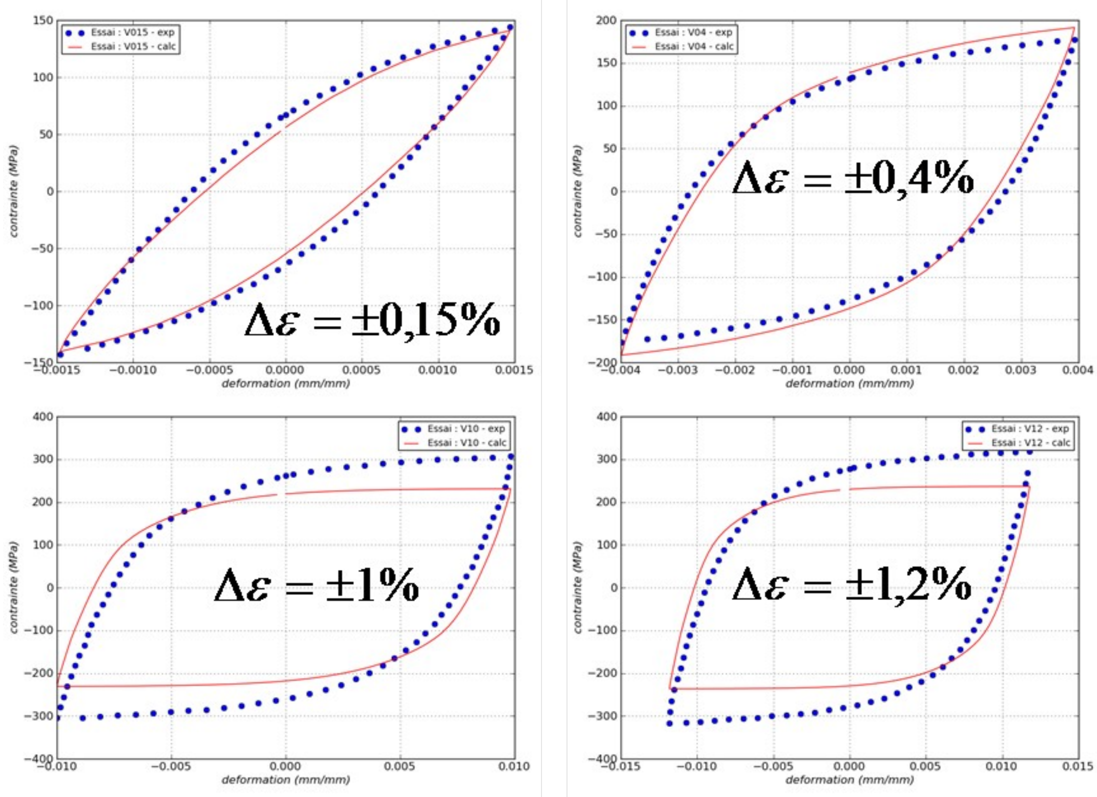


Figure 2-4 : Estimate of the robustness of a law of behavior in the event of extrapolation out of its field of validity.

For simulations anisothermes, several strategies are possible.

Simplest consists in having a law of isothermal behavior 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 law then will integrate the behavior on the basis of interpolated parameter. 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 law of behavior. 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 anisotherme to make sure that the beach of covered temperature does not comprise change of mechanism of deformation for material considered (or of phase shift). 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 mechanical 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 laws of behavior.

3 Bibliography

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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