SSNP143 – Validation of keying-up/sawing for the law of joint of stud of the stoppings

Summary:

Two industrial procedures on the stoppings are tested: keying-up and sawing.
Keying-up is presented in the form of an injection of the concrete under pressure between the studs of a stopping. It is an intermediate stage of the construction of an arch dam, it is used to reinforce its sealing after the phase of construction of vertical studs. Sawing is a similar procedure during which the stopping is sawn in order to slacken the constraints. This can intervene before or after put out of water. This test makes it possible to validate the two procedures by carrying out keying-up/sawing between the two regular studs, which either are embedded on the ground and subjected to the gravitational force (modelings A, B, E, F, G, H), or compressed on the sides (modelings C and D). The procedure is defined via a keyword `PRES_CLAVAGE` and `SAWING` in `DEFI_MATERIAU` for material `JOINT_MECA_RUPT/FROT`. The corresponding laws bear the same names. One tests the behavior of the two-dimensional and three-dimensional joints, corresponding to modelings: `PLAN_JOINT` and `3D_JOINT`.

Modeling a: industrial Keying-up 2D; law `JOINT_MECA_RUPT`
Modeling b: industrial Keying-up 3D; law `JOINT_MECA_RUPT`
Modeling C: Theoretical sawing 2D; laws `JOINT_MECA_RUPT/FROT`
Modeling D: Theoretical sawing 3D; laws `JOINT_MECA_RUPT/FROT`
Modeling E: Industrial sawing 2D; law `JOINT_MECA_RUPT`
Modeling F: Industrial sawing 3D; law `JOINT_MECA_RUPT`
Modeling G: Industrial sawing 2D; law `JOINT_MECA_FROT`
Modeling H: Industrial sawing 3D; law `JOINT_MECA_FROT`

For keying-up one compares the profile thickness of the joints after keying-up with the results provided by another computer code (`SOURCE_EXTERNE` *GEFDYN)*. For sawing one makes a comparison with a theoretical estimate (modeling C and D). In addition one makes tests of `NON_REGRESSION` values thickness of the joint, as well as corresponding efforts.

1 Problem of reference

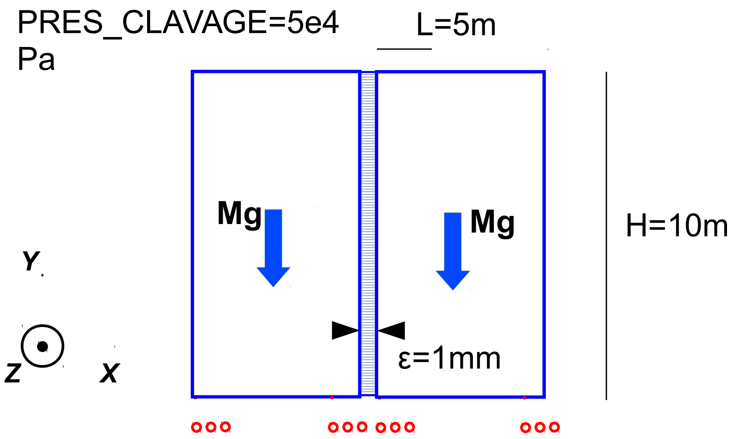
1.1 Geometry and loading

One considers two studs of stopping, represented by regular cubes length $L=5\mathrm{m}$, height $H=10\mathrm{m}$ and depth $P=1\mathrm{m}$. The distance between the studs is supposed nonworthless to simplify the generation of the grid of the joints ($\varepsilon=1\mathrm{mm}$). Embedding varies according to modelings.

1.1.1 Modelings A, B, E, F, G, H

The lower parts of the studs are embedded. The studs are subjected to their gravitational weights. The loading proceeds in two stages:

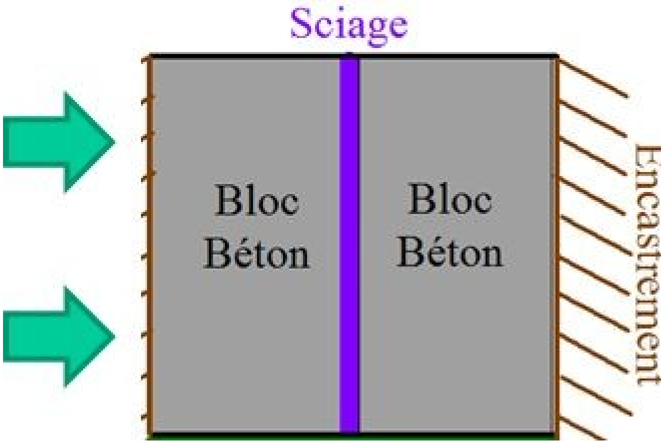
- The studs balance under the gravitational loading. The joint opens in the upper part because of compression of the lower parts of the studs. One applies one of the two industrial procedures thereafter:
    - The procedure of keying-up is activated: “the concrete is injected” between the studs with `PRES_CLAVAGE`= $5\,10^4 Pa$. The profile thickness of joint is then modified of kind to obtain the pressure of keying-up on the lips of the crack. It is this profile which is stored then by one of the internal variables “to memorize” the quantity of concrete injected.
    - The procedure of sawing is activated via key word `SAWING`. The thickness of the saw δ_{scie} is selected so that the high part of stud is sawn only partially.



Drawing 1: Diagram of the studs of stopping, boundary conditions and loading

1.1.2 Modelings C, D

The left side of the stud is embedded, while one applies a displacement imposed to the right side of the stud. The procedure of sawing is activated thereafter via the key word `SAWING`. The thickness of the saw δ_{scie} is selected so that the joint is sawn only partially.



Drawing 2: Modelings C and D, which allow the theoretical validation of sawing

1.2 Properties of material

The values of the mechanical parameters of the studs (Young modulus, Poisson's ratio, voluminal density) are in the following way selected:

$E=3.10^2 Pa \qquad \nu=0,25 \qquad \rho_b=2400 kg/m^3$

The thickness of saw varies according to modeling.

1.2.1 Material `JOINT_MECA_RUPT`

For the joint, one takes the normal stiffness equal to the tangential stiffness. There is no tensile strength. The coupling between the normal opening and the tangential stiffness is selected of kind to have the worthless tangential slope as soon as the joint reaches the threshold of complete normal damage. The slope of softening in rupture is five times stiffer than the normal slope of loading (see R7.01.25 document). One clave after the gravitational mechanical loading with a nonworthless pressure of keying-up:

$K_N=K_T=10^{12} Pa/m \qquad \sigma_{max}=0 Pa \qquad \text{pena\_contact}=0.8$

$\alpha=1 \qquad \text{pena\_rupt}=0.2 \qquad \text{pres\_clav}=4.10^4 Pa$

(NB: values “tests” which do not correspond to any material in particular)

1.2.2 Material `JOINT_MECA_FROT`

For the law of friction associated with the joint, one chooses values “tests” which do not correspond to any material in particular.

$K_N=K_T/2=10^{12} Pa/m \qquad \sigma_{max}=3 MPa$

$\mu=0.35 \qquad \text{adhe}=1000 \qquad \text{ecrouissage}=0.1\,K_T$

2 Reference solution

2.1 Procedure of keying-up

We take as reference the solution given by the computer code *GEFDYN*. This procedure was validated on many industrial works. The opening of the joint after keying-up is tested.

2.2 Procedure of sawing

As for sawing we do not have a solution coming from an external code. The latter is validated then theoretically in modelings C and D, which accept a solution $1\mathrm{D}$.

Initially a homogeneous compression is applied δ_{impo} on the left side of the stud. The loading is quasi $1\mathrm{D}$ and there is thus the equivalence of constraints in the joint and the stud, which enables us to estimate the value of the pressure applied σ :

$$\delta_{plot}+\delta_{joint}=\delta_{impo} \qquad \sigma\, 2\, L/E+\sigma/\mathrm{pena\_contact}/K_N=\delta_{impo}$$

What gives:

$$\sigma=\delta_{impo}/(\frac{1}{2\, L\, E}+\frac{1}{\mathrm{pena\_contact}\; K_N})$$

Once the known constraint, one can apply the law of behavior in order to find the opening of the joint: $\delta_{joint}=\sigma/\mathrm{pena\_contact}/K_N$.

In the event of sawing the value of δ_{impo} is decreased the thickness of the saw, which paramétrise sawing.

These values of σ et δ_{joint} are tested thereafter in modelings C and D.

3 Modeling a: keying-up 2D `JOINT_MECA_RUPT`

3.1 Characteristics of modeling

Simulation is carried out with modeling `PLAN_JOINT`. The elements are of type `TRIA3` for the studs and `QUAD4` for the elements of joint. The corresponding law of behavior is `JOINT_MECA_RUPT`, the associated material bears the same name. The surface elements are elastic.

3.2 Characteristics of the grid

One carries out a linear grid of two studs and crack.
Voluminal elements (studs): 548 `TRIA3`
Elements of joint: 20 `QUAD4`

3.3 Sizes tested and results

3.3.1 External comparison source

The first test is carried out on the values of profile thickness of joint after keying-up by comparing it with the results of GEFDYN. One notes δ_n ($V7$) the normal opening of joint after keying-up:

Size tested	***GEFDYN***	***tolerance***
δ_n with the height : $2\,m$	6.38e-7	6%
δ_n with the height : $5\,m$	2.14e-6	7%
δ_n with the height : $8\,m$	3.88e-6	7%

3.3.2 Tests of nonregression

Values of the normal opening of joint δ_n ($V7$), as well as the normal constraints σ_n are tested with various heights ($2\,m, 4.5\,m, 8.5\,m$).

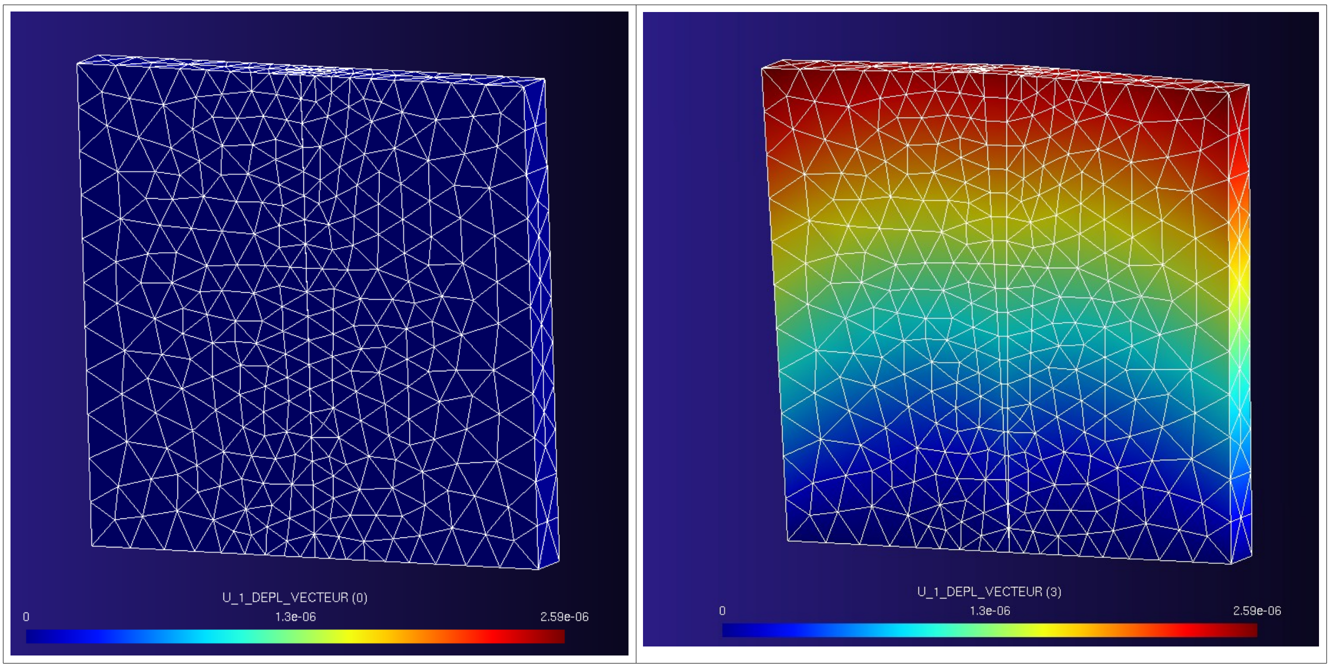
4 Modeling B: keying-up 3D `JOINT_MECA_RUPT`

4.1 Characteristics of modeling

Simulation is carried out with modeling `3D_JOINT`. The elements are of type `TETRA4` for the studs and `PENTA6` for the elements of joint. The corresponding law of behavior is `JOINT_MECA_RUPT`, the associated material bears the same name. The voluminal elements are elastic.

4.2 Characteristics of the grid

One carries out a linear grid not structured by extrusion of the grid 2D (figure below).
Voluminal elements (studs): 2761 `TETRA4`
Elements joint: 92 `PENTA6`



Drawing 3: Grid 3D, on the left the initial state, on the right the state after keying-up

4.3 Sizes tested and results

4.3.1 External comparison source

The first test is carried out on the values of profile thickness of joint after keying-up by comparing it with the results of *GEFDYN*. Grids of *GEFDYN* and of *Code_Aster* are not the same ones what explains the precision of rather high comparison. One notes δ_n ($V7$) the normal opening of joint after keying-up:

Size tested	*GEFDYN*	*tolerance*
δ_n with the height : $2m$	6.38e-7	4%
δ_n with the height : $5m$	2.14e-6	5%
δ_n with the height : $8m$	3.88e-6	4%

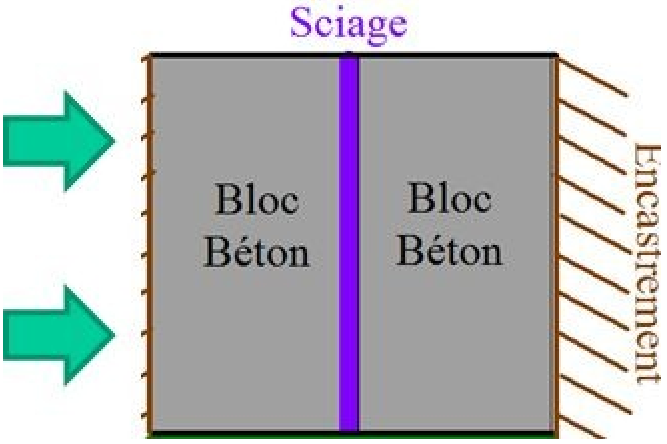
4.3.2 Tests of nonregression

Values of the normal opening of joint δ_n ($V7$), thickness of the joint δ_{offset} ($V10$), as well as the normal constraints σ_n are tested with various heights ($2\,m, 4.5\,m, 8.5\,m$).

5 Modeling C: theoretical sawing 2D

5.1 Characteristics of modeling

Simulation is carried out with modeling `PLAN_JOINT`. The elements are of type `TRIA3` for the studs and `QUAD4` for the elements of joint. The two laws of behavior are tested `JOINT_MECA_FROT` and `JOINT_MECA_RUPT`, the associated material bears the same name. The surface elements are elastic.



5.2 Characteristics of the grid

One carries out a linear grid of two studs and crack.
Voluminal elements (studs): 548 `TRIA3`
Elements of joint: 20 `QUAD4`

5.3 Sizes tested and results

The first tests are carried out right before sawing in state where the joint and the studs are compressed in a homogeneous way. Then one makes the same series of tests after sawing. The values tested are the profiles thickness of joint, like its opening and the constraint. One notes δ_n ($V7$) the normal opening of joint, thickness of the joint δ_{offset} ($V10$), as well as the normal constraints σ_n. The degree of freedom imposed is equal to $\delta_{impo}=-3\text{e-}6$, the thickness of saw is equal $\delta_{scie}=\delta_{impo}/3$

5.3.1 Before sawing, law **`JOINT_MECA_RUPT`**

The solution is given by the resolution of the problem $1\mathrm{D}$:

Size tested	**`'ANALYTICAL'`**	***tolerance***
σ_n with the height : $5\,m$	$\delta_{impo}/(\frac{1}{2\,L\,E}+\frac{1}{\text{pena\_contact}\,K_N})=-6.5454545\text{e}5$	0.1%
δ_n with the height : $2\,m$	$\frac{\sigma_n}{\text{pena\_contact}\,K_N}=-8.181818181\text{e-}7$	0.1%

5.3.2 After sawing, law **`JOINT_MECA_RUPT`**

The solution is given by the resolution of the problem $1\mathrm{D}$:

Size tested	**`'ANALYTICAL'`**	***tolerance***
σ_n with the height : $5\,m$	$(\delta_{impo}+\delta_{scie})/(\frac{1}{2LE}+\frac{1}{\text{pena\_contact}\,K_N})=-4.36364\text{e}5$	0.1%
δ_{offset} with the height : $8\,m$	$-\delta_{scie}=-1\text{e-}6$	0.1%
δ_n with the height : $2\,m$	$\frac{\sigma_n}{\text{pena\_contact}\,K_N}-\delta_{offset}=-1.5454545\text{e-}6$	0.1%

5.3.3 Before sawing, law `JOINT_MECA_FROT`

The solution is given by the resolution of the problem 1D :

Size tested	**`'ANALYTICAL'`**	***tolerance***
σ_n with the height : $5\,m$	$\delta_{impo}/(\frac{1}{2LE}+\frac{1}{K_N})=-6.923076923\text{e}5$	0.1%
δ_n with the height : $2\,m$	$\frac{\sigma_n}{K_N}=-6.923076923\text{e-}7$	0.1%

5.3.4 After sawing, law `JOINT_MECA_FROT`

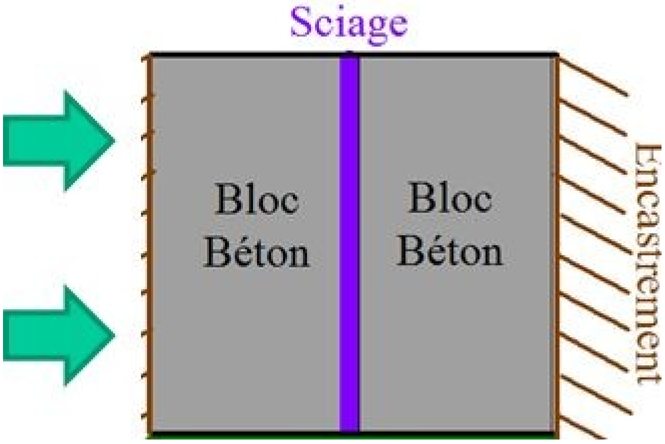
The solution is given by the resolution of the problem 1D :

Size tested	**`'ANALYTICAL'`**	***tolerance***
σ_n with the height : $5\,m$	$(\delta_{impo}+\delta_{scie})/(\frac{1}{2LE}+\frac{1}{K_N})=-4.6153846\text{e}5$	0.1%
δ_{offset} with the height : $8\,m$	$-\delta_{scie}=-1\text{e-}6$	0.1%
δ_n with the height : $2\,m$	$\frac{\sigma_n}{K_N}-\delta_{offset}=-1.46153846\text{e-}6$	0.1%

6 Modeling D: theoretical sawing 3D

6.1 Characteristics of modeling

Simulation is carried out with modeling `3D_JOINT`. The elements are of type `TETRA4` for the studs and `PENTA6` for the elements of joint. The two laws of behavior are tested `JOINT_MECA_FROT` and `JOINT_MECA_RUPT`, the associated material bears the same name. The surface elements are elastic.



6.2 Characteristics of the grid

One carries out a linear grid not structured by extrusion of the grid 2D (figure below).
Voluminal elements (studs): 2761 `TETRA4`
Elements joint: 92 `PENTA6`

6.3 Sizes tested and results

The first tests are carried out right before sawing in state where the joint and the studs are compressed in a homogeneous way. One follows makes the same series of tests after sawing. The values tested are profiles thickness of joint, like its opening and the constraint. One notes δ_n ($V7$) the normal opening of joint, thickness of the joint δ_{offset} ($V10$), as well as the normal constraints σ_n . The degree of freedom imposed is equal to $\delta_{impo}=-3e\text{-}6$, the thickness of saw is equal $\delta_{scie}=\delta_{impo}/3$

6.3.1 Before sawing, law `JOINT_MECA_RUPT`

The solution is given by the resolution of the problem 1D :

Size tested	'ANALYTICAL'	tolerance
σ_n with the height : $5\,m$	$\delta_{impo}/(\frac{1}{2LE}+\frac{1}{\text{pena\_contact}\,K_N})=-6.54545e5$	0.1%
δ_n with the height : $2\,m$	$\frac{\sigma_n}{\text{pena\_contact}\,K_N}=-8.1818182e\text{-}7$	0.1%

6.3.2 After sawing, law `JOINT_MECA_RUPT`

The solution is given by the resolution of the problem 1D :

Size tested	`'ANALYTICAL'`	*tolerance*
σ_n with the height : $5m$	$(\delta_{impo}+\delta_{scie})/(\frac{1}{2LE}+\frac{1}{\text{pena\_contact}\,K_N})=-4.363636\text{e}5$	0.1%
δ_{offset} with the height : $8m$	$-\delta_{scie}=-1\text{e-}6$	0.1%
δ_n with the height : $2m$	$\frac{\sigma_n}{\text{pena\_contact}\,K_N}-\delta_{offset}=-1.5454545\text{e-}6$	0.1%

6.3.3 Before sawing, law `JOINT_MECA_FROT`

The solution is given by the resolution of the problem $1D$:

Size tested	`'ANALYTICAL'`	*tolerance*
σ_n with the height : $5m$	$\delta_{impo}/(\frac{1}{2LE}+\frac{1}{K_N})=-6.923076923\text{e-}7$	0.1%
δ_n with the height : $2m$	$\frac{\sigma_n}{K_N}=-6.923076923\text{e-}7$	0.1%

6.3.4 After sawing, law `JOINT_MECA_FROT`

The solution is given by the resolution of the problem $1D$:

Size tested	`'ANALYTICAL'`	*tolerance*
σ_n with the height : $5m$	$(\delta_{impo}+\delta_{scie})/(\frac{1}{2LE}+\frac{1}{K_N})=-4.6153846\text{e}5$	0.1%
δ_{offset} with the height : $8m$	$-\delta_{scie}=-1\text{e-}6$	0.1%
δ_n with the height : $2m$	$\frac{\sigma_n}{K_N}-\delta_{offset}=-1.46153846\text{e-}6$	0.1%

7 Modeling E: sawing 2D `JOINT_MECA_RUPT`

7.1 Characteristics of modeling

Simulation is carried out with modeling `PLAN_JOINT`. The elements are of type `TRIA3` for the studs and `QUAD4` for the elements of joint. The corresponding law of behavior is `JOINT_MECA_RUPT`, the associated material bears the same name. The surface elements are elastic.

7.2 Characteristics of the grid

One carries out a linear grid of two studs and crack.
Voluminal elements (studs): 548 `TRIA3`
Elements of joint: 20 `QUAD4`

7.3 Sizes tested and results

One validates by the not-regression the procedure close to the industrial process. Values of the normal opening of joint δ_n ($V7$), thickness of the joint δ_{offset} ($V10$), as well as the normal constraints σ_n and tangential σ_t are tested with various heights.

8 Modeling F: sawing 3D `JOINT_MECA_RUPT`

8.1 Characteristics of modeling

Simulation is carried out with modeling `3D_JOINT`. The elements are of type `TETRA4` for the studs and `PENTA6` for the elements of joint. The corresponding law of behavior is `JOINT_MECA_RUPT`, the associated material bears the same name. The voluminal elements are elastic.

8.2 Characteristics of the grid

One carries out a linear grid not structured by extrusion of the grid 2D (figure below).
Voluminal elements (studs): 2761 `TETRA4`
Elements joint: 92 `PENTA6`

8.3 Sizes tested and results

One validates by the not-regression the procedure close to the industrial process. Values of the normal opening of joint δ_n ($V7$), thickness of the joint δ_{offset} ($V10$), as well as the normal constraints σ_n and tangential σ_t are tested with various heights.

9 Modeling G: sawing 2D `JOINT_MECA_FROT`

9.1 Characteristics of modeling

Simulation is carried out with modeling `PLAN_JOINT`. The elements are of type `TRIA3` for the studs and `QUAD4` for the elements of joint. The corresponding law of behavior is `JOINT_MECA_FROT`, the associated material bears the same name. The surface elements are elastic.

9.2 Characteristics of the grid

One carries out a linear grid of two studs and crack.
Voluminal elements (studs): 548 `TRIA3`
Elements of joint: 20 `QUAD4`

9.3 Sizes tested and results

One validates by the not-regression the procedure close to the industrial process. Values of the normal opening of joint δ_n ($V7$), thickness of the joint δ_{offset} ($V10$), as well as the normal constraints σ_n and tangential σ_t are tested with various heights.

10 Modeling H: sawing 3D `JOINT_MECA_FROT`

10.1 Characteristics of modeling

Simulation is carried out with modeling `3D_JOINT`. The elements are of type `TETRA4` for the studs and `PENTA6` for the elements of joint. The corresponding law of behavior is `JOINT_MECA_FROT`, the associated material bears the same name. The voluminal elements are elastic.

10.2 Characteristics of the grid

One carries out a linear grid not structured by extrusion of the grid 2D (figure below).
Voluminal elements (studs): 2761 `TETRA4`
Elements joint: `92 PENTA6`

10.3 Sizes tested and results

One validates by the not-regression the procedure close to the industrial process. Values of the normal opening of joint δ_n ($V7$), thickness of the joint δ_{offset} ($V10$), as well as the normal constraints σ_n and tangential σ_t are tested with various heights.

11 Summary of the results

Procedure of keying-up implemented in *Code_Aster* via the law `JOINT_MECA_RUPT` and the keyword `PRES_CLAVAGE` coincide with the results of the code *GEFDYN*.

Procedure of sawing implemented in *Code_Aster* for laws `JOINT_MECA_RUPT and JOINT_MECA_FROT` via the keyword `SAWING` is validated on a theoretical test $1D$, it gives good performances on tests close to the real situations on the stoppings.