Code_Aster

Version default

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Responsable : DE SOZA Thomas

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Note of calculation to buckling

Summary:

The objective of this documentation is to present a methodological guide for a nonlinear analysis of buckling of a structure. One approaches mainly two features there of *Code_Aster* :

- analysis of buckling linear, known as of Euler, through CALC_MODES (with the keyword TYPE_RESU= 'MODE_FLAMB'),
- the calculation of the quasistatic evolution (operator STAT_NON_LINE) structure which has nongeometrical and behavioral linearities, which one seeks instabilities (option CRIT_STAB), a boundary point, even the répon post-critical.

The first stage is, generally, a calculation of buckling of Euler, who will allow to know the modes of buckling and the critical loads corresponding. From the point of view of the originator, the knowledge of the first mode and its critical load is often sufficient, in order to be defined a margin of operation compared to the imposed loading: the multiplying coefficient between the imposed loading and the critical load weakest gives the safety margin.

Remarks

- *The knowledge of the first mode of buckling can also be used as indication to optimize the management of nonlinear incremental calculation carried out thereafter. Indeed, with the approach of the critical load, one can then decide to modify piloting or to reduce the step of time, to even increase the iteration count of checking of balance in the method of residue, with each step of load.*
- *The pace of the mode of buckling of Euler can as be used for to impose an initial geometrical defect on the structure, in order to make sure, amongst other things, as incremental nonlinear calculation will fork this mode of course.*

The analysis of Euler being per linear definition, it does not make it possible to take into account inelastic relations of behavior, contact or the following aspect of the forces. It is then necessary to do a nonlinear calculation, which into quasi-static will be based on the order STAT_NON_LINE of *Code_Aster*. It is the incremental classical method by residue in balance.

The particular points of its use will be approached thereafter, in particular the use of the non-linear analysis of stability with the keyword CRIT_STAB (which is also available in DYNA_NON_LINE for the dynamic studies).

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1   Analysis of buckling of Euler

The calculation of the modes of buckling within the meaning of Euler [bib5] is done by the operator of resolution of problems to the eigenvalues `CALC_MODES` (with the keyword `TYPE_RESU = 'MODE_FLAMB'`). Within the framework of buckling, there is following typical syntax:

```
MODP1 = CALC_MODES (MATR_RIGI = RAMEP1,
                    MATR_RIGI_GEOM = RAGEP1,
                    TYPE_RESU = 'MODE_FLAMB',
                    OPTION = 'BAND',
                    CALC_CHAR_CRIT = _F ( CHAR_CRIT = (-2.4, - 2.2,),),
                    SOLVEUR_MODAL=_F (METHODE= 'SORENSEN',
                                      DIM_SOUS_ESPACE = 80,
                                      NMAX_ITER_SOREN = 80,),)
```

The argument of the keyword `MATR_RIGI` must be the matrix of rigidity known as material, whereas the keyword `MATR_RIGI_GEOM` waits the geometrical matrix of rigidity.

For recall, the modes of buckling are the clean modes of the problem to the eigenvalues according to:

$$(K + \mu K_g) x = 0 \Leftrightarrow K x = \lambda K_g x$$

with:

K :   matrix of rigidity

K_g :   geometrical matrix of rigidity

λ :   eigenvalue ($\lambda = -\mu$ with μ multiplying coefficient of loading)

Note:

It is well the critical load factor μ and not λ who is stored in the concept result.

Material rigidity (or rubber band) is calculated with the option `'RIGI_MECA'` of `CALC_MATR_ELEM`. Geometrical rigidity is calculated starting from the stress field solution of the linear problem (option `'RIGI_GEOM'` of `CALC_MATR_ELEM`). It is thus necessary to have carried out a static linear calculation prior to the use of `CALC_MODES` for buckling.

If the loading is composed of a fixed part (not controlled) and of a variable part, the multiplying coefficient of the loading should not, of course, relate that to the variable part. The contribution of the other part of the loading is found in the first member. Let us note f_c the fixed loading and f_v the controlled loading (proportional to μ). The problem with the eigenvalues becomes:

$$(K + K_g(f_c + \mu f_v)) x = 0 \Leftrightarrow (K + K_g(f_c)) x = \lambda K_g(f_v) x$$

with:

K :   matrix of material rigidity

$K_g(f_c)$:   geometrical matrix of rigidity for the loading not controlled

$K_g(f_v)$:   geometrical matrix of rigidity for the variable loading

λ :   eigenvalue $\lambda = -\mu$

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In this case, it is thus necessary to solve two preliminary linear elastic problems, to be able to calculate the two different geometrical matrices of rigidity. In order to be exhaustive, the presentation will relate to a structure subjected to the displacements imposed as well as efforts, which will be the combination of a fixed loading and a variable loading that one will control with a coefficient growing being able to lead to buckling.

1.1 Stage 1: Calculation (S) linear (S) preliminary (S)

One will make use of MECA_STATIQUE. The structure, with a grid in elements of type hull (elements of voluminal the hulls type [bib3]), is subjected to boundary conditions of Dirichlet (CONDLIM) and of Neumann. These last break up into:
- WEIGHED : field of gravity,
- PRESPH : field of pressure imposed not controlled,
- PRESPS1 : variable field of pressure imposed.

For the analysis of buckling, it is necessary to separate the constant efforts from those which are variable (controlled by a coefficient). One will thus do two linear static calculations. The first will be the case of the structure subjected to imposed displacements and with the constant efforts, the second will see the structure subjected to imposed displacements and the variable efforts.

Controlled loading:

```
RESC11P1 = MECA_STATIQUE (MODEL = MODEL,
                          CHAM_MATER = CHMAT,
                          CARA_ELEM = CARAELEM,
                          EXCIT = (_F (LOAD = CONDLIM,),
                                   _F (LOAD = PRESPS1,),),
                          OPTION = 'SIEF_ELGA',
                         )
```

Loading not controlled:

```
RESC12P1 = MECA_STATIQUE (MODEL = MODEL,
                          CHAM_MATER = CHMAT,
                          CARA_ELEM = CARAELEM,
                          EXCIT = (_F (LOAD = CONDLIM,),
                                   _F (LOAD = WEIGHED,),
                                   _F (LOAD = PRESPH,),),
                          OPTION = 'SIEF_ELGA',
                         )
```

One will use the stress field to calculate the associated matrices of geometrical rigidity, for the two loadings:

```
SIGC11P1 = CREA_CHAMP (TYPE_CHAM = 'ELGA_SIEF_R',
                       OPERATION = 'EXTR',
                       RESULT = RESC11P1,
                       NOM_CHAM = 'SIEF_ELGA',
                       TYPE_MAXI = 'MINI',
                       TYPE_RESU = 'VALE',)
#
REGC11P1 = CALC_MATR_ELEM (OPTION = 'RIGI_GEOM',
                           MODEL = MODEL,
                           CARA_ELEM = CARAELEM,
                           SIEF_ELGA = SIGC11P1,)
```

REGC11P1 is thus the geometrical matrix of stiffness associated with the variable case of loading

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(PRESPS1).

One calculates, in the same way, the geometrical matrix of stiffness for the constant loading (WEIGHED and PRESPH), from RESC12P1 :

```
SIGC12P1 = CREA_CHAMP (TYPE_CHAM = 'ELGA_SIEF_R',
                       OPERATION = 'EXTR',
                       RESULT = RESC12P1,
                       NOM_CHAM = 'SIEF_ELGA',
                       TYPE_MAXI = 'MINI',
                       TYPE_RESU = 'VALE',)
#
REGC12P1 = CALC_MATR_ELEM (OPTION = 'RIGI_GEOM',
                           MODEL = MODEL,
                           CARA_ELEM = CARAELEM,
                           SIEF_ELGA = SIGC12P1,)
```

It remains to calculate the matrix of material rigidity for the total loading:

```
REMEP1 = CALC_MATR_ELEM (OPTION = 'RIGI_MECA',
                         MODEL = MODEL,
                         CHAM_MATER = CHMAT,
                         CARA_ELEM = CARAELEM,
                         LOAD = (CONDLIM, WEIGHED,
                                 PRESPH, PRESPS1,),)
```

All the elementary matrices are calculated, the following stage is thus their assembly:

```
NUP1 = NUME_DDL (MATR_RIGI = REMEP1,)
#
RAMC1P1 = ASSE_MATRICE (MATR_ELEM = REMEP1,
                        NUME_DDL = NUP1,)
#
RAGEP1 = ASSE_MATRICE (MATR_ELEM = REGC11P1,
                       NUME_DDL = NUP1,)
#
RAGC12P1 = ASSE_MATRICE (MATR_ELEM = REGC12P1,
                         NUME_DDL = NUP1,)
```

One summons then the matrices of material rigidity (RAMC1P1) and geometrical (RAGC12P1) corresponding to the case of constant loading:

```
RAMEP1 = COMB_MATR_ASSE (COMB_R = (_F (MATR_ASSE = RAMC1P1,
                                       COEF_R = 1.0,),
                                   _F (MATR_ASSE = RAGC12P1,
                                       COEF_R = 1.0,),),)
```

The two matrices necessary to the calculation of the modes of buckling are thus built.

1.2   Stage 2: Calculation of the modes of Euler

It can be useful to make tests of STURM (operator INFO_MODE) on the interval of research on which one wants to find the cases of buckling. Thus, that will make it possible to optimize the size of the interval and to control the good progress of later modal calculation since one will know the number of existing modes in advance. Syntax is:

```
INFO_MODE  (MATR_RIGI = RAMEP1,
            MATR_RIGI_GEOM = RAGEP1,
            TYPE_MODE = 'MODE_FLAMB',
            CHAR_CRIT = (- 2.4, - 2.2)  )
```

Once the interval of search for critical load of buckling chosen, one can then implement CALC_MODES as follows:

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```
MODP1 = CALC_MODES (MATR_RIGI = RAMEP1,
                    MATR_RIGI_GEOM = RAGEP1,
                    TYPE_RESU = 'MODE_FLAMB',
                    OPTION = 'BAND',
                    CALC_ CHAR_CRIT =_F ( CHAR_CRIT = (-2.4, - 2.2,),),
                    SOLVEUR_MODAL=_F (DIM_SOUS_ESPACE = 80,
                                      NMAX_ITER_SOREN = 80,),)
```

Notice

> *If the algorithm does not converge or if the number of modes is not that predicted by INFO_MODE , it can be useful to increase the values of DIM_SOUS_ESPACE and NMAX_ITER_SOREN .*

One normalizes the modes [bib6], only while making use of the degrees of freedom of translation:

```
MODP1 = NORM_MODE (reuse = MODP1
                   MODE = MODP1,
                   = 'TRAN NORMALIZES',)
```

The modes can then be post-treaties.

Remarks

- *It is essential to check that the geometrical stiffness of the selected model is well an option available in Code_Aster.*
- *A finer discretization leads normally to a fall of the critical loads.*
- *The discretization must be ready to collect the modes of buckling, knowing that these modes can generate localised deformations (folds). The preliminary calculation of the dynamic modes can constitute a first indication on the quality of the grid, although these modes can be very different from the modes of buckling.*
- *The critical loads of the various modes are proportional to the Young modulus E .*
- *With this method, one cannot take account of the following character of the forces. Indeed, the geometrical calculation of stiffness made with the option RIGI_GEOM of CALC_MATR_ELEM bases itself on the assumption that all the forces imposed on the mechanical problem are of type forces dead. If one wants to take account of the following character of certain requests, should obligatorily be used the non-linear operators STAT_NON_LINE or DYNA_NON_LINE, with the keyword CRIT_STAB, as one will see it in the continuation of this document.*

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2 Quasi-static nonlinear study of the structure

This stage is justified if the structure has strong not linearities, whose analysis of Euler cannot take account. The operator of resolution of the nonlinear problems into quasistatic names himself STAT_NON_LINE [bib7].

These nonlinearities can be related to the material which can have an elastoplastic behavior [bib8], as in the example which will follow. The taking into account of the contact, even of friction, is another source of nonlinearities. One can also quote the case of the following loadings, like the pressure ([bib1] and [bib2] for the elements of voluminal the hulls type), which require a nonlinear approach in *Code_Aster*.

One can distinguish two types of non-linear analyses of stability, being able to combine.
On the one hand the generalization of the analysis of Euler introduced previously: one will make follow-up of the critical loads and modes associated during incremental calculation non-linear. That results in an analysis of the type Euler on the matrices of reactualized stiffnesses. This kind of analysis is often done on a structure without initial defect.

In addition, one can take account of defects introduced on the perfect model, in order to "force" the junction in solution and to make follow-up of branch to analyze the post-critical answer.
Obviously, this follow-up of post-critical solution can be initiated by the analysis with the eigenvalues on matrices of reactualized stiffnesses, in particular for detecting the junction well and defining the defect then introduced while being based on the mode of buckling observed.

2.1 Analysis of stability on matrices of reactualized stiffnesses

That it is into quasistatic (operator STAT_NON_LINE) or in dynamics (operator DYNA_NON_LINE), *Code_Aster* allows to carry out incremental analyses of stability within the meaning of buckling on the current matrices of stiffness. These stages of calculation are managed by the keyword factor CRIT_STAB with the option TYPE = 'BUCKLING' (*cf.* [U4.51.03] and [U4.53.01]).

Remarks for the transitory analysis

The option CRIT_STAB acts as for the quasistatic case: one always carries out an analysis of buckling (thus basing itself only on the study of the matrices of stiffness), not a dynamic analysis of instability (damping becoming negative).
With modeling coupled fluid-structure (u, p, ϕ) [R4.02.02], it is necessary to modify the matrix of assembled stiffness (as well as the geometrical stiffness when it is used). For that, it is necessary to inform the keyword following, under CRIT_STAB :
•MODI_RIGI = 'YES' ,
•DDL_EXCLUS= ('PHI', 'NEAR', 'DH',) .
The list of the excluded degrees of freedom must comprise all the types of degrees of freedom related to the fluid model: in the example of CAS-test FDNV100 there is thus the potential PHI, pressure NEAR and vertical displacement on the level of free surface DH. If this treatment is not made, then the call to CRIT_STAB will plant due to singular matrix and no strategy of shift could surmount that.
Into quasi-static, this problem does not arise because modeling coupled fluid-structure then does not have a direction.

This keyword makes it possible to start calculation, at the end of each increment of time, of a criterion of stability. This criterion is useful to detect, during the loading, the point from which one loses stability (by buckling for example).

This criterion is calculated way following: at the end of a step of time, in small disturbances, one solves $det(K^T + \mu . K^g) = 0$. K^T is the coherent tangent matrix at this moment. K^g is the geometrical matrix of rigidity, calculated starting from the stress field at this moment and μ the critical load factor.

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In practice, the loading is unstable if $|\mu| < 1$ (in fact $0 < \mu < 1$). One calculates the eigenvalues by the method of Sorensen (*cf.* CALC_MODES [U4.52.02]). This can be expensive enough for the problems of big size.

The keyword CHAR_CRIT allows to save time by making only one test of Sturm in the provided waveband. If at least a frequency is found, then one really calculates values of the critical loads in this interval.

For great displacements and the great deformations, one solves $det\left(K^T + \mu . I\right) = 0$ because K^T contains then K^g.

The criterion is then a criterion of instability: when μ change sign (thus passes by 0) the loading is unstable.

Remarks concerning the geometrical matrix of stiffness

> *The analysis of stability will be more precise if one has the geometrical matrix of stiffness: indeed, in its absence, certain instabilities cannot be detected like, for example, in the purely elastic cases. Between sufficiently realistic models, it is thus necessary to privilege the use, for precise analyses of stability, models allowing the calculation of this geometrical stiffness.*

The keyword NB_MODE indicate the number of critical loads to calculate. Often the first is enough but there can be multiple modes.

One stores the clean mode the corresponding to smallest critical load (in absolute value) in the result object, under the name MODE_FLAMB. This clean mode can be extracted and visualized (like a field of displacements or a classical clean mode). It is standardized to 1 on the largest component of displacement. All the calculated critical loads are displayed in the file .mess.

In practice, in order to limit the overcost of calculation, one advises to optimize the calls to CRIT_STAB. One can for that use the keywords LIST_INST/INST/PAS_CALCUL in the keyword factor CRIT_STAB. One can thus specify with which steps of time one will calculate the modes of buckling. In complement, it is judicious not to use CRIT_STAB that on the time intervals where one suspects the possibility of instabilities.

Lastly, if one wants a very good load estimating critical, it is advisable to refine well the step of time to the approach of this zone. This council is all the more relevant into quasi-static because the user then resorts often to steps of times larger than in dynamics.

It is possible to properly stop (bases reusable in continuation) a calculation with STAT_NON_LINE or DYNA_NON_LINE during the detection of an instability. It is not operation by default where the code will try to continue to solve the problem, and if there is convergence, then that means that one succeeded in following one of the branches of solution.
To manage this stop (*cf.* CAS-test ERREU10), it is necessary as a preliminary to have used DEFI_LIST_INST with the following arguments:

        ECHEC=_F (EVENEMENT=' INSTABILITE', ACTION=' ARRET',),

What means that in the event of event of type instability, the started action will be the stop.

Under CRIT_STAB, the following optional options make it possible to control this criterion of stop:
*   PREC_INSTAB to define the precision (adimensional) criterion of stop,
*   SIGN to specify the breaking values to consider.

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The second keyword is useful only when the geometrical matrix of stiffness is used. By default one considers the solution as being unstable if the critical load becomes ranging between 1 and -1, but one can, if need be, to take into account only the positive or negative part of this interval.

Without geometrical matrix of stiffness, instability will be detected when an eigenvalue of the matrix of assembled total stiffness, is:
 • will tend towards 0 (with a relative precision given by PREC_INSTAB),
 • will change sign.

For example, in the case of a tank filled with water under earthquake, one can begin incremental or transitory calculation with a critical load being worth 0.8 (analyzes with geometrical stiffness): what means that the tank would flame if one imposed a depression being worth 0.8 times the imposed hydrostatic pressure (the positive value of the critical load corresponds to an inversion of direction of the loading considered). Thus if nothing is specified, calculation would be considered unstable and would stop. Like, in this case, one makes the assumption then that there will not be depressurisation (for example by draining), one clears the interval $[0,1]$ in the analysis of stability. Thus the problem will become unstable if the critical load reaches the interval $[-1,0]$.

For the analyses in monotonous evolution this kind of reasoning is easily conceived, which is well the case for the static part of the loading, but for the dynamic part, the loading being cyclic, and except having specific information, it is surer and more conservative to keep the option by default and thus to consider the unstable structure if the critical load becomes lower than 1 in absolute value.

At the time of a stop on instability, calculation will stop by closing the base properly: the user will be able to exploit it in continuation.

2.2   Unstable follow-up of solution

For the study of a structure potentially unstable or likely to know a boundary point, which is thus likely to meet a junction in solution during the evolution of the loading, it is often useful to be able to choose a branch of particular solution (often the physical solution when it is defined *a priori* without ambiguities). For that, the user can have to introduce an initial defect which "will force" the structure to fork on the branch of particular solution.
Several methods exist to define this defect.

 • One the most adapted of is pre-to slightly deform the structure according to the pace of the mode of buckling corresponding to the branch than one wants to follow. The amplitude of this predeformation must be low, for example less than 1/10ème thickness for a mean structure. The ideal being to find the defect minimal which is compatible with a satisfactory performance of the algorithm of residue in balance. Indeed, a too weak defect can involve a difficulty of convergence of the residue, mainly in the case of a piloting in effort. This initial defect can extremely judiciously be built starting from the mode of instability calculated with the option CRIT_STAB of STAT_NON_LINE / DYNA_NON_LINE (*cf.* preceding paragraph). This mode then takes account of all the non-linearities introduced into the complete model. The more economic alternative is to use the mode of buckling of Euler, but who corresponds to the linear case.
 • The geometrical defect can also be defined by experimental measurements of the real part whose geometry could not be perfect.
 • The defect can also take the shape of a disturbance of the loading (misalignment, addition of a loading located,…) or of the mechanical characteristics of the material (local weakening of the Young modulus, for example). He can nevertheless be then more difficult to adapt the defect to the mode of wished buckling, especially if the structure presents relatively nearby modes.

Notice

In certain cases, even on the nondisturbed problem, the loading is such as it causes the desired junction.

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One of the other particular points, related to instability, is the choice of the technique of piloting of the algorithm `STAT_NON_LINE`. Indeed, classical piloting in effort is not adapted any more because it cannot collect an unstable branch of solution. In the same way, with the approach of a boundary point, convergence with piloting in effort will become increasingly difficult, the matrix of tangent rigidity becoming singular. It is then necessary to reduce the increment of load and to increase the maximum number of iteration to continue calculation.

One can also serve as the possibility of stopping properly in the event of instability (*cf.* preceding paragraph) to manage in continuation the junction on the branch of solution chosen by initiating the continuation of calculation by a disturbance according to this mode of instability.

There exist techniques of piloting [bib9] making it possible to circumvent these digital difficulties. Among the methods suggested by *Code_Aster*, that called by length of arc [bib12] (option `TYPE='LONG_ARC'` keyword `PILOTING` in `STAT_NON_LINE`), which is adapted for instabilities of type buckling, in the case of "soft" snap-backs possible [bib13]. In the case of more brutal snap-backs, Crisfield proposes an alternative [bib13], nonavailable in *Code_Aster*.
Other methods exist, like that of Riks [bib14] (nonavailable either), which treats also the dynamic case.

If one wants only to obtain the boundary point, including with a good precision, a piloting in loading can be enough, on condition that managing well the parameters of step of increment of load (think of using the order `DEFI_LIST_INST`) and of maximum iteration count authorized (`ITER_GLOB_MAXI` of `CONVERGENCE`). It can also be useful, with the approach of the boundary point, not to more use the tangent matrix reactualized for the solvor, since it is quasi-singular. One can then be satisfied not to reactualize this matrix with each calculation (parameters `REAC_INCR` and `REAC_ITER`) or, in the worst of the cases, to adopt the basic elastic matrix (`PREDICTION=' ELASTIQUE'` and `MATRICE=' ELASTIQUE'` keyword `NEWTON`).

Here an example of use of `STAT_NON_LINE` for an elastoplastic calculation in great displacements ([bib4] for the elements employed, which are of voluminal hulls type), with piloting in efforts:

```
RESU = STAT_NON_LINE (…
                    EXCIT = (_F (LOAD = CONDLIM,
                            TYPE_CHARGE = 'FIXE_CSTE',),
                        _F (LOAD = WEIGHED,
                            TYPE_CHARGE = 'FIXE_CSTE',),
                        _F (LOAD = PRESPH,
                            FONC_MULT = FONCMUL2,
                            TYPE_CHARGE = 'SUIV',),
                        _F (LOAD = PRESPS1,
                            FONC_MULT = FONCMUL,
                            TYPE_CHARGE = 'SUIV',),),
                    …)
```

Remarks

- *One uses the tangent matrix reactualized with each calculation, by authorizing the under-cutting of the step of load.*
- *The imposed pressures are following efforts (`TYPE_CHARGE=' SUIV'`).*
- *In the case of a modeling in solid elements, the tensor of deformation recommended in great displacements is '`SIMO_MIEHE`' .*

If one wants to replace piloting in effort by a method by length of arc, it is enough to add:

```
RESU = STAT_NON_LINE (…
                    PILOTING = _F (GROUP_NO = 'G',
                            TYPE = 'LONG_ARC',
                            NOM_CMP = ('DY',),
                            COEF_MULT = 7. ),

                    …)
```

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Remarks

• *In Code_Aster, one cannot control following forces.*
• *For piloting by length of arc, it, in general, is recommended that* `GROUP_NO` *all the structure contains.*

To finish, let us quote two articles of Crisfield which give a good general vision of the problems and methods involved in nonlinear calculations being able to present various types of instabilities ([bib15] and [bib11]).

Documentation [U2.06.11] shows an example of use of `CRIT_STAB` for the study of the behavior of a metal tank.

Some CAS-tests of *Code_Aster* treating buckling:

Modes of Euler:
• sdls504
• sdls505
• ssll103
• ssll105
• ssll403
• ssll404
• ssls110

Modes of Euler and nonlinear calculation:
• ssnl123

Nonlinear modes (`CRIT_STAB`):
• sdnv106 (presents moreover `MODE_VIBR` for the calculation of the oscillatory modes on reactualized stiffness)
• ssll105
• ssnl126
• ssnp306

Nonlinear calculation:
• ssnl502
• ssnp305: calculation until a snap-through

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2) Following pressure for the voluminal elements of hulls [R3.03.07].

3) Finite elements of voluminal hulls [R3.07.04].

4) Voluminal elements of hulls into nonlinear geometrical [R3.07.05].

5) Algorithm of resolution for the generalized problem [R5.01.01].

6) Modal parameters and standard of the clean vectors [R5.01.03].

7) Quasi static nonlinear algorithm [R5.03.01].

8) Integration of the relations of elastoplastic behavior of Von Mises [R5.03.02].

9) Methods of piloting of the loading [R5.03.80].

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