Modeling of the cables of prestressing

Summary

To improve resistance of certain structures of civil engineer, prestressed concrete is used: for that, the concrete is compressed using cables of prestressed out of steel. In *Code_Aster*, it is possible to do calculations of such structures: the cables of prestressing are modelled, that is to say by elements BAR with two nodes is by elements CABLE_GAINE with 3 nodes, which are then kinematically related to the elements of volume or plate which constitute structural the concrete part. To carry out this calculation, there exist three orders specific to these cables of prestressing, DEFI_CABLE_BP who allows geometrically to define the cable and the conditions of setting in tension, AFFE_CHAR_MECA, operand RELA_CINE_BP, which makes it possible to transform the information calculated by DEFI_CABLE_BP in loading for the structure, and CALC_PRECONT who allows the application of prestressing on the structure.

Principal specificities of the modeling based on the elements BAR or CABLE_GAINE in the adherent case are the following ones:

- The profile of tension along a cable can be calculated (I) either according to regulation BPEL 91 [bib1] by taking account of the retreat of anchoring, of the loss by rectilinear and curvilinear friction, of the relieving of the cables, the creep and the shrinking of the concrete, (II) or according to regulation ETC-C while holding of the retreat of anchoring, of the loss by friction and relieving of the cables. In these two cases, the connection cables/concrete is supposed to be perfect, with the image of the sheaths injected by a coulis.
- It is possible to define a zone of anchoring (instead of a point of anchoring) in order to attenuate the singularities of constraints due to the application of the tension on only one node of the cable (effect of modeling).
- The behavior of the cables is elastoplastic, thermal dilation being able to be taken into account.
- Thanks to the operator CALC_PRECONT, one can simulate the phasage of the setting in tension of the cables and the setting in tension can be done in several steps of time in the event of appearance of non-linearities. Lastly, the final tension in the cable is strictly equal to the tension prescribed by the BPEL.
- The cables being modelled by finite elements, their rigidity remains active throughout the analyses.

Principal specificities of the modeling based on the elements CABLE_GAINE, in the cases not-members are the following ones:

- It is possible to model adherent connections cable-concrete, slipping or rubbing.
- In the adherent case, it is the profile of tension calculated according to the BPEL91 which is imposed; in the rubbing and slipping cases, the profile is obtained by simulating the setting in tension of the cable and possibly the retreat of anchoring. The other types of loss cannot be taken into account.

Operators DEFI_CABLE_BP and CALC_PRECONT are compatible with all the types of mechanical finite elements voluminal and the elements of plate (DKT, Q4GG) for the description of the concrete medium crossed by the cables of prestressed and the setting in tension.

Contents

1 Preliminaries

Certain structures of civil engineer are made up not only of concrete and passive steel reinforcements, but also of cables of prestressings. The analysis of these structures by the finite element method then requires to integrate not only the geometrical and material characteristics of these cables but also their initial tension.
The operator `DEFI_CABLE_BP` was conceived according to the regulations of the regulation BPEL 91 which makes it possible to define the contractual tension of way. The mechanisms taken into account by this operator are then the following:

- the setting in tension of a cable by one or two ends,
- the loss of tension due to the frictions developed along the rectilinear and curvilinear ways,
- the loss of tension due to the retreat of anchoring,
- the loss of tension due to the relieving of the cable,
- the loss of tension due to the shrinking and the creep of the concrete.

It is also possible to use the regulations of the ETC-C to define the tension. In this case, the mechanisms taken into account are the following:

- the setting in tension of a cable by one or two ends,
- the loss of tension due to frictions and on-line losses,
- the loss of tension due to the retreat of anchoring,
- the loss of tension due to the relieving of the cable.

Lastly, one can obtain the tension in the cable by a mechanical calculation by using modeling `CABLE_GAINE` and the law `CABLE_GAINE_FROT` who takes as a starting point the `BPEL 91`. In this case, the mechanisms taken into account are the following:

- the setting in tension of a cable by one or two ends,
- the loss of tension due to the frictions developed along the rectilinear and curvilinear ways,
- the loss of tension due to the retreat of anchoring.

The cables are modelled by elements `BAR` with two nodes or by elements `CABLE_GAINE` with 3 nodes, which implies to adopt a layout approached in the case of the layouts in curve. This can be made with more close to reality without major restriction (the nodes of cables must be inside the volume of the concrete elements) taking into consideration grid to the elements to the concrete. Structural the concrete part can be modelled thanks to any type of voluminal element $2D$ and $3D$ or with the elements plates `DKT`. The operator `DEFI_CABLE_BP` the possibility has of creating conditions kinematics between the nodes of elements `BAR` and elements $2D$ or $3D$ who do not coincide in space. This has the advantage of simplifying the creation of the grid and of leaving free choice to the user in terms of provision of the elements and their number. For the elements `BAR` and elements `CABLE_GAINE` in the adherent case, the connection cables of prestressed/concrete is of perfect type, without possibility of relative slip. In the other cases, the cable can slip into its sheath. The operator also allows to define a cone of diffusion of the constraints around anchorings (only if the cable is adherent) in order to limit to it the stress concentrations much higher than reality and which are due to modeling.

The second principal function of the operator `DEFI_CABLE_BP` is to evaluate the profile of the tension along the cables of prestressed by considering the technological aspects of their implementation. At the time of the installation of the cables, prestressing is obtained thanks to the hydraulic actuating cylinders placed at one or two ends of the cables. The profile of tension along a cable is affected by friction (rectilinear and/or curvilinear), by the deformation of the surrounding concrete, the retreat of anchorings at the ends of the cables and by the relieving of steels.
This tension can then be taken into account like an initial state of stress at the time of the resolution of the problem complete finite element. The problem, it is that in this case, under the effect of the tension of the cable, the concrete unit and cable are compressed involving a reduction in the tension of the cable. To avoid this problem and to have exactly the tension prescribed by the BPEL or the ETC-C in the structure in balance, the tension must be applied by the means of the macro-order

CALC_PRECONT. In more thanks to this method, it is possible to make phasage on the setting in tension of the cables or to impose the loading in several steps of time, which can be interesting if the behavior of the concrete becomes non-linear as of the phase of setting in tension of the cables.

In the cases slipping and rubbing element CABLE_GAINE, profile of tension calculated by DEFI_CABLE_BP is not used. The setting in tension is obtained by a calculation finite elements by always using the macro-order CALC_PRECONT.

2 The operator DEFI_CABLE_BP

2.1 Evaluation of the characteristics of the layout of the cables

2.1.1 Cubic interpolation by spline

We present here the method used to obtain a geometrical interpolation of the cables, which is essential to precisely calculate the curvilinear X-coordinate and the angle α used in the formulas of loss of prestressing.
One starts by building an interpolation of the trajectory of the cable (in fact an interpolation of two projections of the trajectory in the two plans Oxy and Oxz), then starting from these interpolations, one considers the X-coordinate curvilinear, and the angular deviation cumulated, according to the formulas:

$$s(x)=\int_0^x \sqrt{1+y'^2(x)+z'^2(x)}\,dx \quad \text{éq 2.1-1}$$

$$\alpha(x)=\int_0^x \frac{\sqrt{y''^2(x)+z''^2(x)+\left[y''(x)z'(x)-y'(x)z''(x)\right]^2}}{1+y'^2(x)+z'^2(x)}\,dx \quad \text{éq 2.1-2}$$

In order to preserve the topology of the cable (and in particular the scheduling of the nodes which composes it) the operator `DEFI_CABLE_BP` work starting from meshs and of groups of meshs, (rather than of nodes and groups of nodes), in order to be able to calculate the sizes while following the sequence of the nodes along the cable.
The interpolation used for the calculation of prestressing in the concrete will be a cubic Spline interpolation carried out in parallel on the three space coordinates according to the curvilinear X-coordinate. The coordinates of the nodes of the cable are the “real” coordinates, i.e. the coordinates defined by the grid of the cable.

All the calculations presented within the framework of the operator `DEFI_CABLE_BP` are defined starting from the real geometry of the structures and the real positions of the nodes. Calculations of tension to the nodes will be carried out nodes in nodes, in the order given by the topology of the grid, starting from the formulas quoted above [éq 2.1-1] and [éq 2.1-2].
The calculation of the cumulated angular deviation and the curvilinear X-coordinate requires the precise calculation of the derivative of the trajectory of the cable defined in the operator in a discrete way by the position of the nodes of the grid of cable. The polynomials of Lagrange have instabilities, in particular for irregular grids. Moreover, one significant number of points of discretization will lead to polynomials of high degrees. In addition a small uncertainty on the coefficients of interpolation will have as a consequence an important error on the results, in term of derivative. By choosing a polynomial interpolation of small degree, one will obtain derivative second worthless or not continuous (according to the degree).
The interest of a cubic interpolation of Spline type is to obtain drifts second continuous and costs of calculations of order n , if n is the number of points of the function tabulée to interpolate, with polynomials of small degree. The principle of this method of interpolation is described exclusively in the case of a function of the form $x\rightarrow f(x)$.
One supposes that one carries out an interpolation of the tabulée function, starting from the values of the function at the points of discretization $x_1, x_2, \ldots, x_n$, and of its derivative second. One can thus build a polynomial of order 3, on each interval x_i, x_{i+1} , of which the polynomial expression is the following one:

$$y=\frac{x_{j+1}-x}{x_{j+1}-x_j}y_j+\frac{x-x_j}{x_{j+1}-x_j}y_{j+1}+Cy_j''+Dy_{j+1}''$$

with:

$$C=\frac{1}{6}\left[\left(\frac{x_{j+1}-x}{x_{j+1}-x_j}\right)^3-\left(\frac{x_{j+1}-x}{x_{j+1}-x_j}\right)\right]\left(x_{j+1}-x_j\right)^2$$

$$D=\frac{1}{6}\left[\left(\frac{x-x_j}{x_{j+1}-x_j}\right)^3-\left(\frac{x-x_j}{x_{j+1}-x_j}\right)\right]\left(x_{j+1}-x_j\right)^2$$

One can check easily that:

$$y(x_j)=y_j \quad \text{et} \quad y''(x_j)=y_j''$$
$$y(x_{j+1})=y_{j+1} \quad \text{et} \quad y''(x_{j+1})=y_{j+1}''$$

It is then necessary to estimate the values of the derivative second with the points of interpolation. By writing the equality of the interpolations on the intervals $[x_{i-1}, x_i]$, and $[x_i, x_{i+1}]$ derivative of order one, at the point x_i, the following expression is obtained:

$$\frac{x_j-x_{j-1}}{6}y_{j-1}''+\frac{x_{j+1}-x_{j-1}}{3}y_j''+\frac{x_{j+1}-x_j}{6}y_{j+1}''=\frac{y_{j+1}-y_j}{x_{j+1}-x_j}-\frac{y_j-y_{j-1}}{x_j-x_{j-1}}$$

One obtains thus $(n-2)$ equations connecting the values of the derivative second to the points of discretization $x_1, x_2, \ldots, x_n$. By writing the boundary conditions in x_1 and x_n on the values of the derivative second, one obtains a system (n, n) which one can determine in a single way the value of all the derivative, and thus obtain the function of interpolation. Two solutions arise then for the establishment of the boundary conditions:

- to arbitrarily fix the value of the derivative second at the points x_1, and x_n, to zero for example,
- to allot the actual values of the derivative second in these points, if this data is accessible.

One obtains a system of equations having for unknown factors them n derived seconds from the function tabulée to interpolate. This linear system has the characteristic to be tri-diagonal, which means that the resolution is about $O(n)$. In practice the interpolation breaks up into two stages:

- the first consists in calculating the values estimated of the derivative second with the points, operation which is carried out only once,
- the second consists in calculating, for a value given of x, the value of the interpolated function, operation which can be repeated as many times as one wish it.

Tests carried out on the function sine, three periods, show that the results are strongly dependent amongst points, as well as distribution of the points of the curve to be interpolated, (expected result), but that even in delicate situations (few points and very irregular curve) the interpolation does not diverge. In other words, even if the correlation concerning the trajectory of the cable is not the very good (interpolation with very few points) interpolation is roughly located in a fork close to the real trajectory. This case will not arise in practice, but makes it possible to check the stability of the method of interpolation.

For the problem that we consider here, one cannot always write the trajectory of the cable in the form $[y(x)],[z(x)]$, whenever this curve is not bijective, in particular when projection of the trajectory in one of the two plans Oxy or Oxz cyclic or is closed (case of a circular concrete structure).

By taking an intermediate variable of the type $u=\int |x'|$, parameter always growing and of increase identical in absolute value to that in variable x , one can bring back oneself to expressions $[y(u)]$ bijective functions of the variable u . The cubic interpolation Spline described above is then applicable to the function $y(u)$ (like with the function $z(u)$). In practice, that led however to problems of connections of tangent (angular points) at the points where the variable x change direction of variation, and with specific irregularities.

One describes the trajectory of the cable like a parametric curve. Knowing a set of points of the curve, the parameter most easily accessible is then the curvilinear X-coordinate. One writes the trajectory of the cable in the form $[x(p), y(p)]$, in the plan Oxy , (respectively $[x(p), y(p), z(p)]$ in a space with three dimensions).

The cumulated cord p discretized at the tabulés points of the function which one interpolates $P^1, P^{2,}..., P^n$ is calculated in the following way:

$p(1)=0$ at the point P^1 ,
$p(k)=p(k-1)$ + distance $(P^{k-1}P^k)$ at the point P^k

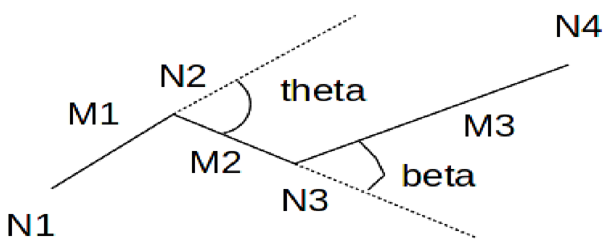
One thus has two curves defined by a set of couple [X (I), p (I)] and [there (I), p (I)] which one can directly apply the cubic Spline interpolation presented before, and which makes it possible to be freed from the difficulties encountered previously. The interpolation is made for the two coordinates, (or three coordinates, in dimension 3), independently one of the other.

2.1.2 Method without interpolation

It is possible to simply calculate the curvilinear X-coordinate and the angle α without making interpolation. This method is obviously less precise but it is very robust. Moreover, more the grid is fine, plus its precision increases. However the problems involved in the interpolation by spline precisely occur when the grid is too fine compared to the irregularities which it contains.
This method without interpolation is used when the interpolation by spline failed (see 2.1.3).

The calculation of the curvilinear X-coordinates is very simple. It consists in summoning the length of the meshs of cables.

Calculation of the cumulated angular deviation:



The following example is enough to describe the calculation of the angular deviation by this method. Meshs M_1
, M_2 and M_3 constitute a cable. N_1 is the first node of the cable, the value of its cumulated angular deviation is $\alpha=0$. The angle $theta$ is the angular deviation between the meshs M_1 and M_2 .
In any point of $]N_1 N_2[$ the cumulated angular deviation is always worthless because the tangent vector with the curve in these points is $\overrightarrow{N_1 N_2}$. In any point of $]N_2 N_3[$, the cumulated angular deviation is equal to $theta$ because the tangent vector each one of these points is $\overrightarrow{N_2 N_3}$ ($theta$ is the angle enters $\overrightarrow{N_1 N_2}$ and $\overrightarrow{N_2 N_3}$). It was decided, that the tangent vector with the curve in N_2

is the average of $\overrightarrow{N_1 N_2}$ and $\overrightarrow{N_2 N_3}$. What gives that the angular deviation cumulated in N_2 is $\alpha = \frac{theta}{2}$.

With same logic, the angular deviation cumulated in N_3 is $\alpha = theta + \frac{beta}{2}$, and $theta + beta$ in N_4.

2.1.3 Control of the interpolation by spline

In order to control if the interpolations by spline for the three coordinates of space are correct, one calculates the number of changes of variation of the derivative first and the number of changes of sign of the derivative second. If the number of changes of sign is smaller than the number of changes of variation (+ a whole constant fixed at 10), it is considered that the interpolation is of good quality. In the contrary case, one passes to the method without interpolation.

2.2 Determination of the profile of tension in the cable according to BPEL 91

2.2.1 General formula

The operator `DEFI_CABLE_BP` allows to calculate the tension $F(s)$ along the curvilinear X-coordinate s cable. This one is given starting from the rules of the BPEL 91 [bib1].
All in all, one leads to the following formulation:

$$F(s) = \tilde{F}(s) - \left\{ x_{flu} \times F_0 + x_{ret} \times F_0 + r(j) \times \frac{5}{100} \times \rho_{1000} \left[\frac{\tilde{F}(s)}{S_a \times \sigma_y} - \mu_0 \right] \times \tilde{F}(s) \right\} \quad \text{éq 2.2.1-1}$$

where s indicate the curvilinear X-coordinate along the cable. The parameters introduced into this expression are:

- F_0 initial tension,
- x_{flu} standard rate of loss of tension by creep of the concrete, compared to the initial tension,
- x_{ret} standard rate of loss of tension by shrinking of the concrete, compared to the initial tension,
- ρ_{1000} relieving of steel at 1000 hours, expressed in %,
- S_a surface of the cross-section of the cable,
- σ_y elastic ultimate stress of steel,
- μ_0 adimensional coefficient of relieving of prestressed steel.

In this formula, F_0 indicate the initial tension with anchorings (before retreat), $\tilde{F}(s)$ represent the tension after the taking into account of the losses by friction and retreat of anchoring, $x_{flu} \times F_0$ represent the loss of tension by creep of the concrete, $x_{ret} \times F_0$ the loss of tension by shrinking of the concrete, $r(j) \times \frac{5}{100} \times \rho_{1000} \left[\frac{\tilde{F}(s)}{S_a \times s_y} - m_0 \right] \times \tilde{F}(s)$ losses by relieving of steels.

Note:

The introduction into these elements of losses of tension is optional. Thus, if one plans to do a calculation of creep and/or shrinking of the concrete by using a suitable law with `STAT_NON_LINE`, one should not introduce these elements into the losses calculated by `DEFI_CABLE_BP`.

The evaluation of the losses requires the knowledge of the curvilinear X-coordinate s and of the cumulated angular deviation α calculated as from the derivative first and second of the trajectory of the cable. The precise calculation of these derivative requires an interpolation between the points of passage of the cable. This interpolation is carried out using Splines, better than the polynomials of Lagrange which have instabilities, in particular for irregular grids (cf preceding paragraph).
In what follows each mechanism intervening in the calculation of the tension is detailed.

2.2.2 Loss of tension by friction

We start by calculating the tension along the cable by taking account of the losses per contact between the cable and the concrete: $F_c(s)=F_0 \exp(-f\,\alpha-\phi\, s)$
where α indicate the cumulated angular deviation and the introduced parameters are:

- f coefficient of friction of the cable on the partly curved concrete, in rad^{-1},
- φ coefficient of friction per unit of length, in m^{-1},
- F_0 tension applied to one or the two ends of the cable.
-

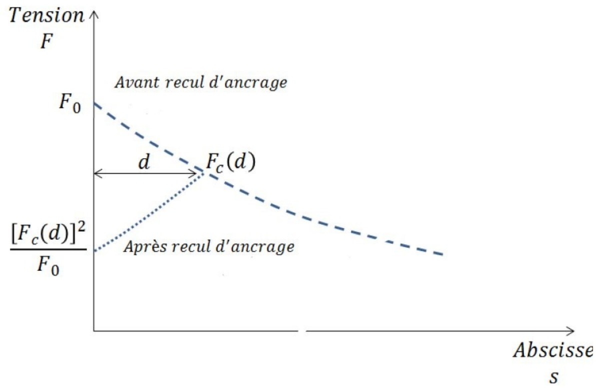
2.2.3 Loss of tension by retreat of anchoring

To take into account the retreat of anchoring, the following reasoning is made:
the tension along the cable is affected by the retreat of anchoring at a distance d that one calculates by solving a problem with two unknown factors: the function $F^*(s)$ who represents the force after retreat of anchoring and the scalar d :

$$\Delta=\frac{1}{E_a S_a}\int_0^d [F(s)-F^*(s)]\,ds \;,$$

$F(s)$ is worth $F_0 e^{(-f\alpha-\varphi s)}$

Δ is the value of the retreat of anchoring (it is a data)



$F^*(s)$, the force after retreat of anchoring, is given starting from the formula [bib1]:

$$[F(s).F^*(s)]=[F(d)]^2 \;,$$

The length d will be given in an iterative way thanks to the preceding integral. Other authors use different relations such as:

$$[F(s)-F(d)]=[F(d)-F^*(s)]$$

For the calculation of d , three typical cases can arise:

1) This loss by retreat of anchoring is localised in the zone of anchoring. If the cable is curved, and the sufficiently short length of the cable, it can happen that d that is to say larger than the length of the cable. In this case, the loss of prestressing due to the retreat of anchoring applies everywhere. It is necessary to calculate the surface ranging between the two curves $F(s)$ and $F^*(s)$, which must be equal to $E_a S_a \Delta$, and which thus makes it possible to calculate $F^*(s)$.

2) If a tension is applied to each of the two ends of the cable, let us call $F_1(s)$ the distribution of initial tension calculated as if the tension were applied only to the first anchoring, and $F_2(s)$ the distribution of initial tension calculated as if the tension were applied only to the second anchoring. The value which must be retained in any point of the cable as initial tension is $F(s)=Max(F_1(s), F_2(s))$.
3) Lastly, if *D* is larger than the length of the cable, and when a tension is applied to each of the two ends of the cable (superposition of the two preceding cases), one must apply the following procedure:
   - calculation of $F_1(s)$ calculated initial tension as if the tension were applied only to the first anchoring and by taking account of the retreat of anchoring (as in typical case 1),
   - calculation of $F_2(s)$ calculated initial tension as if the tension were applied only to the second anchoring and by taking account of the retreat of anchoring (as in typical case 1),
   - calculation of $F(s)=Min\left(F_1(s), F_2(s)\right)$.

2.2.4 Deformations differed from steel

The loss by relieving of steel, for an infinite time, is expressed in the following way:

$$r(j)\times\frac{5}{100}\times\rho_{1000}\left[\frac{\tilde{F}(s)}{S_a\times\sigma_y}-\mu_0\right]\times\tilde{F}(s)$$

(ρ_{1000} relieving with 1000 hour in %; μ_0 the coefficient of relieving of prestressed steel and σ_y the guaranteed value of the maximum loading to the rupture of the cable).
This relation expresses the loss by relieving of the cables for an infinite time. The BPEL 91 proposes the following formula: $r(j)=\frac{j}{j+9.r_m^0}$ where j indicate the age of the work in days and r_m^0 a ray characteristic obtained by submitting the report of the section of the concrete structure, in m^2 , by the perimeter of the section (in meters) of concrete.

2.2.5 Loss of tension by instantaneous strains of the concrete

The instantaneous losses are not taken into account in the formula [éq 2.2.1-1] used in *Code_Aster*. What the BPEL calls loss of instantaneous tension is in fact the loss of tension induced in cables already posed by the installation of a new group of cables. To model this phenomenon, it is necessary to represent the phasage of setting in prestressed in Code_Aster calculation, i.e. not to tighten the whole of the cables at the same time but in a successive way by connecting them `CALC_PRECONT` (see test SSNV164).

2.3 Determination of the profile of tension in the cable according to the ETC-C

2.3.1 General formula

The operator `DEFI_CABLE_BP` allows to calculate the tension $F(s)$ along the curvilinear X-coordinate s cable according to the rules of the ETC-C [bib4].

The theoretical formula is the following one:

$F(s)=F_0-\Delta F_{\mu}-\Delta F_{anc}-\Delta F_{el}-\Delta F_r-\Delta \epsilon_{cs}-\Delta \epsilon_{cc}$
where:
- F_0 is the initial tension applied to the cable

- ΔF_{μ} are the losses of tension by friction,
- ΔF_{anc} are the losses of tension due to the retreat of anchoring,
- ΔF_{el} are the losses of tension due to the elastic strain of the concrete,
- ΔF_{r} are the losses of tension due to the relieving of steels,
- ΔF_{cs} are the losses of tension due to the shrinking of the concrete,
- ΔF_{cc} are the losses of tension due to the creep of the concrete.

The losses due to the elastic strain are estimated according to the ETC-C at:

$$\Delta F_{el}(s)=\frac{A_p E_p \Delta \sigma_c(x)}{2E}$$

with E Young modulus of the concrete, A_p and E_p the section and Young the modulus of steel, and $\Delta \sigma_c(x)$ the constraint induced in the concrete by prestressing.
They can be estimated by simulating the phasage of the setting in prestressed thanks to the operator CALC_PRECONT. These losses are not taken into account in the operator DEFI_CABLE_BP.

Losses of tension due to the shrinking of the concrete ΔF_{cc} and with the creep of the concrete ΔF_{cs} , can be obtained by imposing an equivalent field of deformation after the setting in tension of the cables. Still, they are thus not taken into account in the operator DEFI_CABLE_BP.

With final, the formula established in DEFI_CABLE_BP is the following one:

$$F(s)=F_0-\Delta F_{\mu}-\Delta F_{anc}-\Delta F_r \qquad \text{éq. 2.3.1-1}$$

The 3 types of loss are detailed in the paragraphs below.

2.3.2 Losses of tension by friction

In accordance with the ETC-C, the losses by friction are estimated by the following formula:

$$F_c(s)=F_0\left(1-e^{-\mu(\alpha+k\ s)}\right) \qquad \text{[éq. 2.3.2-1]}$$

where α indicate the cumulated angular deviation and the introduced parameters are:

- μ coefficient of friction of the cable on the concrete E
- k the loss ratio on line $[m^{-1}]$
- F_0 tension applied to one or the two ends of the cable.
-

2.3.3 Losses of tension by retreat of anchoring

The formula is identical to the BPEL. To refer to the §2.2.3.

2.3.4 Losses due to the relieving of steel

The formula given by the ETC-C is the following one:

$$\Delta F_r(s)=0{,}8\times0{,}66\,\rho_{1000}.\exp^{9{,}1\,\tilde{F}(s)/F_{prg}}.\left(\frac{nh}{1000}\right)^{0{,}75(1-\tilde{F}(s))/F_{prg}}.10^{-5}\,\tilde{F}(s) \qquad \text{éq 2 3.4-1}$$

where:

- s indicate the curvilinear X-coordinate along the cable.
- ρ_{1000} relieving of steel at 1000 hours, expressed in %,
- F_{prg} constraint with rupture in steel,

- nh the number of hours after the setting into prestressed corresponding to the date or the losses by relieving of steel are calculated.

In this formula, $\tilde{F}(s)$ represent the tension after the taking into account of the losses by friction and retreat of anchoring like normally after taking into account of the elastic losses.

Two options of calculation are proposed corresponding to the choice `TYPE_RELAX=' ETCC_DIRECT'` or `TYPE_RELAX=' ETCC_DIRECT'`.

If the user chooses the option `TYPE_RELAX=' ETCC_DIRECT'`, then the tension used to calculate the loss due to the relieving of steels does not take into account the elastic losses but only the losses by friction and retreat of anchoring.

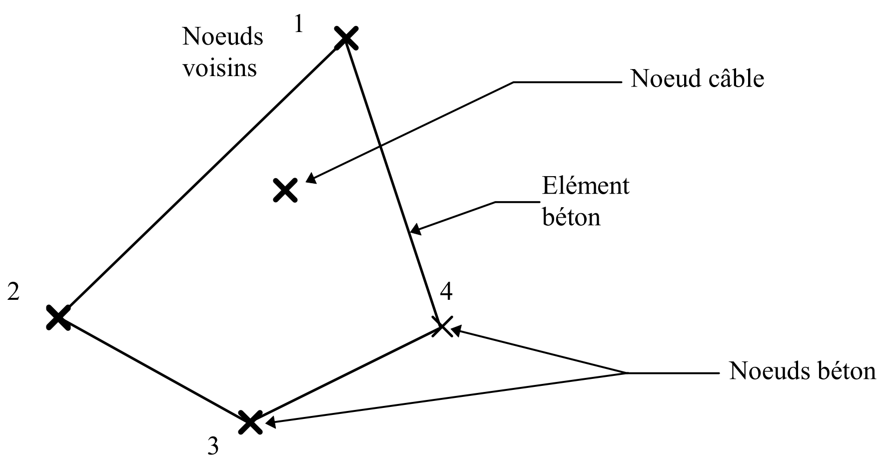
If the user chooses the option `TYPE_RELAX=' ETCC_REPRISE'`, then the tension used to calculate the loss due to the relieving of steels takes the 3 types of losses of prestressed into account. This tension must be provided by the user (keyword `TENSION_CT` under `DEFI_CABLE`). It will have been obtained during the first calculation that one can qualify state with "short-term" by modelling the losses, by friction, retreat of anchoring and the elastic losses per modeling of the phasage (cf test SSNV229B for example of implementation).

2.4 Determination of the relations kinematics between steel and concrete

Since the nodes of the grid of cable do not coincide inevitably with the nodes of the concrete grid, it is necessary to define relations kinematics modelling perfect adhesion between the cables and the concrete.
The following paragraphs describe in the order the space geometrical considerations making it possible to define the concept of vicinity between the nodes of elements of cable and concrete, then the method of calculating of the coefficients of the relations kinematics.

2.4.1 Definition of the close nodes

The calculation of the coefficients of the relations kinematics requires to determine the nodes "close" to each node of the grid of the cable. The diagram which follows symbolizes a node cables and a mesh concrete:



The mesh defined by the nodes $1,2,3,4$ the node contains cables. The close nodes are thus the tops $1,2,3,4$. If the node cable is located inside an element at p nodes $P_1, P_2, \ldots, P_n$, then nodes $P_1, P_2, \ldots, P_n$ "nodes close" to the node are called cables.
One treats in the same way, the elements of plate without offsetting, and the solid elements. The calculation of the offsetting of each node of the grid cable is necessary for the calculation of the coefficients of the relations kinematics.

In the case of elements of plate, when the node cable is characterized by a offsetting not no one, one defines the nodes close as the unit to the nodes top of the element which contains the projection of the node cables in the tangent plan with the grid concrete. If the node cables (or well its projection in the tangent plan with the grid concrete) belongs to a border of an element, in fact the tops of this border form the whole of the close nodes.

2.4.2 Calculation of the coefficients of the relations kinematics

In the whole of descriptions which follow the sizes are systematically expressed in the total reference mark of the grid. The connections kinematics are thus expressed according to the degrees of freedom expressed in this base. The normals and vectors rotation are expressed in the total reference mark, except explicit contrary mention.
In modeling finite elements of the structure cable-concrete, the displacement of a material structural concrete point can be expressed easily using the functions of form of the element or mesh concrete whose tops form the close nodes, according to displacements of the nodes close to the discretization “concrete”. In the same way, a size or a displacement of a point of the cable, (or of its projection on the tangent level of the grid concrete) is identical to the value of this size at the material structural concrete point which occupies this same position (perfect connection between the concrete and steel), and is thus expressed according to the value of this same size at the tops of the element, using the functions of form.
If (x, y, z) are the coordinates of the node cables, or those of its projection, and $N_1, N_2, \ldots, N_n$ functions of forms associated with the nodes concrete $P_1, P_2, \ldots, P_n$ tops of an element of the grid concrete (or tops of a border of an element of the grid concrete), and (x_i, y_i, z_i) coordinates of the node i , then the interpolation of a variable u on the element is written:

$$u(x, y, z)=\sum_{i=1}^{n} N_i(x, y, z).u(x_i, y_i, z_i)=\sum_{i=1}^{n} N_i(x, y, z).u_i$$

u being able to be a coordinate, or any other nodal data.
The connections kinematics make it possible to express the identity of displacement between the node of the grid cables, and the material point concrete which occupies the same position. This corresponds to the assumption of a perfect connection between the concrete and the cable.

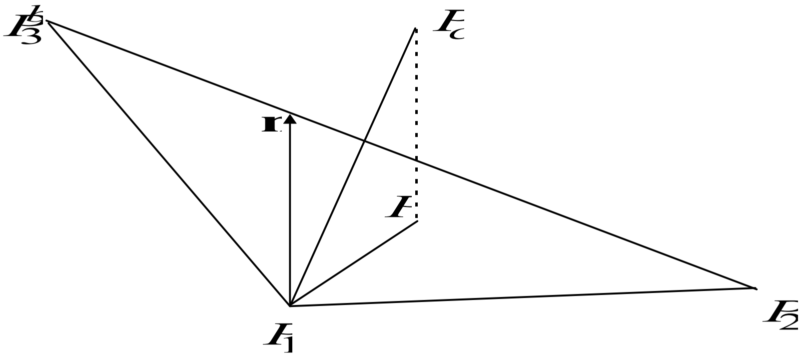
2.4.2.1 Case where the concrete is modelled by massive finite elements

By taking again the preceding notations and while considering dx^c, dy^c, dz^c displacements of the node cables, and dx_j^b, dy_j^b, dz_j^b displacements of the nodes j ($j=1,n$) structure concrete neighbors of the node of the cable we obtain the following relations:

$$\begin{cases} dx^c=\sum_{i=1}^{n} N_i(x^c, y^c, z^c)\, dx_{i^b} \\ dy^c=\sum_{i=1}^{n} N_i(x^c, y^c, z^c)\, dy_{i^b} \\ dz^c=\sum_{i=1}^{n} N_i(x^c, y^c, z^c)\, dz_{i^b} \end{cases}$$

n being the number of nodes of the element concrete neighbors of the node of the cable, or that of one of its borders. For each node of the cable, one obtains 3 relations kinematics between displacements of the nodes of the two grids cables and concrete.

2.4.2.2 Case where the concrete is modelled by finite elements of plate



That is to say P_0^c the initial position of a point of cable in the not deformed geometry and is P^c the position of this same point after deformation. Let us call P_0^p the projection of P_0^c on the surface of the average layer of the concrete hull not deformed and P^p the projection of P^c on the surface of the average layer of the concrete hull deformed. That is to say $\vec{n}_0$ the normal with the average plan of the concrete hull in P_0^p and $\vec{n}$ that in P^p.

P_O^p is given by: $\begin{Bmatrix} x_0^p \\ y_0^p \\ z_0^p \end{Bmatrix} = \begin{Bmatrix} x_0^c \\ y_0^c \\ z_0^c \end{Bmatrix} - \left[\begin{Bmatrix} x_0^c - x_0^b \\ y_0^c - y_0^b \\ z_0^p - y_0^b \end{Bmatrix} \cdot \begin{Bmatrix} n_{0x} \\ n_{0y} \\ n_{0z} \end{Bmatrix} \right] \cdot \begin{Bmatrix} n_{0x} \\ n_{0y} \\ n_{0z} \end{Bmatrix}$

P^p is given by: $\begin{Bmatrix} x^p \\ y^p \\ z^p \end{Bmatrix} = \begin{Bmatrix} x^c \\ y^c \\ z^c \end{Bmatrix} - \left[\begin{Bmatrix} x^c - x^b \\ y^c - y^b \\ z^p - y^b \end{Bmatrix} \cdot \begin{Bmatrix} n\,x \\ n\,y \\ n\,z \end{Bmatrix} \right] \cdot \begin{Bmatrix} n\,x \\ n\,y \\ n\,z \end{Bmatrix}$

The point P_O^p belongs to a mesh of concrete plate whose nodes are noted $P_1^b, P_2^b \text{et} P_3^b$.
One defines the offsetting of the cable compared to the concrete hull as the distance $e = \|\overrightarrow{P_0^p P_0^c}\|$ and the assumption is made that this offsetting does not vary when the structure becomes deformed: $e = \|\overrightarrow{P_0^p P_0^c}\| = \|\overrightarrow{P^p P^c}\|$
One introduces displacements of the points of the cable and his projection:

$$\overrightarrow{P_0^c P^c} = \begin{cases} d\,x^c \\ d\,y^c \\ d\,z^c \end{cases} \qquad \overrightarrow{P_0^p P^p} = \begin{cases} dx^p = \sum_{i=1}^{n} N_i(x_0^p, y_0^p, z_0^p)\, dx_{i^b} \\ dy^p = \sum_{i=1}^{n} N_i(x_0^p, y_0^p, z_0^p)\, dy_{i^b} \\ dz^p = \sum_{i=1}^{n} N_i(x_0^p, y_0^p, z_0^p)\, dz_{i^b} \end{cases}$$

One introduces the vector “rotation” $\vec{\theta}$ plate at the point P^p and degrees of freedom of rotation of the nodes of the plate: $\vec{\theta}=\begin{cases} drx^b=\sum_{i=1}^{n} N_i(x_0^p, y_0^p, z_0^p)\, drx_{i^b} \\ dry^b=\sum_{i=1}^{n} N_i(x_0^p, y_0^p, z_0^p)\, dry_{i^b} \\ drz^b=\sum_{i=1}^{n} N_i(x_0^p, y_0^p, z_0^p)\, drz_{i^b} \end{cases}$

By definition of $\vec{\theta}$, one a: $\vec{n}-\vec{n}_0=\vec{\theta}\wedge\vec{n}_0$
One can then write:

$$\overrightarrow{P_0^p P_0^c}=e\,\vec{n}_0$$
$$\overrightarrow{P^p P^c}=e\,\vec{n}$$

By withdrawing these two equations, by taking account of the definition of $\vec{\theta}$ one finds:

$$\begin{cases} dx^c-dx^p=e.\left(dry^p.n_{0z}-drz^p.n_{0y}\right) \\ dy^c-dy^p=e.\left(drz^p.n_{0x}-drx^p.n_{0z}\right) \\ dz^c-dz^p=e.\left(drx^p.n_{0y}-dry^p.n_{0x}\right) \end{cases}$$

By injecting into this last equation the functions of form, one has finally:

$$\begin{cases} dx^c-\left(\sum_{i=1}^{n} N_i(x^p, y^p, z^p)\, dx_i^b\right)=e.\left(\left(\sum_{i=1}^{n} N_i(x^p, y^p, z^p)\, dry_i^b\right).n_{0z}-\left(\sum_{i=1}^{n} N_i(x^p, y^p, z^p)\, drz_i^b\right).n_{0y}\right) \\ dy^c-\left(\sum_{i=1}^{n} N_i(x^p, y^p, z^p)\, dx_i^b\right)=e.\left(\left(\sum_{i=1}^{n} N_i(x^p, y^p, z^p)\, drz_i^b\right).n_{0x}-\left(\sum_{i=1}^{n} N_i(x^p, y^p, z^p)\, drx_i^b\right).n_{0z}\right) \\ dz^c-\left(\sum_{i=1}^{n} N_i(x^p, y^p, z^p)\, dx_i^b\right)=e.\left(\left(\sum_{i=1}^{n} N_i(x^p, y^p, z^p)\, drx_i^b\right).n_{0y}-\left(\sum_{i=1}^{n} N_i(x^p, y^p, z^p)\, dry_i^b\right).n_{0x}\right) \end{cases}$$

2.4.2.3 Case where the node of the cable is projected on a node of the grid concrete

The distance enters projection P_0^p node cables P_0^c and a node concrete P_i^b is given by:

$$d=\|P_0^P P_i^b\|=\left\|\begin{pmatrix} x^c-x_i^b \\ y^c-y_i^b \\ z^c-z_i^b \end{pmatrix}-\left[\begin{pmatrix} x^c-x_i^b \\ y^c-y_i^b \\ z^c-z_i^b \end{pmatrix}.\vec{n}_0\right].\vec{n}_0\right\|$$

If it happens that this distance is worthless (in practice lower than 10^{-5}), it is that the node cable is projected at the top of a concrete mesh, and then the relations kinematics are simplified:

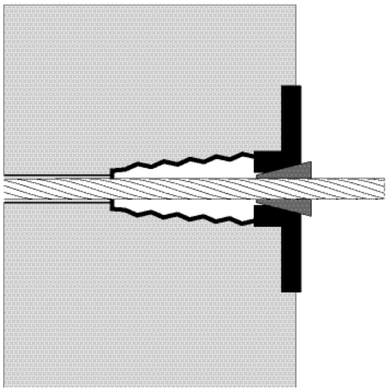
$$\begin{cases} dx^c-dx_i^p=e.\left(dry_i^p.n_{0z}-drz_i^p.n_{0y}\right) \\ dy^c-dy_i^p=e.\left(drz_i^p.n_{0x}-drx_i^p.n_{0z}\right) \\ dz^c-dz_i^p=e.\left(drx_i^p.n_{0y}-dry_i^p.n_{0x}\right) \end{cases}$$

These relations are the general relations in which: $N_j(x^p, y^p, z^p)=0$ if $j \neq i$.

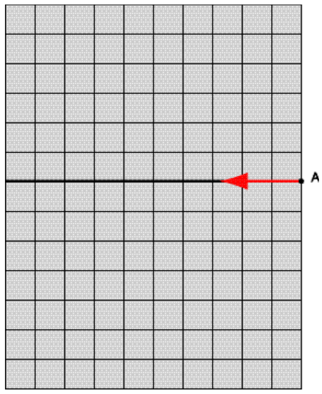
2.5 Treatment of the zones of end of the cable

The modeling of a cable of prestressed such as it is made in *Code_Aster* consist in representing the unit cables, sheath of passage, and all the parts of anchoring, only thanks to one continuation of elements of bar. The link between the elements of cables and the concrete medium is ensured by conditions kinematics on the degrees of freedom of each node of the cable, and those of the crossed elements concrete.

When the setting in tension of the cable is applied, it is observed that the reactions generated at the ends of the cables on the concrete create levels of constraints much higher than reality, and cause the damage of the concrete. As example, in certain studies, one could observe compressive stresses of more than $200\,MPa$, which largely exceeds the experimental value observed ($40\,MPa$). In reality, this phenomenon is not observed thanks to the installation of a cone of diffusion of constraint (see drawing below) which distributes the force of prestressed on a large surface of the concrete. In the case of the model with the finite elements, this surface does not exist, since the force is directly taken again by a node.



Real situation

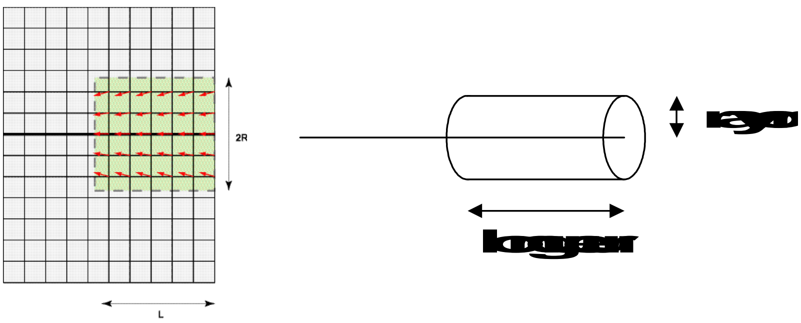


Model EF without cone

This way of modeling has several disadvantages:

- the concentration of this effort crushes the concrete,
- the space discretization of the model changes the results.

To cure this problem, the keyword `CONE` of the operator `DEFI_CABLE_BP` allows to distribute this force of prestressed either on a node, but on all the nodes contained in a volume (all the nodes of this volume are dependent between them to form a rigid solid) delimited by a cylinder of ray R and length L , representing the equivalent of the zone of influence of the cone of blooming of an anchoring (see figure below).



The identification and the creation of the relations kinematics between the nodes of the concrete and the cable are made in an automatic way by the order `DEFI_CABLE_BP` , where new data R and L will be to provide by the user.

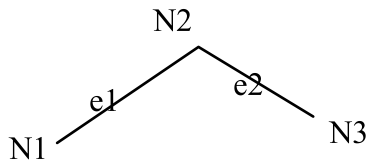
2.6 Note: calculation of the tension of the cable as a mechanical loading

We made the choice to leave the elements of cable in the mechanical model support of calculation by finite elements (linear or not). So there is no calculation of equivalent force to defer to the nodes of the grid. One is simply satisfied to say that the cables of prestressing have a state of initial stress not no one. This state of stress is that deduced from the tension as calculated by `DEFI_CABLE_BP`.

For reasons of simplicity, the data-processing object created by the operator `DEFI_CABLE_BP` is a table memorizing of the values to the nodes of the cable. Then let us consider two related elements of the cable:

$e1$ tops $N1$ and $N2$, and
$e2$ of top $N2$ and $N3$.

We suppose that l_1 and S_1 are the length and the section of an element $e1$ and that l_2 and S_2 are the length and the section of the element $e2$.



`DEFI_CABLE_BP` will calculate with the node $N2$ a tension T_{N_2} defined by:

$$T_{N_2}=\frac{1}{2}\left(\frac{\int_{e_1} T(s)\,ds}{l_1}+\frac{\int_{e_2} T(s)\,ds}{l_2}\right)$$

Conversely, for calculation finite element, the operator `STAT_NON_LINE` will consider that the initial constraint in the element $e1$ is $\sigma_0^{e1}=\frac{T_{N_1}+T_{N_2}}{2S_1}$

Note:

It will be always considered that the law of behavior of the cable is of incremental type.

3 The macro-order `CALC_PRECONT`

The macro-order `CALC_PRECONT` is to carry out the setting in tension of the cables in the concrete starting from the data contained in the concept `cable_precont` resulting from `DEFI_CABLE_BP`.

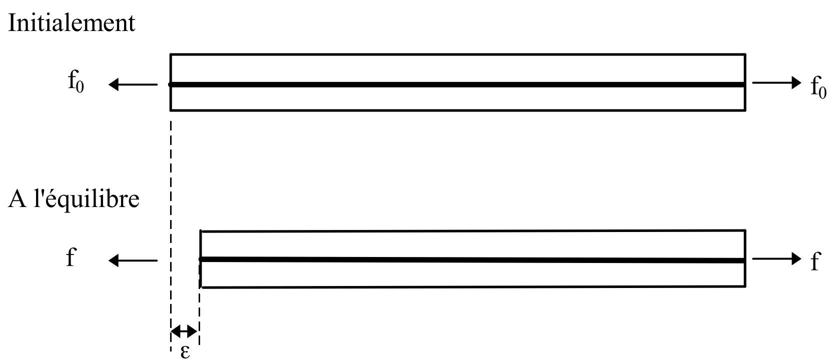
Two procedures different of setting in tension of the cables are present in this macro-order. One or the other of these procedures is automatically selected according to whether the concept `cable_precont` was created with the keyword `MEMBER = 'YES'` or `'NOT'`.

If `MEMBER = 'YES'`, profile of tension calculated in `DEFI_CABLE_BP` is transformed into initial loading by `AFFE_CHAR_MECA`.

If not, the setting in tension is simulated completely by a mechanical calculation by imposing forces on the degrees of freedom of slip of the elements CABLE_GAINE starting from the contained information in the concept cable_precont.

3.1 Adherent case: why an macro-order for the setting in tension?

It is possible to transform the tension in the cables, calculated by DEFI_CABLE_BP, in a loading directly taken into account by STAT_NON_LINE thanks to the order AFFE_CHAR_MECA operand RELA_CINE_BP (SIGM_BPEL=' OUI'). In this case, the tension is taken into account as an initial state of stress at the time of the resolution of the complete problem finite elements.



The resolution of the problem makes it possible to reach a state of balance between the cable of prestressed and the rest of the structure after instantaneous strain. Indeed, under the action of the tension of the cable, the unit cables (S) and concrete will be compressed compared to the initial position (cable in tension, grid not deformed). The length of the cable will thus decrease, and the initial tension also, consequently, will decrease. One thus obtains a final state with a tension in the cable different from the tension calculated initially. It is then essential proportionally to increase the tension applied *in situ* on the level them anchorings to take account of this loss.

The use of the macro-order CALC_PRECONT allows to avoid this phase of correction, by obtaining the state of balance of the structure with a tension in the cables equal to the lawful tension. In addition because of adopted method, it allows besides applying the tension in several steps of time, which can be interesting in the event of plasticization or of damage of the concrete. It makes it possible moreover to tighten the cables in a nonsimultaneous way and thus in a way closer to reality of the building sites.

To profit from these advantages, the loading is applied in the form of an external loading and not like an initial state, which allows the progressive loading of the structure. In addition, to avoid the loss of tension in the cable, the idea is not to make act the rigidity of the cables during the phase of setting in tension (cf [bib3]).
The various stages carried out by the macro-order are here detailed.

3.1.1 Stage 1: calculation of the equivalent nodal forces

This stage consists in transforming the internal tensions of the cables calculated by DEFI_CABLE_BP in an external loading. For that, a first is carried out STAT_NON_LINE only on the cables which one wishes to put in prestressing, with the following loading:

- embedded cable
- the tension given by DEFI_CABLE_BP

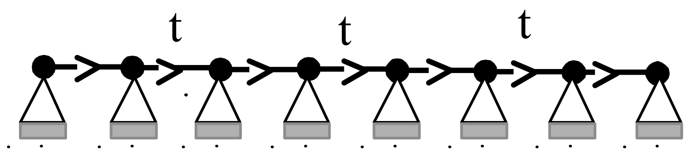


Figure 3.1.1-a: Loading at stage 1

One calculates the nodal efforts on the cable. One recovers these efforts thanks to `CREA_CHAMP`. And one builds the vector associated loading F.

3.1.2 Stage 2: application of prestressing to the concrete

The following stage consists in applying prestressing to the concrete structure, without making take part the rigidity of the cable. For that, one supposes for this calculation that the Young modulus of steel is null. One can choose to apply the loading of prestressed in only one step of time or several steps of time if the concrete is damaged.
The loading is thus the following:

- blocking of the rigid movements of body for the concrete,
- nodal efforts resulting from the first calculation on the cable,
- the connections kinematics between the cable and the concrete.

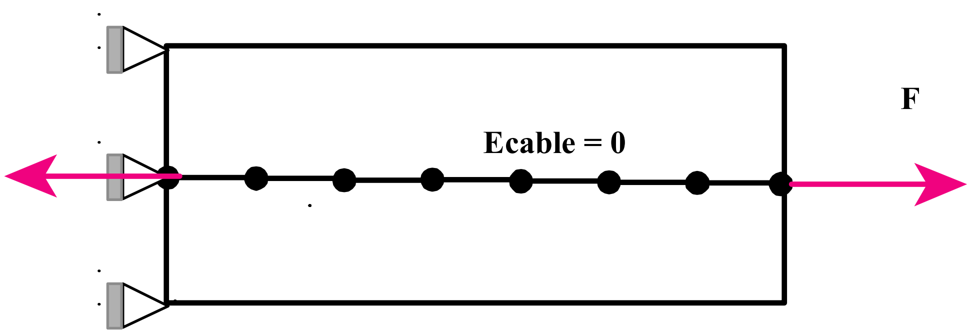


Figure 3.1.2-a: Loading at stage 2

3.1.3 Stage 3: swing of the external efforts in interior efforts

Before continuing calculation in a traditional way, it is necessary of retransformer the external efforts which made it possible to deform the concrete structure in interior efforts. This operation is done without modification on displacements and the constraints of the whole of the structure, since balance was reached at stage 2: it is about a simple artifice to be able to continue calculation. The loading is thus the following:

- blocking of the rigid movements of body for the concrete,
- the connections kinematics between the cable and the concrete,
- tension in the cables.

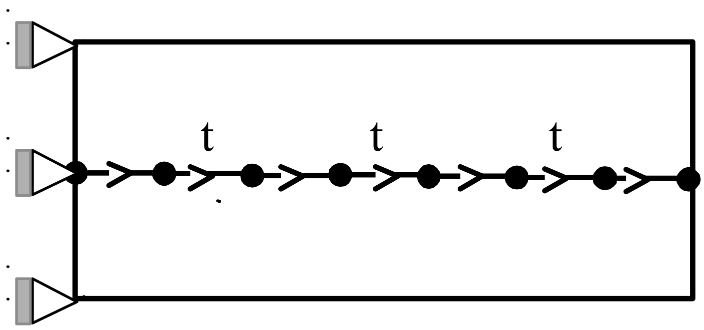


Figure 3.1.3-a: Loading at stage 3

3.2 Nonadherent case

The value given to the keyword TENSION_INIT of DEFI_CABLE_BP is imposed in force on the degree of freedom GLIS active nodes of anchoring of the cable whereas with the passive nodes this degree of freedom is blocked to zero.
In the case of an anchoring ACTIF/ACTIF, it is necessary to proceed in two times:

1. A force is imposed on the first active anchoring while the degree of freedom GLIS is blocked on the second.
2. One takes again calculation by imposing the force on the second anchoring, the degree of freedom GLIS first is then blocked to zero with a load of the type DIDI.

If a retreat of anchoring is specified in DEFI_CABLE_BP, another calculation is launched while imposing on the degree of freedom GLIS a displacement equal to the retreat of anchoring given. This load being also of type DIDI.

To continue calculation afterwards CALC_PRECONT, it is enough to block the degree of freedom GLIS nodes of anchoring with a load DIDI.

4 Procedure of modeling for a cable modelled in BAR

4.1 Various stages: standard case

To manage to model a prestressed concrete structure the procedure to be followed is the following one:

- to model the concrete elements (DKT, Q4GG, 2D or 3D),
- to model the cables of prestressed by elements bars with two nodes (BAR),
- to allot to the elements bars the mechanical characteristics of the cables of prestressing,
- to define the parameters materials for steel like BPEL_ACIER and BPEL_BETON or ETCC_ACIER and ETCC_BETON,
- thanks to the operator DEFI_CABLE_BP to calculate the data kinematics (relations kinematics between the nodes of the cable and those of the concrete elements) and statics (profile of tension along the cables),
- to define the data kinematics like mechanical loading,
- to call upon the operator CALC_PRECONT,
- to solve the problem with the operator STAT_NON_LINE by integrating only the data kinematics and the loadings other than prestressing.

For more practical information, to refer to the document [U2.03.06].

4.2 Typical case

So for a reason where the other, the user does not wish to use the macro-order CALC_PRECONT it is possible to adopt the following procedure:

- to model the concrete elements,
- to model the cables of prestressed by elements bars with two nodes (BAR),
- to allot to the elements bars the mechanical characteristics of the cables of prestressing,
- thanks to the operator DEFI_CABLE_BP to calculate the data kinematics (relations kinematics between the nodes of the cable and those of the concrete elements) and statics (profile of tension along the cables),
- to apply these data kinematics and statics like a mechanical loading,
- to solve the problem with the operator STAT_NON_LINE by integrating all the loadings.

At the conclusion of this calculation, it is necessary to determine the coefficients of correction to apply to the initial tensions applied to the cables (on the level of the declaration of the operator DEFI_CABLE_BP) allowing to compensate for the loss by instantaneous strain of the structure.

Once the command file modified by these coefficients of correction, the modeling of the cables of prestressing is accomplished.

Attention, in the case of sequence of STAT_NON_LINE, it is appropriate starting from the second call, to include in the loading only the relations kinematics and not the tension in the cables, under penalty of adding this tension, with each calculation.

4.3 Precautions of use and remarks

It is recommended to limit the recourse to a large number of relations kinematics under penalty of weighing down the computing time. However, when a node of the elements of bar constituting the cables coincides topologically with a node concrete, there is no kinematic addition of relation.
If a first is carried out STAT_NON_LINE before putting in tension in the cables, it is preferable to disable the cables, either by not taking them into account in the model, or in their affecting a tension constantly worthless (law of behavior WITHOUT), and by including in the loading the relations kinematics binding the cable to the concrete.
If one carries out a phasage of the setting in prestressing, it is necessary to think of including the relations kinematics in the loading for the cables already tended at the preceding stages.

5 Procedure of modeling for a cable modelled in CABLE_GAINE

To manage to model a prestressed concrete structure the procedure to be followed is the following one:

- to model the concrete elements (3D),
- to model the cables of prestressed by elements 1D with three nodes (CABLE_GAINE), while taking care that the elements are not linear under penalty of not being able to evaluate the losses by friction due to the curve,
- to allot to the elements CABLE_GAINE mechanical characteristics of the cables of prestressing,
- to define the parameters materials for the steel and the law of friction (CABLE_GAINE_FROT), but too BPEL_ACIER and BPEL_BETON (even if in practice, the parameters are not used in the rubbing cases),
- thanks to the operator DEFI_CABLE_BP to calculate the data kinematics (relations kinematics between the nodes of the cable and those of the concrete elements) and statics (profile of tension along the cables),

- to define the data kinematics like mechanical loading,
- to call upon the operator CALC_PRECONT,
- to solve the problem with the operator STAT_NON_LINE by integrating only the data kinematics and the loadings other than prestressing, and by blocking the degree of freedom GLIS nodes of anchoring with a loading of TYPE=' DIDI'.

For CALC_PRECONT and STAT_NON_LINE, the convergence criteria should be used preferably RESI_REFE_RELA to be sure to have reached convergence.

6 Features and checking

The orders evoked in this document are checked by the cases following tests:

CALC_PRECONT		
SSLV115	[V3.04.115]	Prestressed concrete element in compression and gravity
SSNV164	[V6.04.164]	Setting in tension of cables of prestressed in a beam 3D
SSLS137	[V3.03.137]	Prestressed concrete plate with excentré cable in inflection
ZZZZ347	[V6.01.347]	Validation of the rubbing cables CABLE_GAINE

DEFI_CABLE_BP		
SSLV115	[V3.04.115]	Prestressed concrete element in compression and gravity
SSNV164	[V6.04.164]	Setting in tension of cables of prestressed in a beam 3D
SSNP108	[V6.03.108]	Prestressed concrete element in compression
SSNP109	[V6.03.109]	Cable of prestressing excentré in a right concrete beam
SSNV137	[V6.04.137]	Cable of prestressed in a right concrete beam
SSNV229	[V6.04.229]	Validation of formulas ETCC in DEFI_CABLE_BP
ZZZZ111	[V1.01.111]	Validation of the operator DEFI_CABLE_BP

7 Bibliography

1) Rules BPEL 91, technical Rules of design and calculation of the works and prestressed concrete constructions following the method of the limiting states. CSTB, ISBN 2-86891-214-1.

2) [R3.07.03] "Elements of plate DKT, DST, DKTG and Q4g" Manuel de Référence Aster.

3) S. GHAVAMIAN, E. LORENTZ: Improvement of the features of the taking into account of prestressing in *Code_Aster*, CR – AMA 2002-01

4) ETC-C 2010 Edition, EPR Technical codes for civil works, AFCEN.

8 Description of the versions of the document

Version Aster	Author (S) Organization (S)	Description of the modifications
6	*S. MICHEL-PONNELLE, A. ASSIRE (EDF-R&D/AMA)*	Initial text
7	*S. MICHEL-PONNELLE, A. ASSIRE (EDF-R&D/AMA)*	
11	*S. MICHEL-PONNELLE, A. ASSIRE (EDF-R&D/AMA)*	Hulls usable with `CALC_PRECONT` Addition of formulas ETC-C for calculation of tension
12	*S. MICHEL-PONNELLE*	Addition modeling `CABLE_GAINE`