UNIMORE
UNIVERSITÀ DEGLI STUDI DI MODENA E REGGIO EMILIA

Dipartimento di Ingegneria
“Enzo Ferrari”

Progettazione Assistita di Organi di Macchine

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Agenda

MSC Marc Mentat: Select entities

- Method & Mode;
- Store;
- Identify set.

Thin-walled profile in torsion

- Opened vs closed cross-section;
- Mesh convergence.

References

Agenda

MSC Marc Mentat: Select entities

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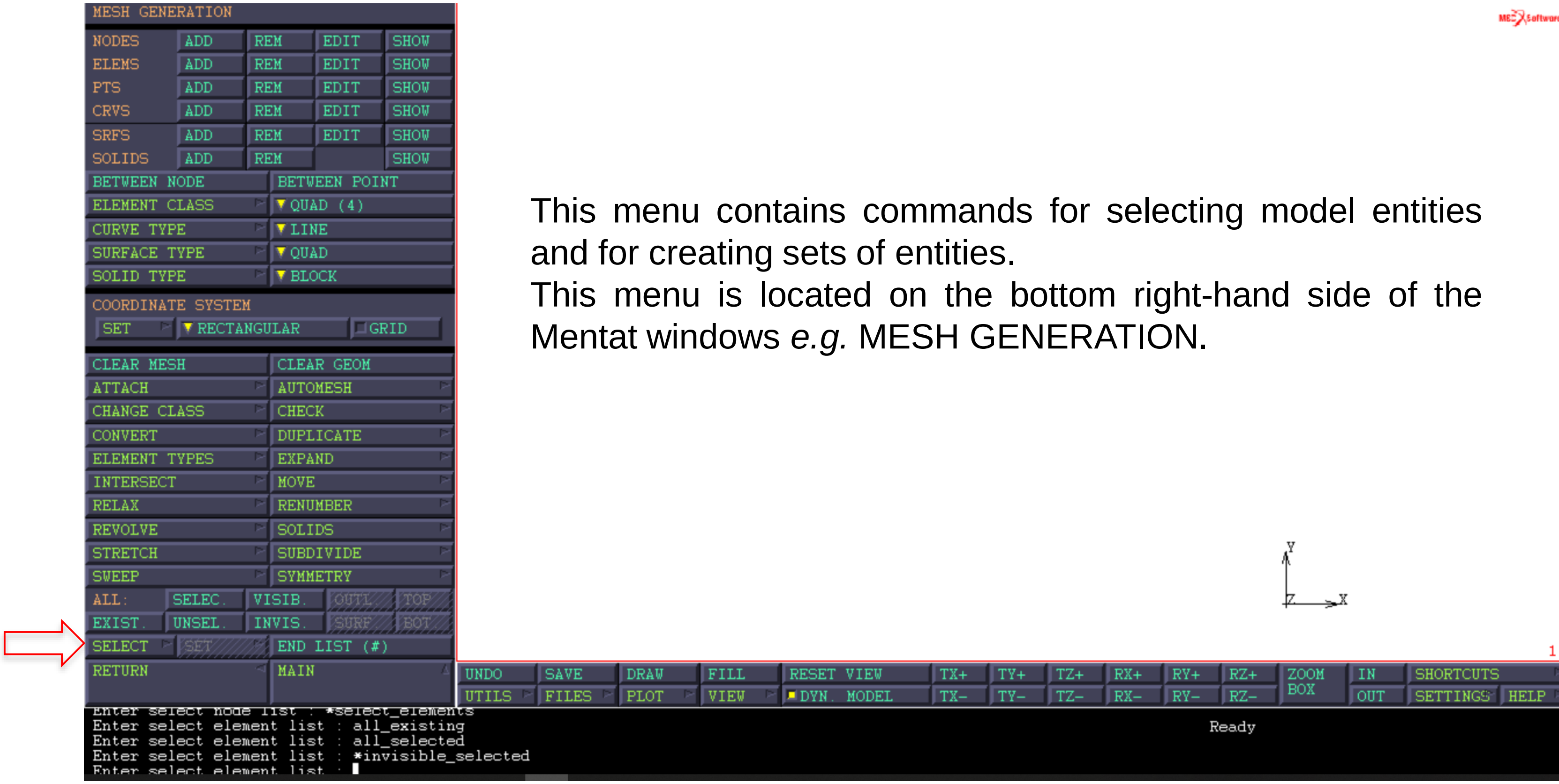
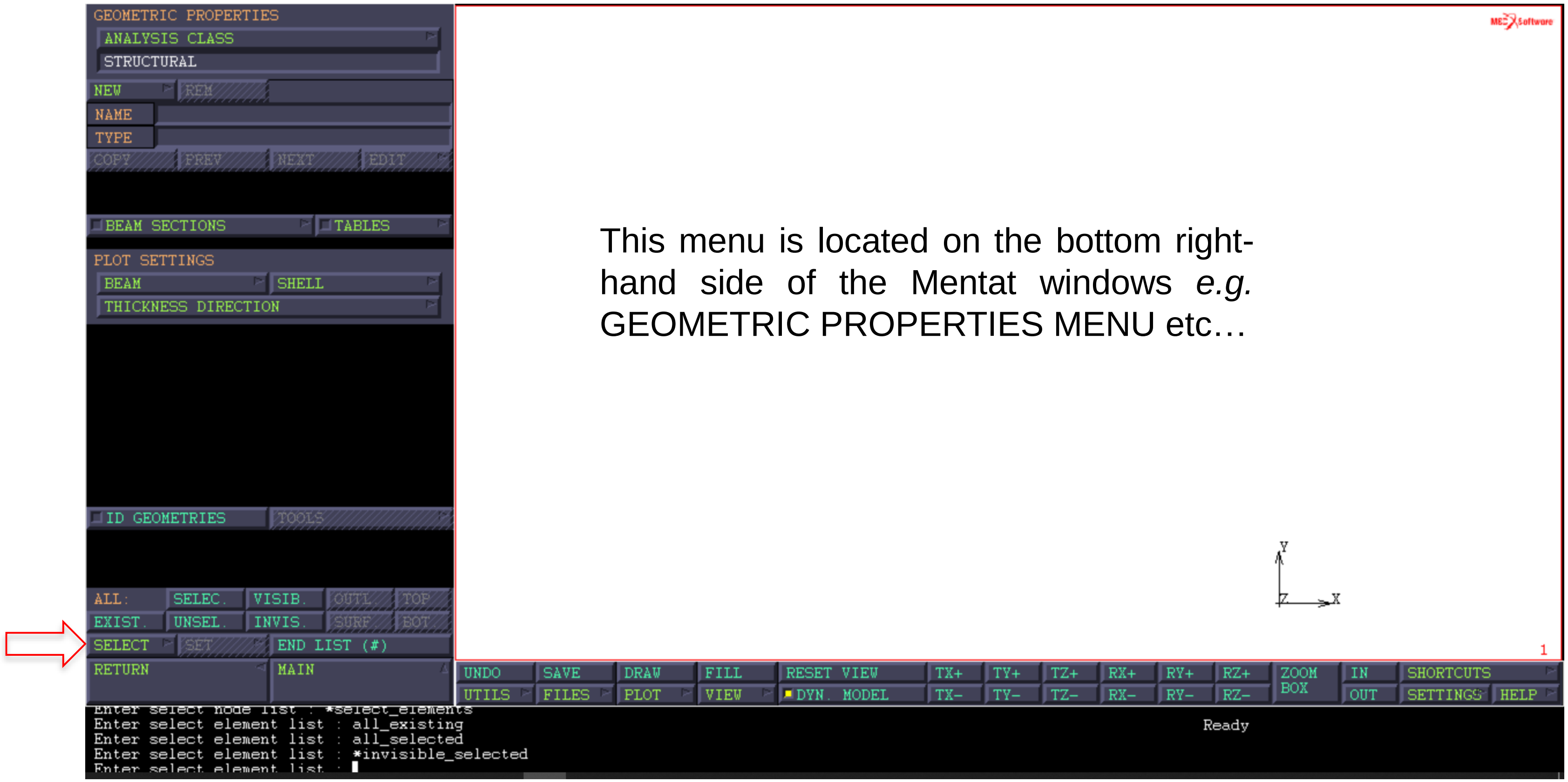
References

MENU: SELECT



This menu contains commands for selecting model entities and for creating sets of entities.
This menu is located on the bottom right-hand side of the Mentat windows *e.g.* MESH GENERATION.

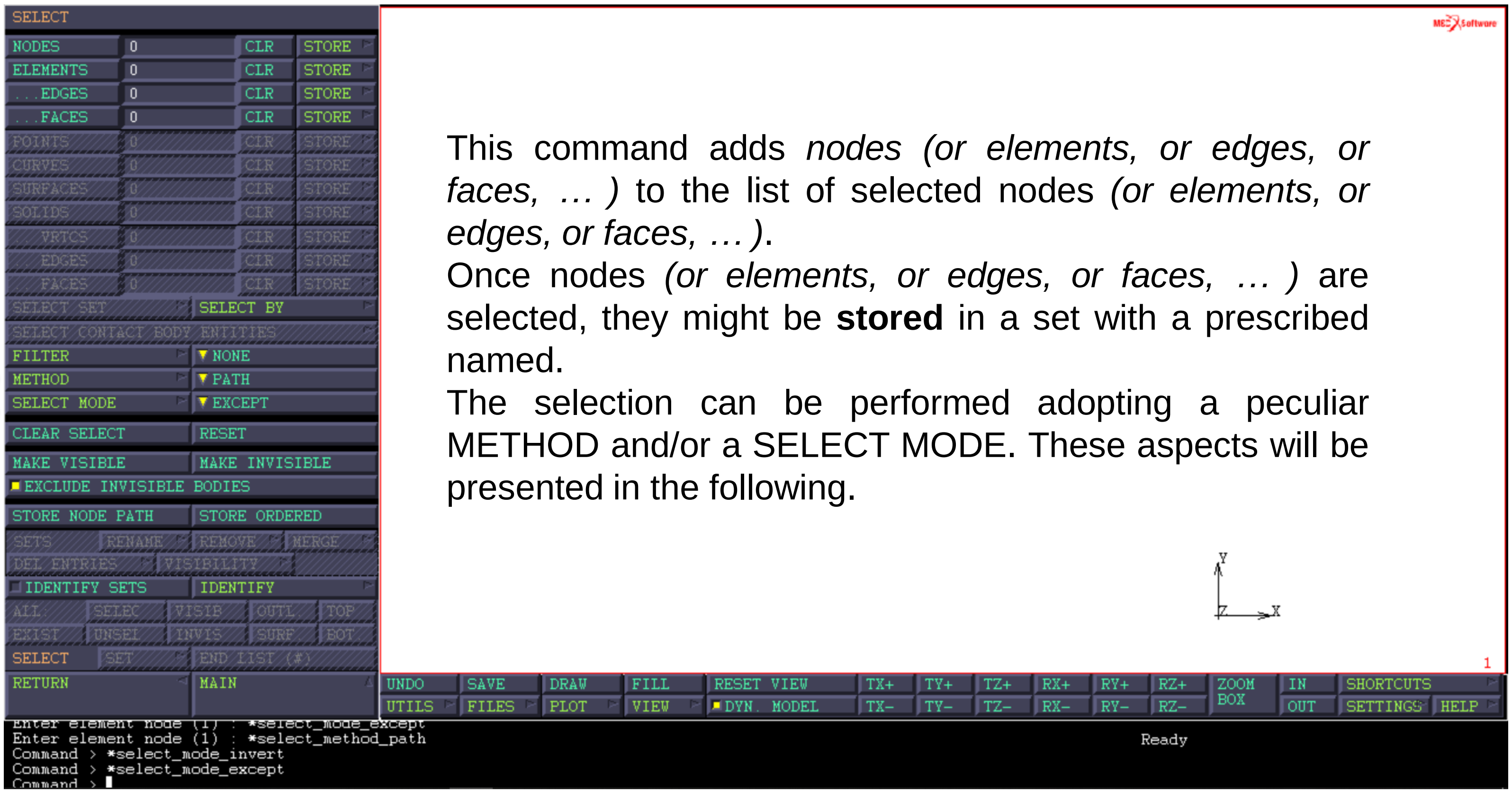
MENU: SELECT



This menu is located on the bottom right-hand side of the Mentat windows *e.g.* GEOMETRIC PROPERTIES MENU etc…

Select entities

e.g. nodes, elements, points, curves, …



This command adds *nodes (or elements, or edges, or faces, …)* to the list of selected nodes *(or elements, or edges, or faces, …)*.

Once nodes *(or elements, or edges, or faces, …)* are selected, they might be **stored** in a set with a prescribed named.

The selection can be performed adopting a peculiar METHOD and/or a SELECT MODE. These aspects will be presented in the following.

Select entities: METHOD

e.g. nodes, elements, points, curves, …

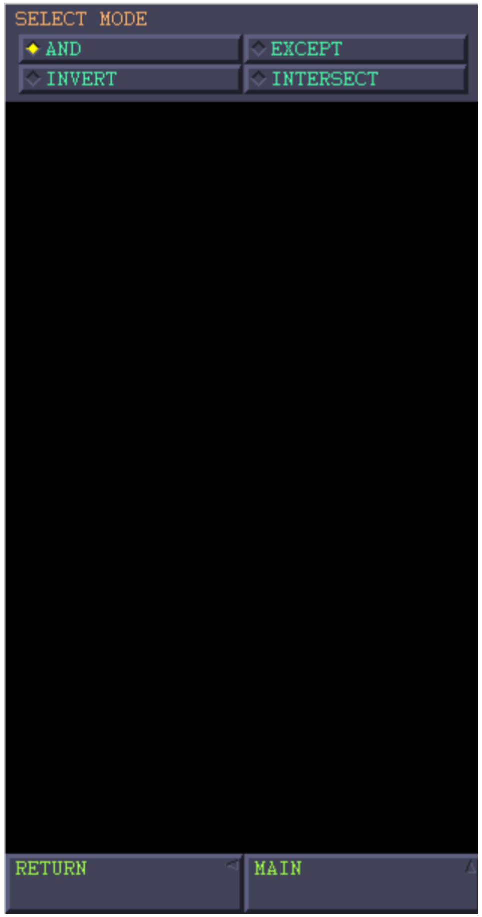
SINGLE: this method allows the user to select entities singly by specifying their *IDs* or by manual selection (mouse). This method is the *default method.*

PATH: this method allows the user to select connected nodes or points along a path from the first entity specified to the last. You may specify only the beginning and end of the path, or choose entities at various location along the path.

BOX: this method allows the user to select items within a specified region in space therefore a volume assessed by coordinates. All items that fall within the specified box (global coordinate system) become selected.

Select entities: MODE

e.g. nodes, elements, points, curves, …



AND: adopting this mode, additionally selected entities are added with those already in the selected list, thus adding them to the list. This mode is the *default mode.*

EXCEPT: by this mode, additionally selected entities are removed from the list of selected entities.

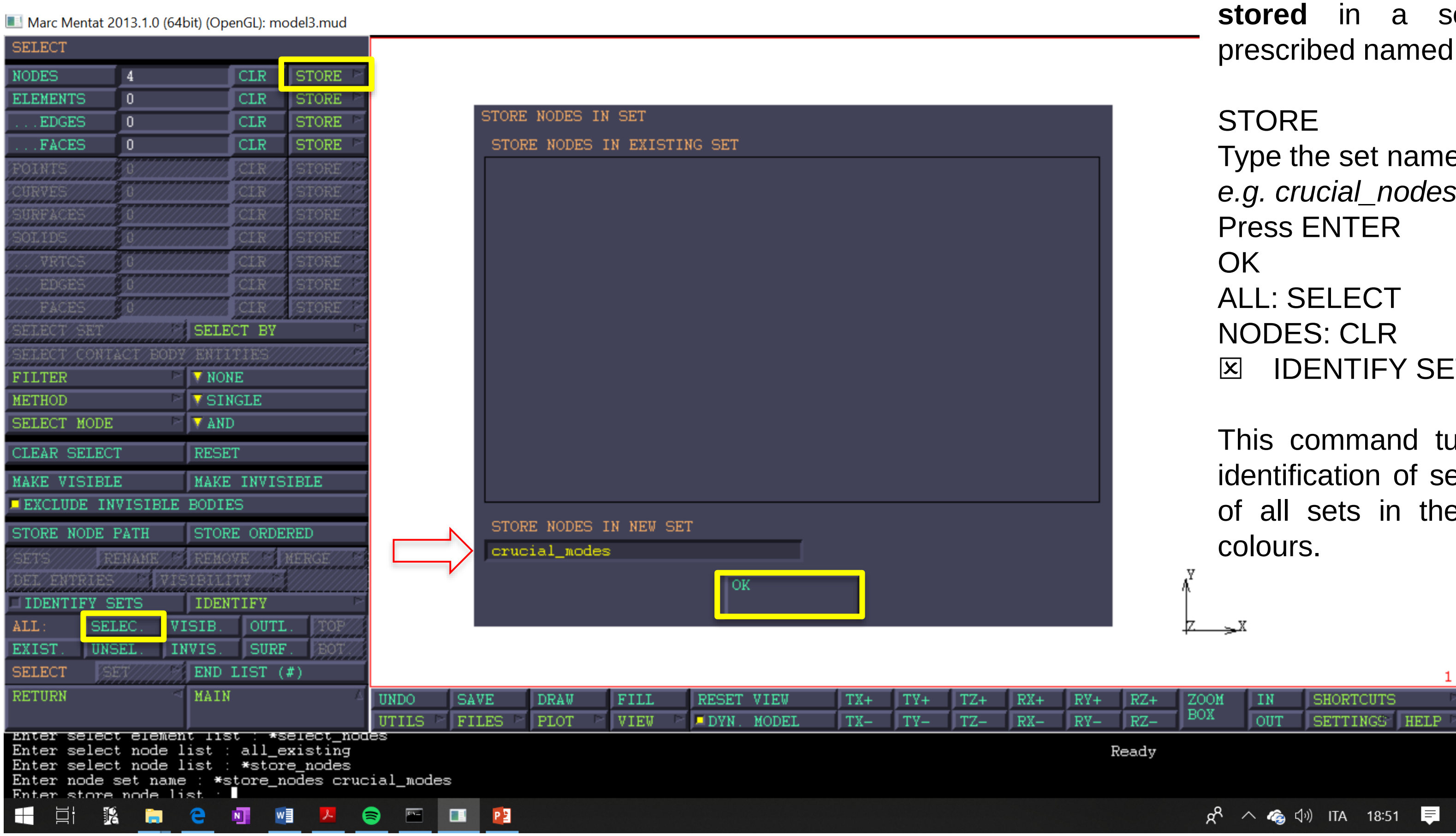
INVERT: in this mode, additionally selected entities are added to the list of selected entities if they do NOT belong to it and are removed if they do already belong to it.

INTERSECT: in this mode, additionally selected entities are intersected with the current list of selected entities to form the new list.

→ I suggest you to do some exercises!!!!

Select entities: STORE

e.g. nodes



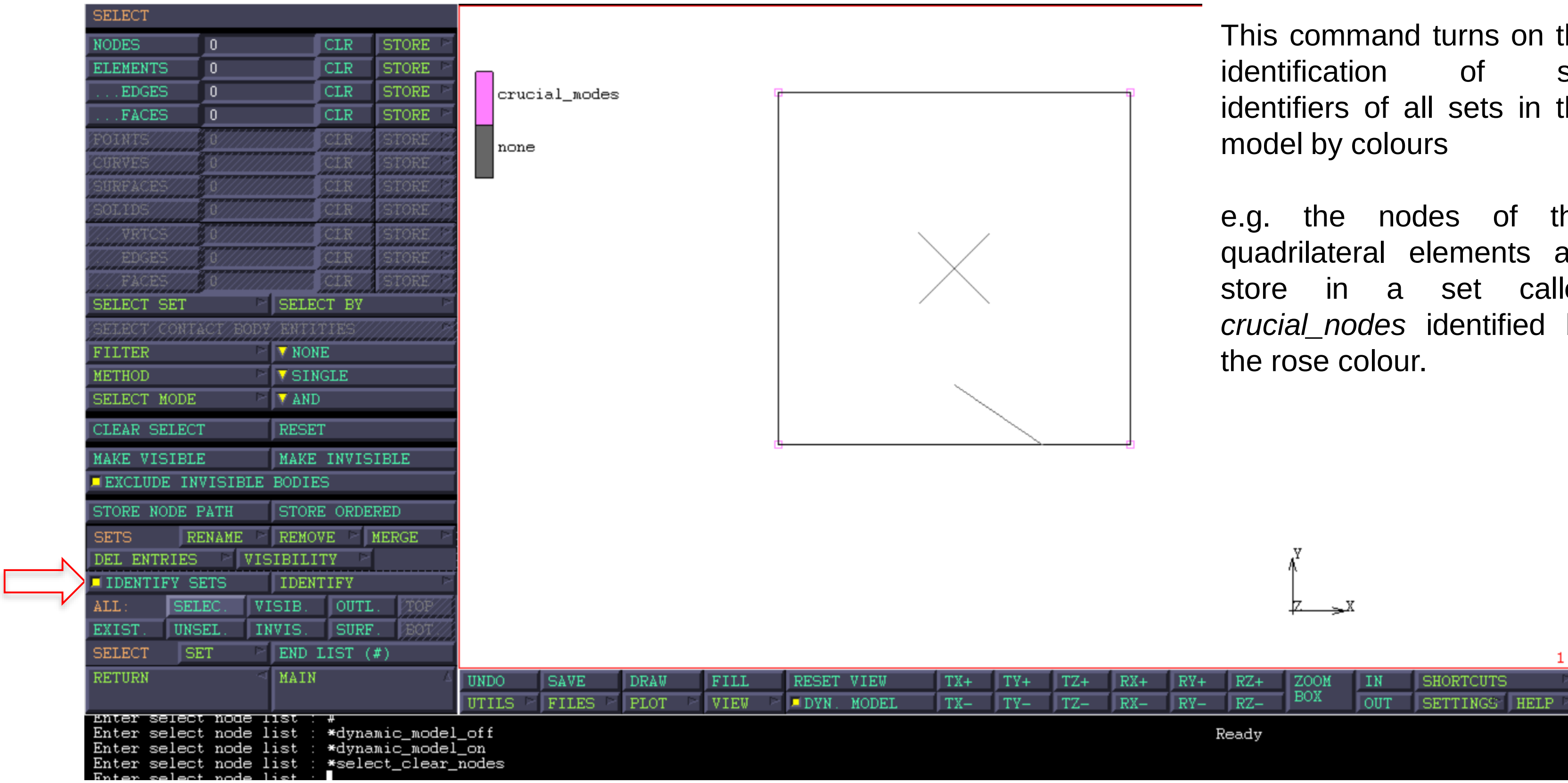
Once nodes *(or elements, or edges, or faces, …)* are selected, they might be **stored** in a set with a prescribed named.

STORE
Type the set named
e.g. crucial_nodes
Press ENTER
OK
ALL: SELECT
NODES: CLR
☒ IDENTIFY SETS

This command turns on the identification of set identifiers of all sets in the model by colours.

Select entities: IDENTIFY SETS

e.g. nodes



☒ IDENTIFY SETS

This command turns on the identification of set identifiers of all sets in the model by colours

e.g. the nodes of this quadrilateral elements are store in a set called *crucial_nodes* identified by the rose colour.

Agenda

MSC Marc Mentat: Select entities

- Method & Mode;
- Store;
- Identify set.

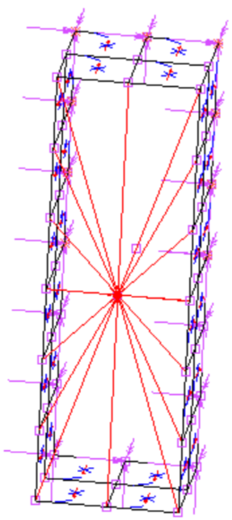
Thin-walled profile in torsion

- Opened vs closed cross-section;
- Mesh convergence.

References

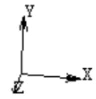
Thin-walled profile in torsion

Opened vs closed cross-section



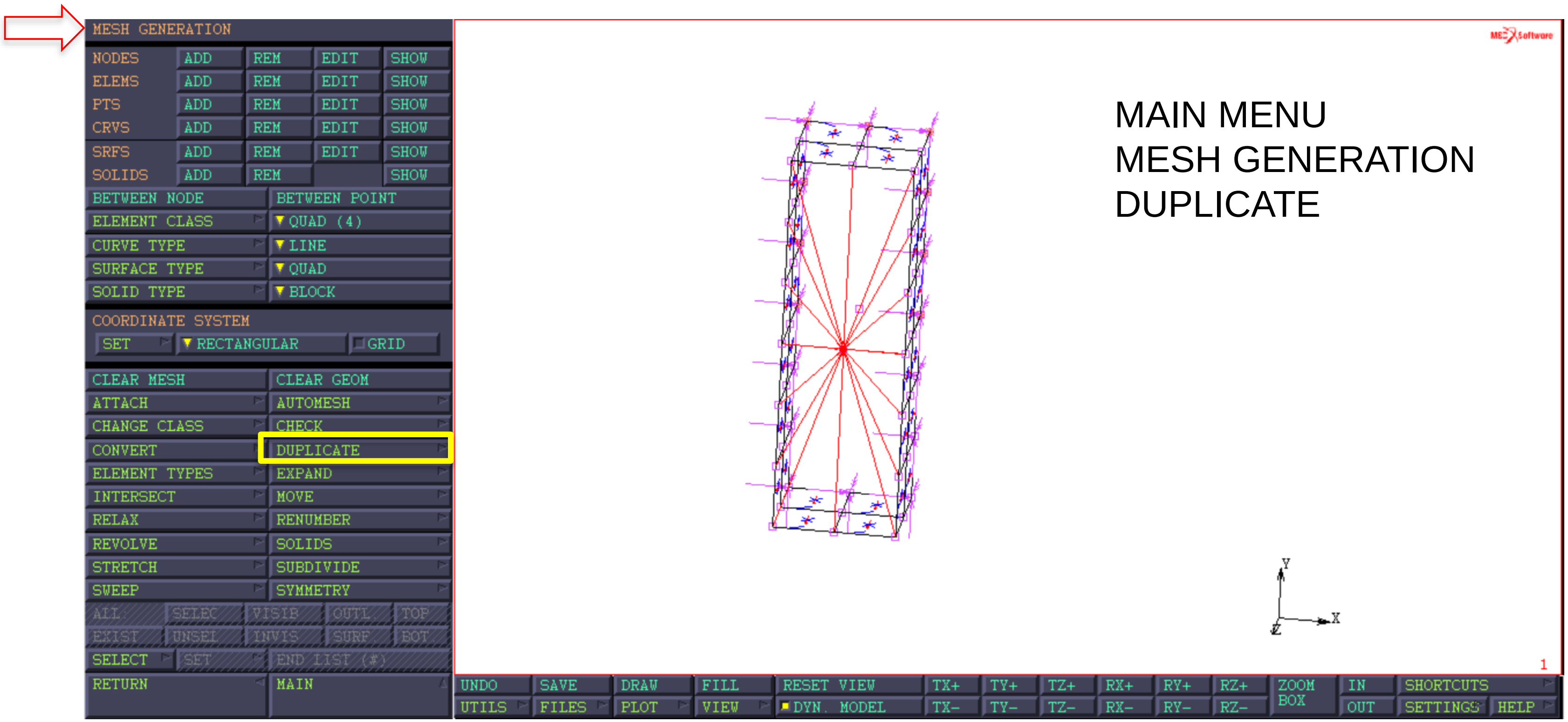
GOAL:
Open the reference model named `torsione_rev01_nolabile.mud` this profile is characterized by a lateral crack (open-cross section).
It is loaded on the free extremity by an imposed rotation.

Starting from this model, we will compare the response of the open section profile with the homologous closed profile calculating their torsional stiffness.
`torsione_rev01_nolabile_open_vs_close.mud`



MESH GENERATION

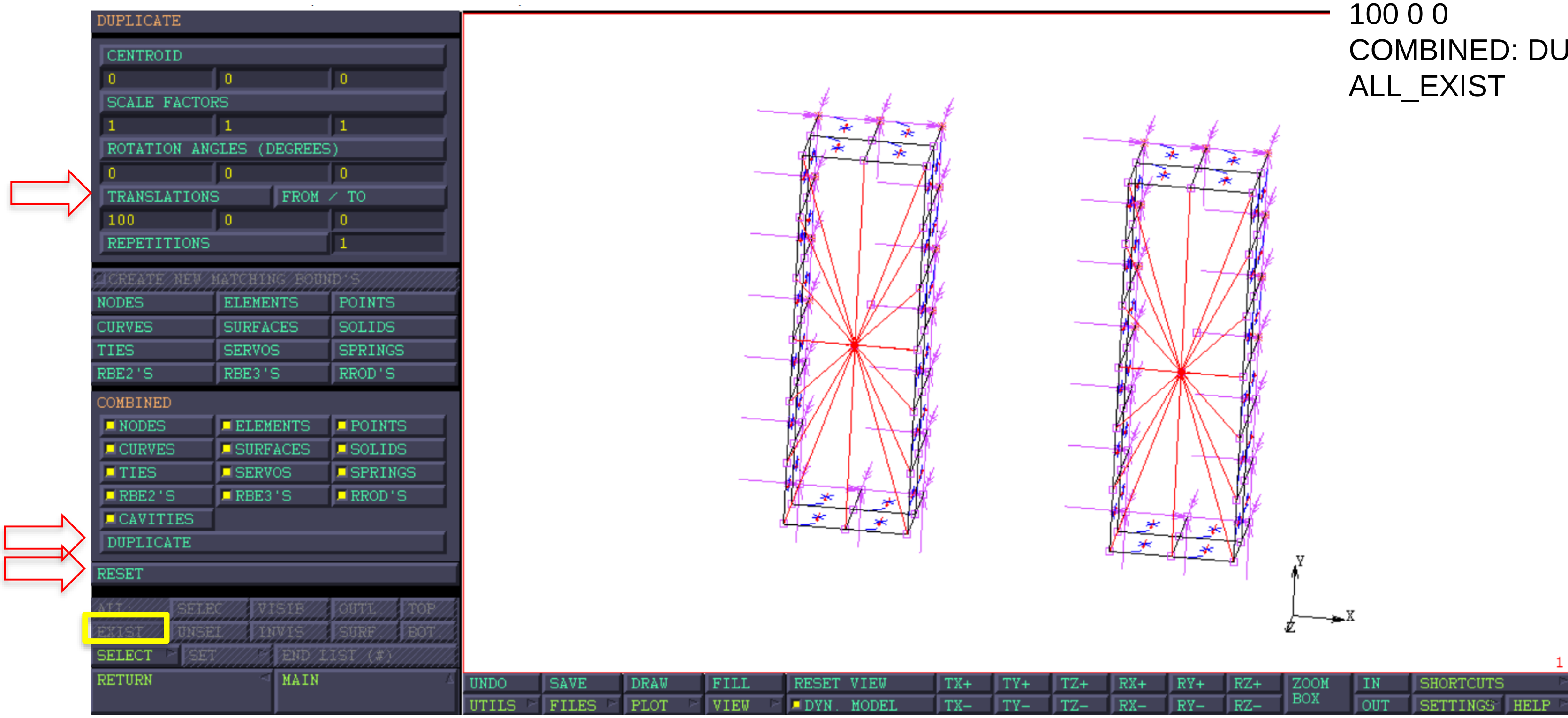
Duplicate



Duplicate

Combined

DUPLICATE RESET
TRANSLATIONS
100 0 0
COMBINED: DUPLICATE
ALL_EXIST

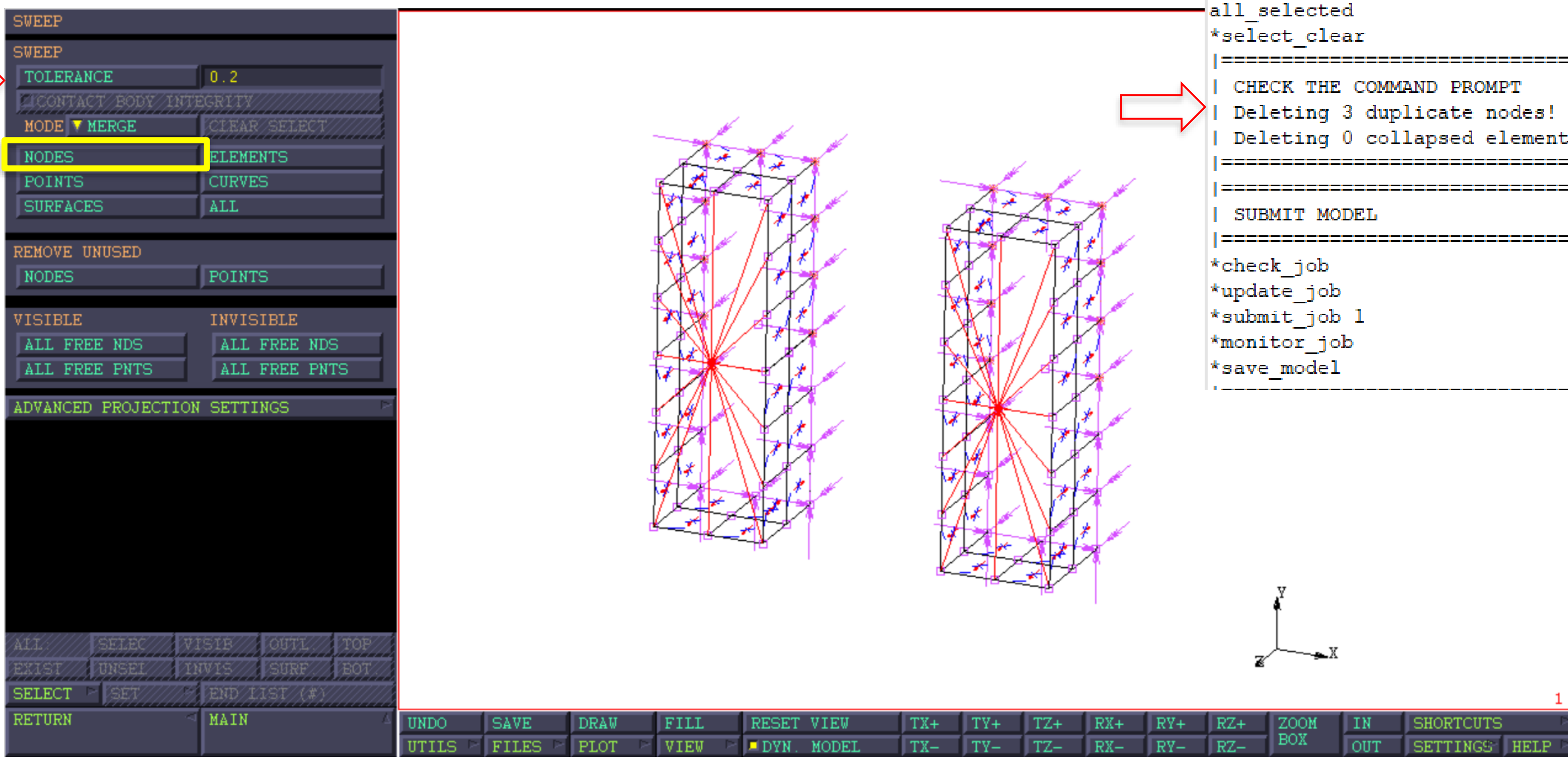


The reference model will be **completely** duplicated (*e.g.* nodes, elements, BCs, links) , it will be located at a distance of 100 mm from the origin (0,0,0) along X-direction referring to the global coordinate system of the model.

Sweep

The left-hand side model is the profile with the open cross-section, named OPENED
The right-hand side model is the profile with the open cross-section, named CLOSED.
Therefore, the lateral crack of the right-hand side model will be removed by the SWEEP NODES function as shown here.
Finally, the model is ready to be calculated (SUBMIT).

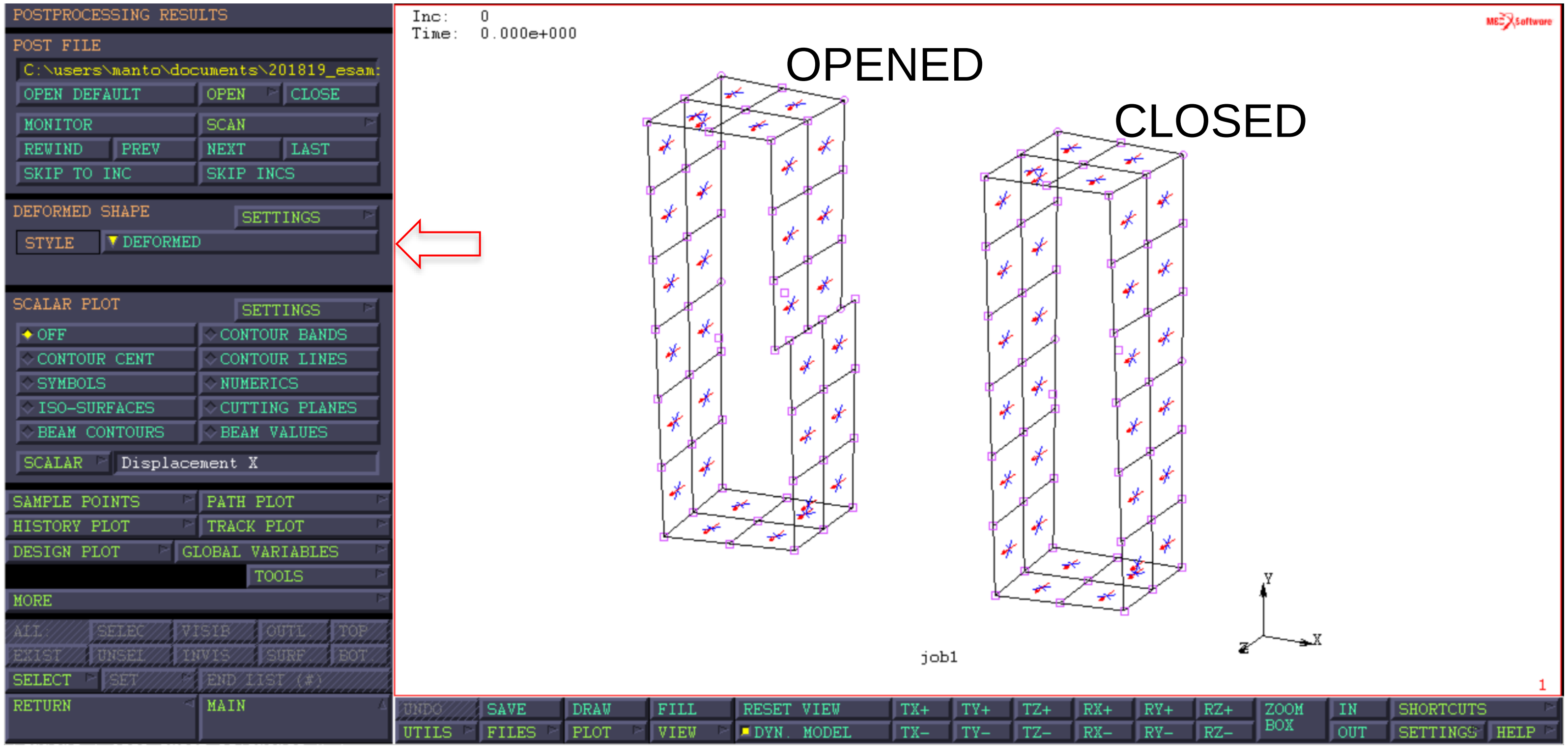
```
|===================================
| SWEEP NODES - CLOSE LATERAL CRACK
| the tolerance (t) must be:
| at least upper then the crack size;
| lower than the elements size;
| therefore  0.1 < t < 20
| I consider a tolerance value equal to 0.2
|===================================
*set_sweep_tolerance
0.2
*sweep_nodes
all_selected
*select_clear
|===================================
| CHECK THE COMMAND PROMPT
| Deleting 3 duplicate nodes!
| Deleting 0 collapsed elements!
|===================================
|===================================
| SUBMIT MODEL
|===================================
*check_job
*update_job
*submit_job 1
*monitor_job
*save_model
|-----------------------------------
```



Thin-walled profile in torsion

Opened vs closed cross-section: RESULTS

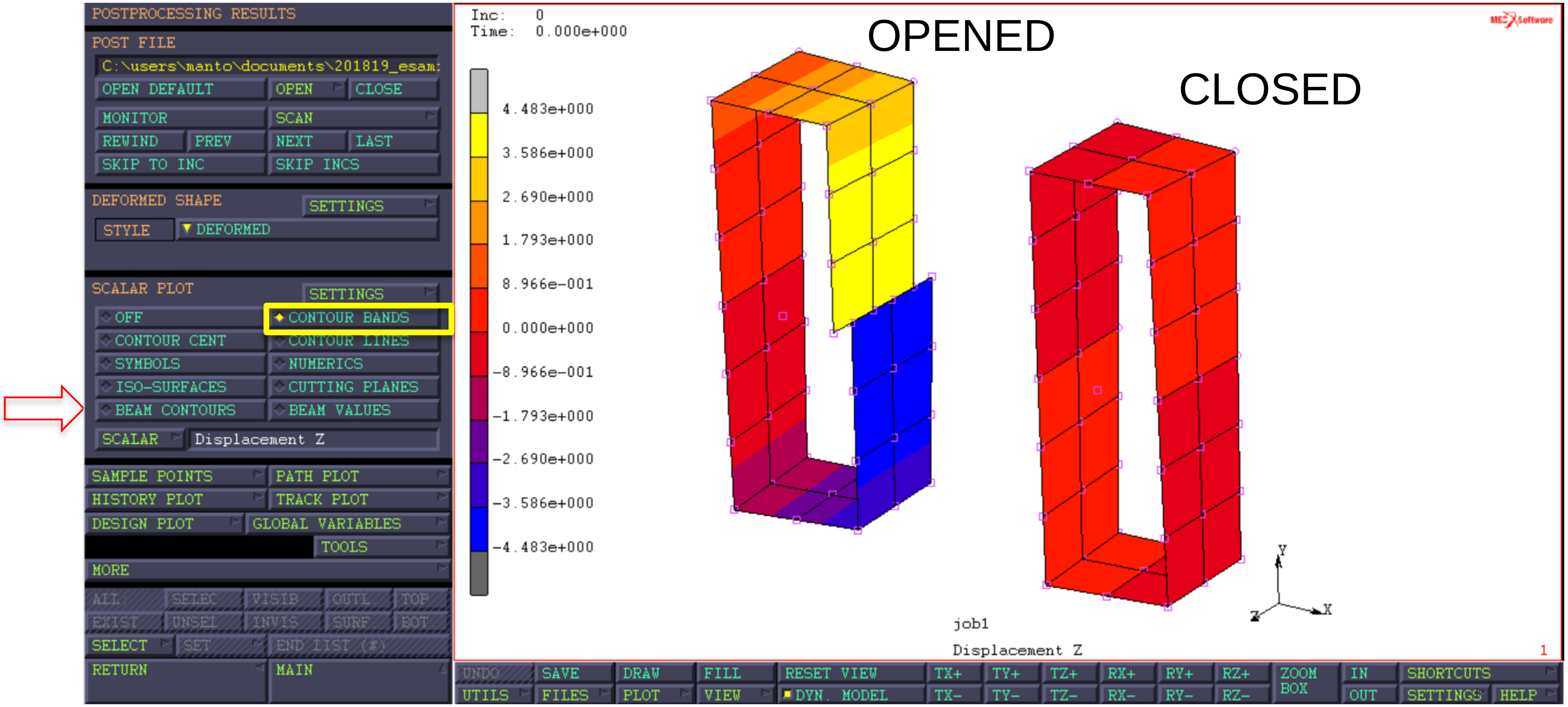
Open the results file. Check if the **deformation** of the models is coherent with you expected!!!



Thin-walled profile in torsion
Opened vs closed cross-section: RESULTS

Check the warping of the profile cross-section at their free extremity!! The simplest way is monitoring the displacement of the section along the Z direction (Displacement Z).

OPENED PROFILE: the maximum (minimum) Z-displacement is equal to 4.483 mm (-4.483 mm);
CLOSED PROFILE: the maximum (minimum) Z-displacement is equal to 0.57 mm (-0.57 mm).

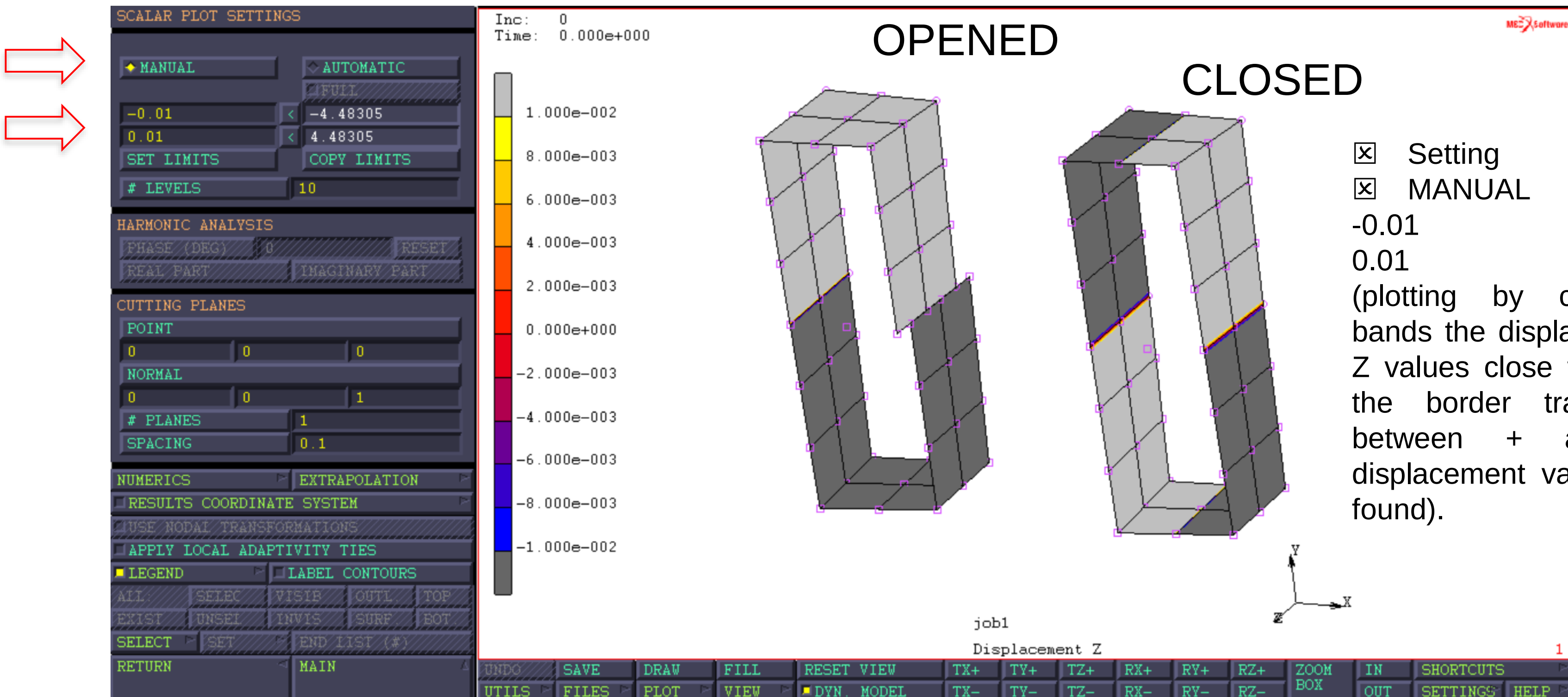


Moving from a opened to a closed section, the warping decreases significantly.

Thin-walled profile in torsion

Opened vs closed cross-section: RESULTS

Check the warping of the profile cross-section at their free extremity!! The simplest way is monitoring the displacement of the section along the Z direction (Displacement Z).
Some regions evidence a null deformation along the Z direction; therefore; along this segments, the warping does not occur.

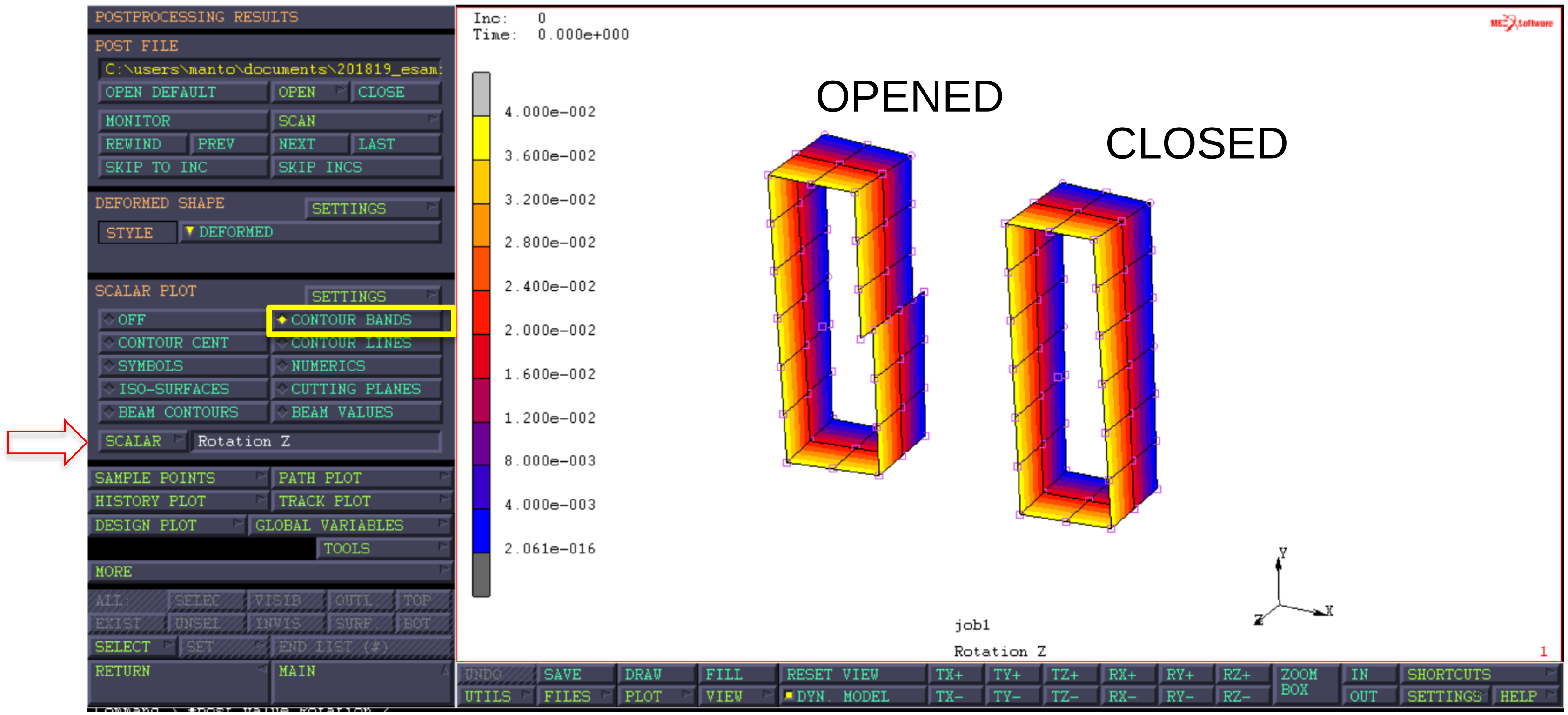


☒ Setting
☒ MANUAL
-0.01
0.01
(plotting by coloured bands the displacement Z values close to zero, the border transition, between + and – displacement values. is found).

Thin-walled profile in torsion

Opened vs closed cross-section: RESULTS

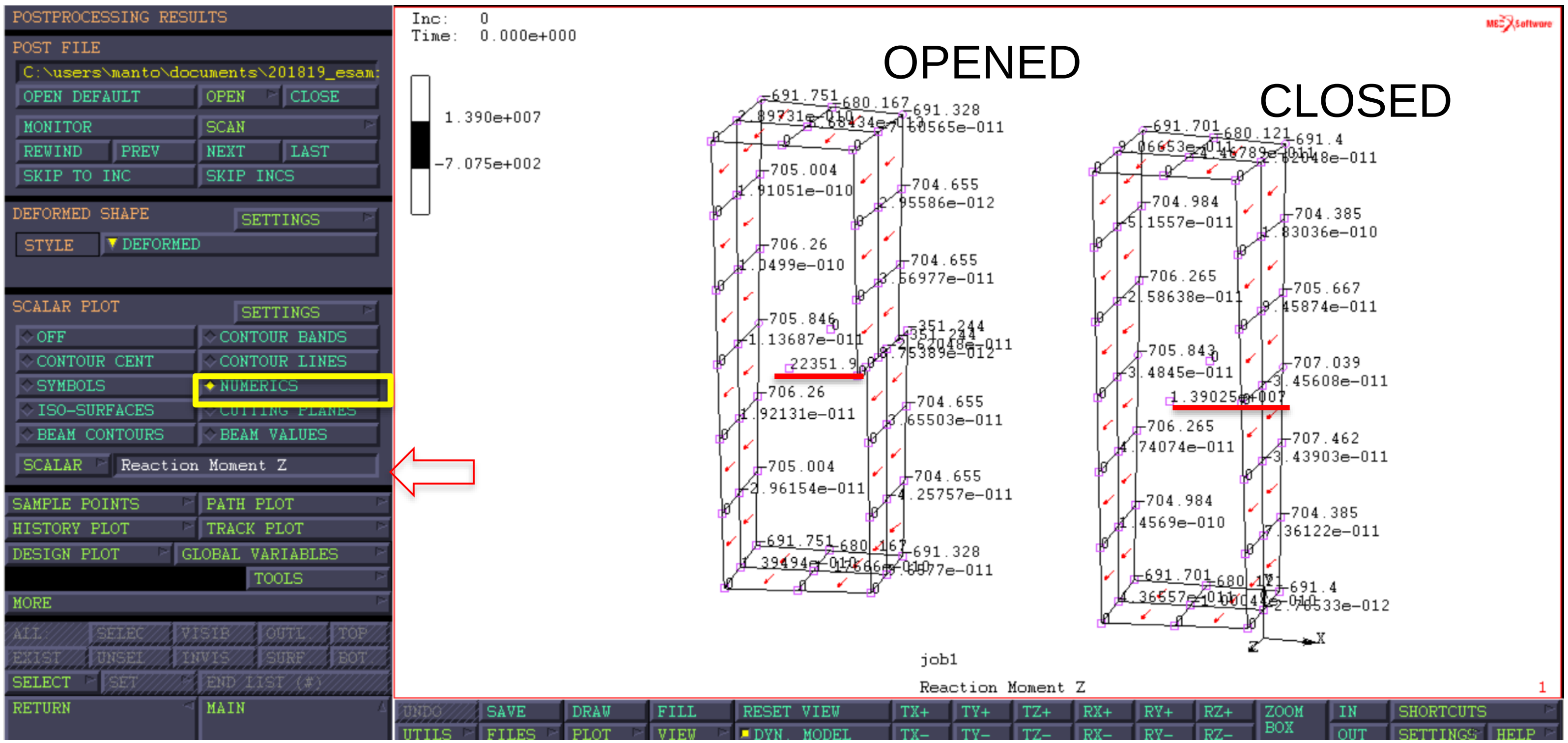
Check if the **rotation along the Z axis (Rotation Z)** of the models is coherent with you expected!!! The models do not rotate at the skew symmetry plane (Z=0), and the maximum rotation is equal to 0.04 radians, and it is located at the free extremity of the model.



Thin-walled profile in torsion

Opened vs closed cross-section: RESULTS

Collect the values of **Reaction Moment Z** to compare the stiffness of the two profiles accounting the influence of the lateral crack.



For the same rotation, the reaction moment increases moving from an opened to a closed section profile. Therefore, the torsional stiffness will be increased significantly, too.

Thin-walled profile in torsion

Opened vs closed cross-section: RESULTS

1			input cell			
2	**Beam profile dimensions**					
3	heigth, at the midsurface	_h	118	mm		
4	width, at the midsurface	_b	38	mm		
5	wall thickness	_s	2	mm		
6	fillet radius	_r	0	mm		
7	section characteristic dimension	_l	120	mm		
8	modeled profile portion length (half the overall length)	_dz	**40**	mm		
9	profile wall perimeter	_p	312	mm		
10	profile wall midurve enclosed area	_BredtArea	4484	mm^2		
11						
12	**Predicted torsional stiffness values**					
13	open thin walled section	_Kt_otw	832	mm^4		
14	closed thin walled section, Bredt Formula	_Kt_ctw	515545,026	mm^4		
15						
16	**Predicted shear stress values**					
17	open thin walled section	_tau_otw	53,8461538	MPa		
18	closed thin walled section, Bredt Formula	_tau_ctw	773,865878	MPa		
19						
20	**material properties**					
21	shear modulus (G12 in-plane shear modulus if orthot	_G	26923,0769	MPa		
22						
23	**imposed displacements**					
24	twist rate	_dtheta_dz	0,001	rad/mm		
25	torsional counter-rotation at the profile terminals	_theta_z	0,04	rad		
26						
27	**measured reaction torque (of FE models), complete section**					
28	open thin walled section, free warping at both ends	_Mt_otw_warp	22351,9	Nmm		
29	closed thin walled section, free warping at both ends	_Mt_ctw_warp	1,39E+07	Nmm		
32						
33	**results**					
34	profile section torsional stiffness coefficient					
35	open thin walled section, free warping at both ends	_Kt_otw_warp	830,213429	mm^4		formula rigidezza tors. Sez. Sottili aperte
36	closed thin walled section, free warping at both ends	_Kt_ctw_warp	516378,571	mm^4		formula di Bredt
39						
40	**result comparison**		ratio	relative variation		
41	otw, free warp, FE vs theoretical ratio		0,99785268	-0,21%		
42	ctw, free warp, FE vs theoretical ratio		1,00161682	0,16%		
43						
44	free warp, FE, otw vs ctw ratio		0,00160776	-99,84%		
45						
46	OTW constrained terminals stiffening factor		733,396266	73239,63%		
47	CTW constrained terminals stiffening factor		1,21610502	21,61%		
48						

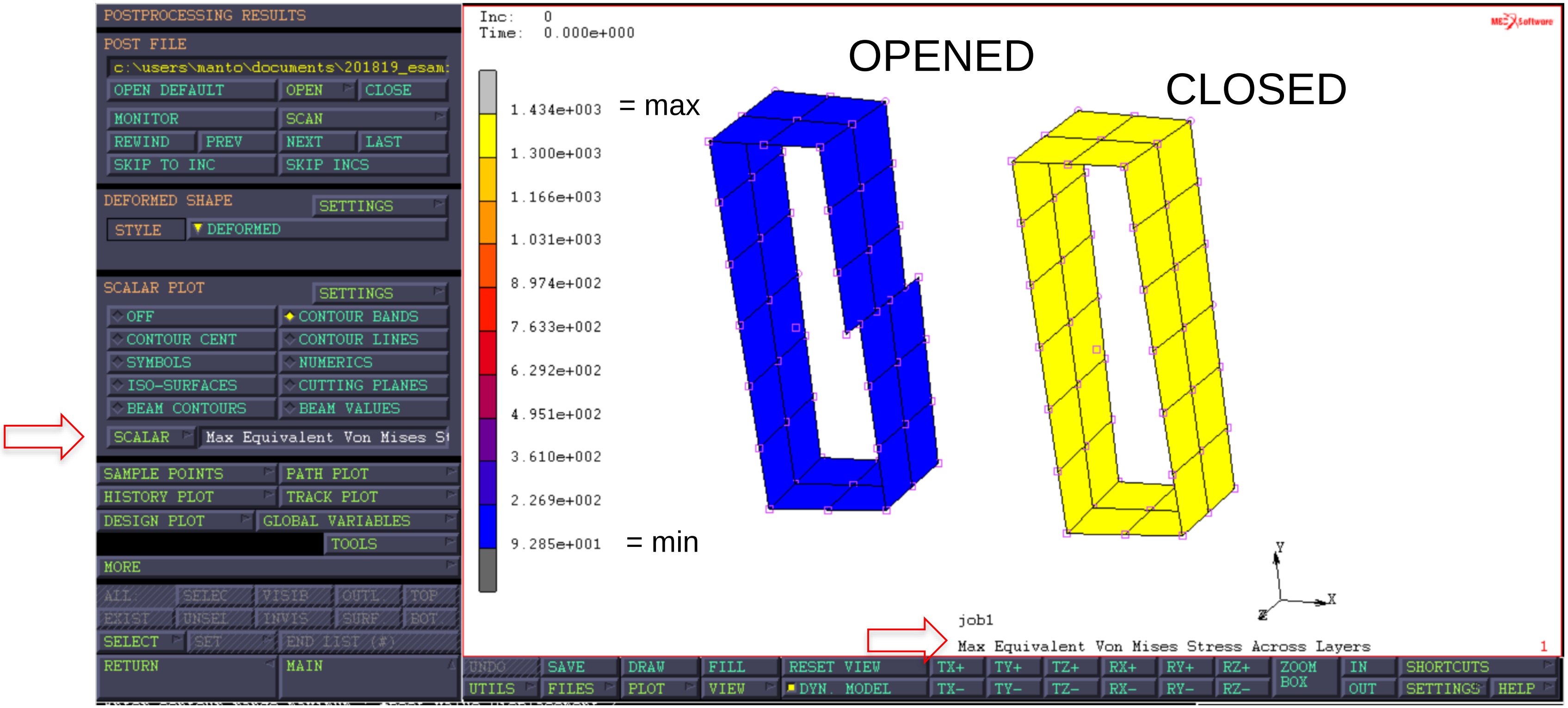
The stiffness of the profiles has been analytically calculated adopting the Bredt approach for the closed section, and the formulae for the open thin section under torsion.

The analytical results are compared to the FE results, under the hypothesis of free warping of the structures.

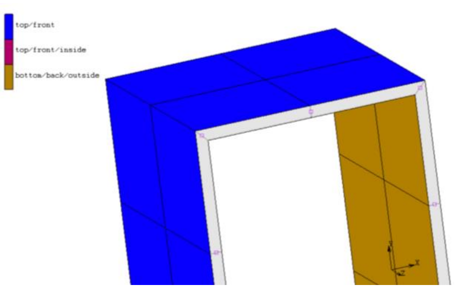
Reference:
`torsional_stiffness_evaluation_paom2019_v001.ods;`
`spreadsheet: section_property_dz_40`

Thin-walled profile in torsion

Opened vs closed cross-section: RESULTS



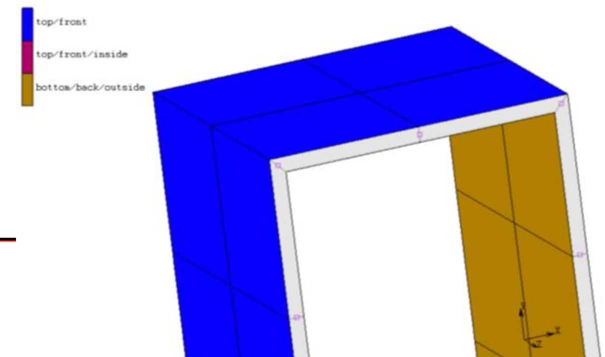
The maximum equivalent Von Mise stress occuring across the layers (top, middle, bottom) is plotted, and the opened and the closed profiles achieve the maximum stress value equal to 93 MPa and 1434 MPa, respectively.

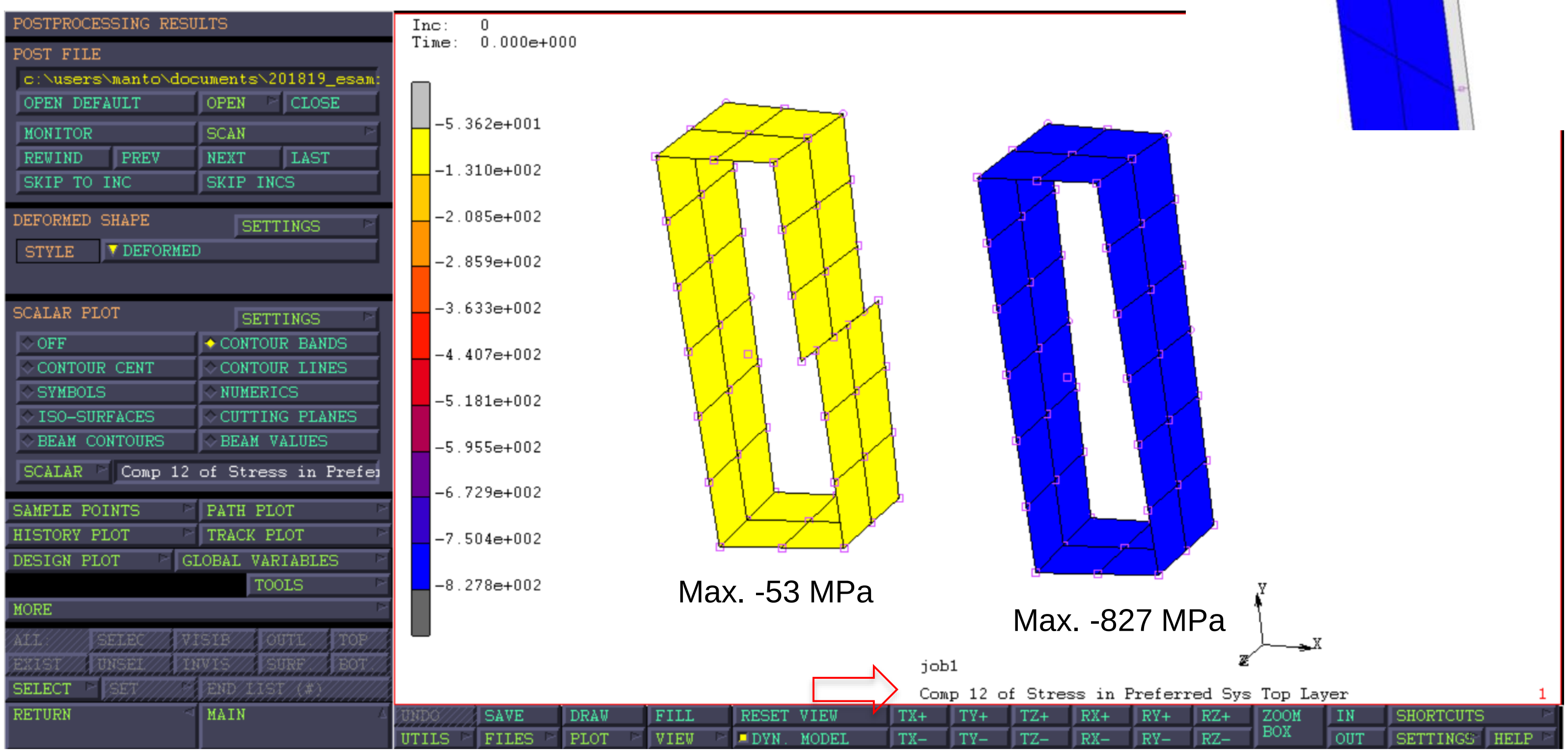


Thin-walled profile in torsion

Opened vs closde cross-section: RESULTS

From the analysis of the components of stress at the TOP SURFACE, the stress that contributes significantly to the evaluation of the equivalent von Mises stress is the shear stress (`Comp. 12 of stress in preferred system`). The further stresses are negligible ($\approx 10^{-11}$).

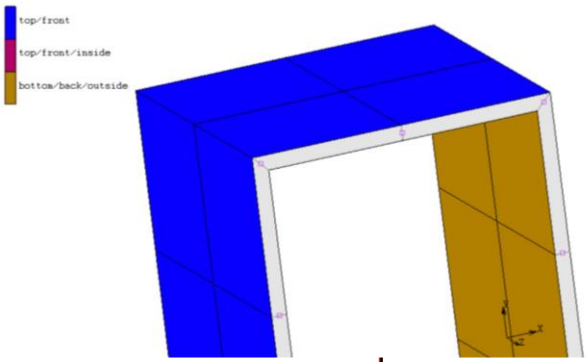


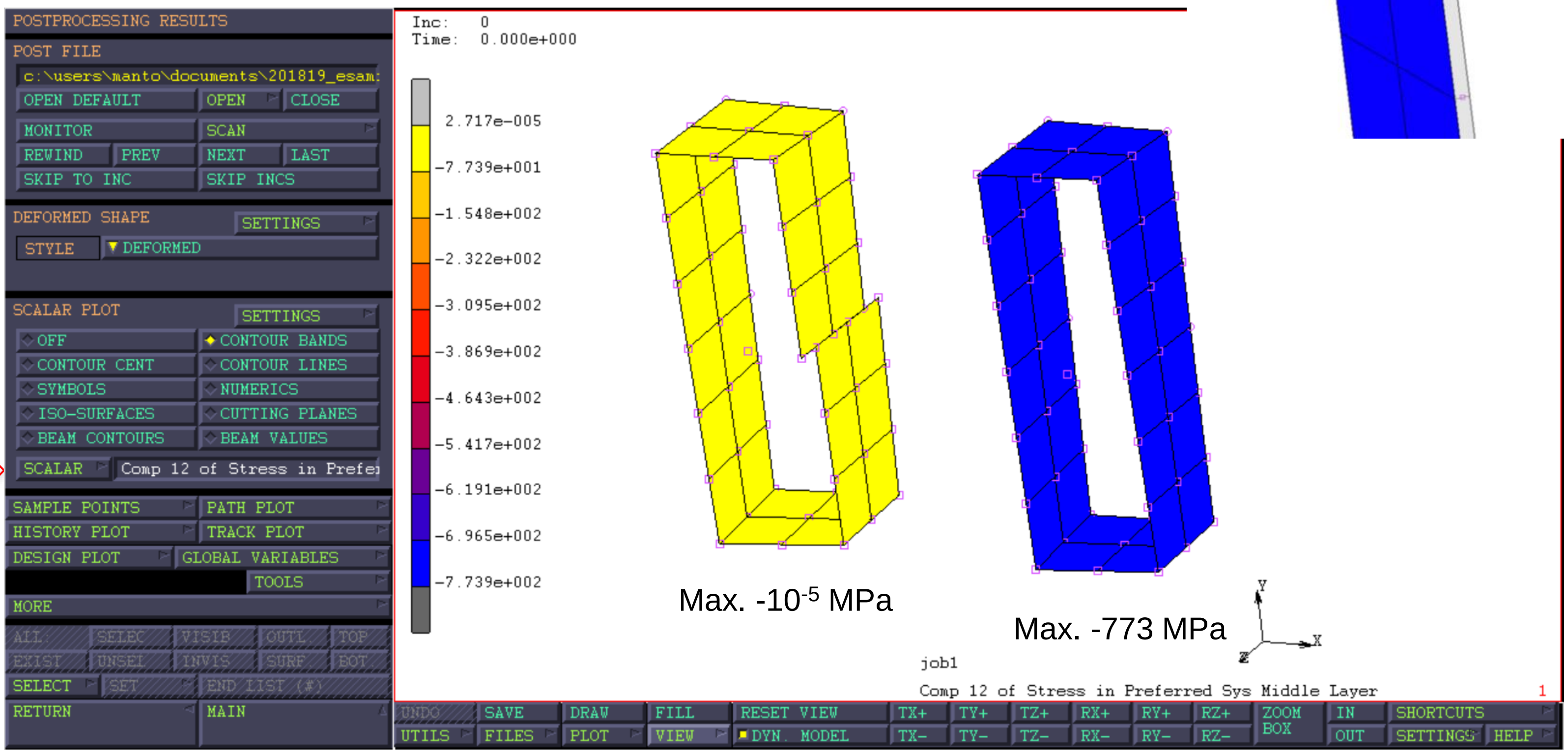


Thin-walled profile in torsion

Opened vs closed cross-section: RESULTS

From the analysis of the components of stress at the MIDDLE SURFACE, the stress that contributes significantly to the evaluation of the equivalent von Mises stress is the shear stress (`Comp. 12 of stress in preferred system`). The further stresses are negligible ($\approx 10^{-11}$).

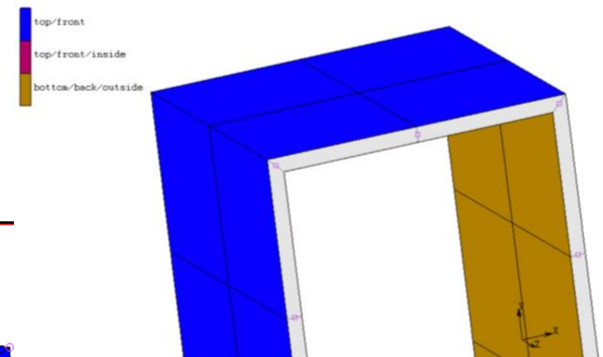


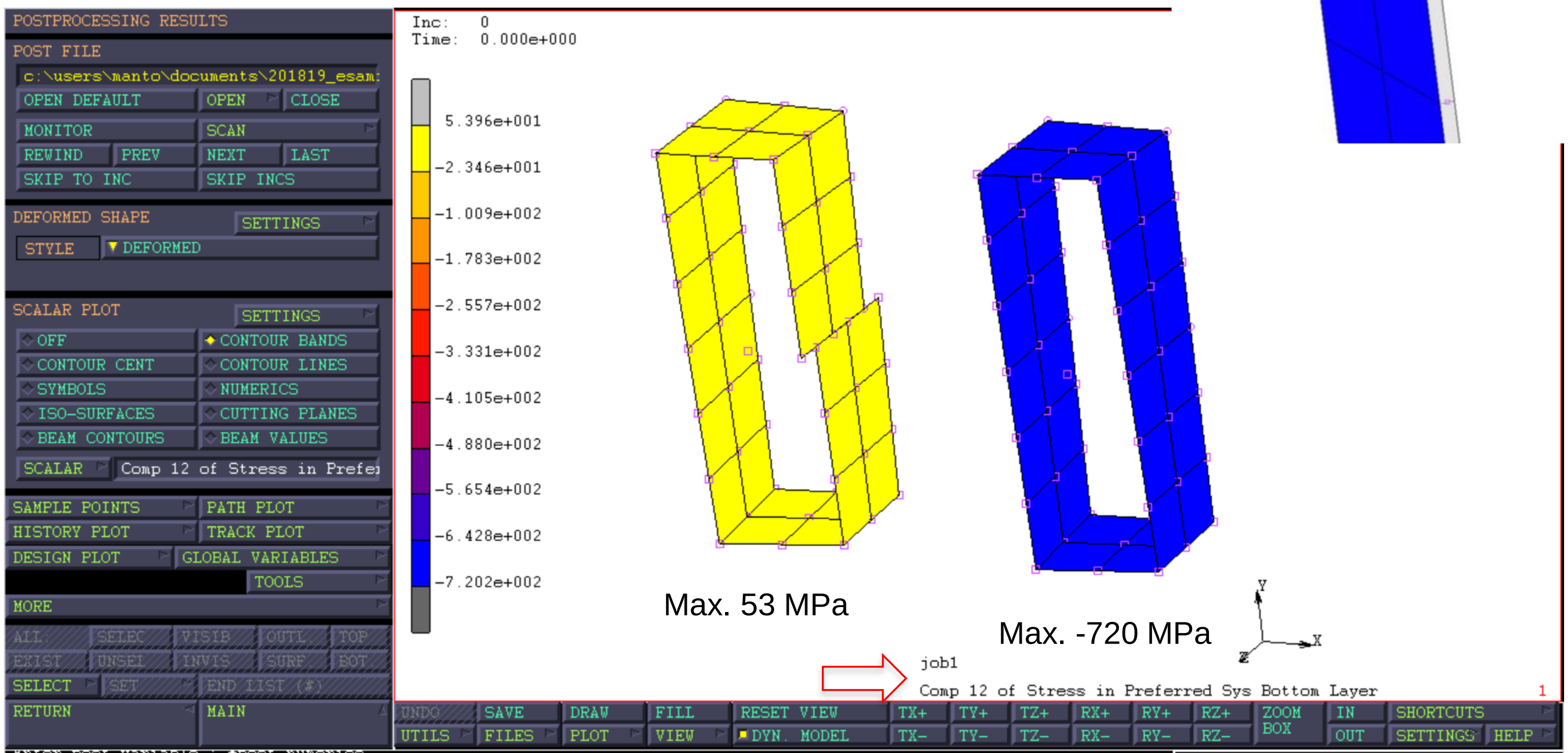


Thin-walled profile in torsion

Opened vs closed cross-section: RESULTS

From the analysis of the components of stress at the BOTTOM SURFACE, the stress that contributes significantly to the evaluation of the equivalent von Mises stress is the shear stress (`Comp. 12 of stress in preferred system`). The further stresses are negligible (≈ 10^{-11}).

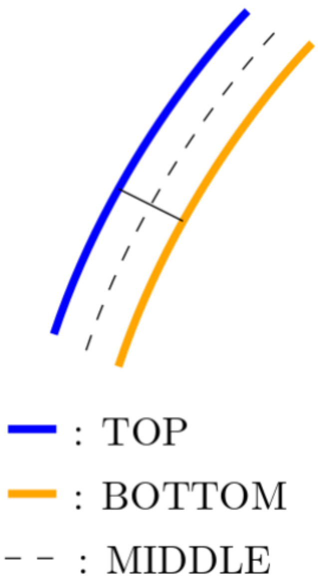


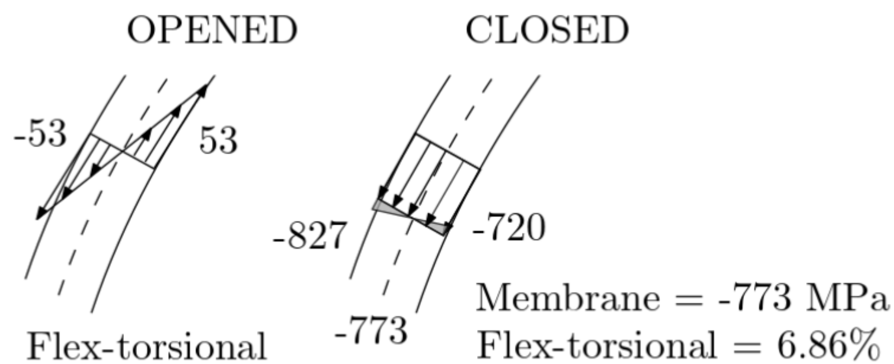


Thin-walled profile in torsion

Opened vs closed cross-section: τ_{12}

Hp) Twist rate: 0.001 rad/mm





Thin-walled profile in torsion
Opened vs closed cross-section: RESULTS

In the closed and the opened cases, the stiffness (K_t) evaluated by FE and by the analytical solution are compared, and the relative error has been evaluated as follows:

Error % = $\frac{(FE - Analytical)}{Analytical} * 100 = (ratio\ - 1) * 100.$

Section	K_t_Analytical [mm^4]	K_t_ FE [mm^4]	FE-Analytical ratio	Error %
Closed	515545,03	516378,57	1,00162	0,16
Opened	832,00	830,21	0,99785	-0,21

The comparison of the stiffness, between the closed and the opened FE models, evidences that:

Error % = $\frac{(Opened - Closed)}{Closed} * 100 = (ratio\ - 1) * 100 = -99{,}84\%.$

Agenda

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- Method & Mode;
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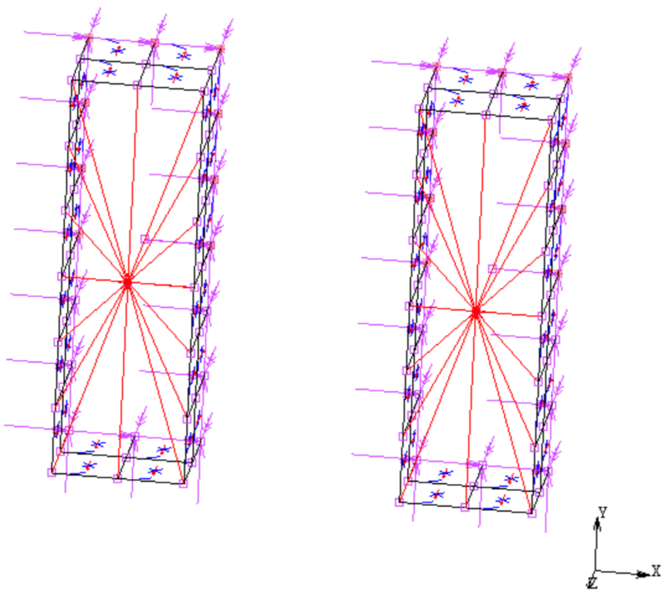
Thin-walled profile in torsion

- Opened vs closed cross-section;
- Mesh convergence.

References

Thin-walled profile in torsion
Mesh convergence



GOAL:
Open the reference model named `torsione_rev01_nolabile_open_vs_close.mud` two profiles are present, characterized by an opened and a closed section, respectively. They are loaded on the free extremity by an imposed rotation.
Starting from this model, we will compare the influence of the mesh size on the evaluation of torsional stiffness by FE.

The element size under investigation is in the range of [20, 10, 5, 2.5, 1.25] mm

The new models is called `torsione_rev01_nolabile_open_vs_close_convergence.mud`

Thin-walled profile in torsion

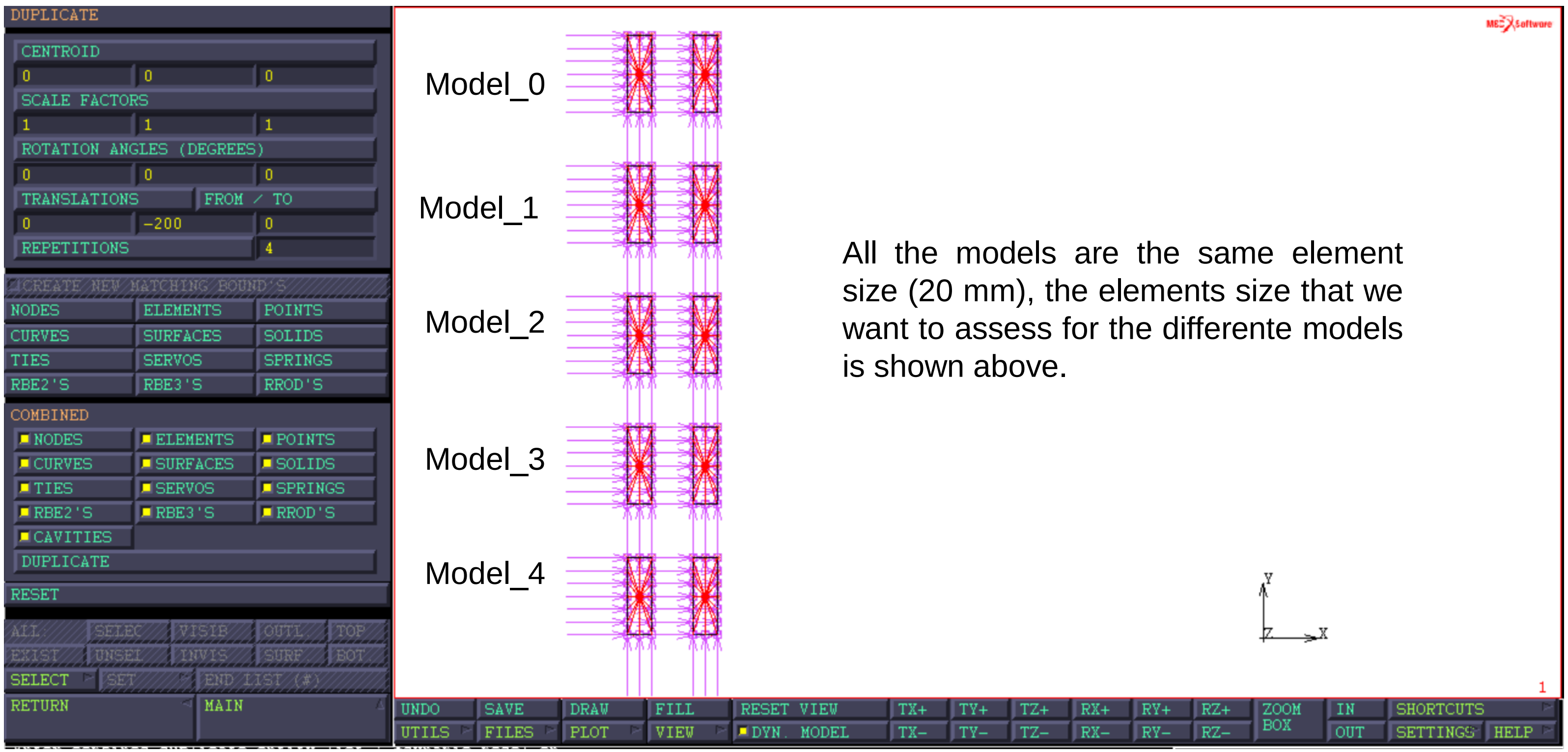
Duplicate Combined

```
|===================================
|        DUPLICATE MODEL
| the opened and the closed profiles will be duplicated four times
| and with a distance of 200 mm defined along the Y direction
| from the reference models.
| left-hand side: closed section profiles
| right-hand side: opened section profiles
|===================================
*set_duplicate_translations
*set_duplicate_translation y -200
*set_duplicate_repetitions 4
*duplicate_combined
all_existing
|===================================
```

Thin-walled profile in torsion

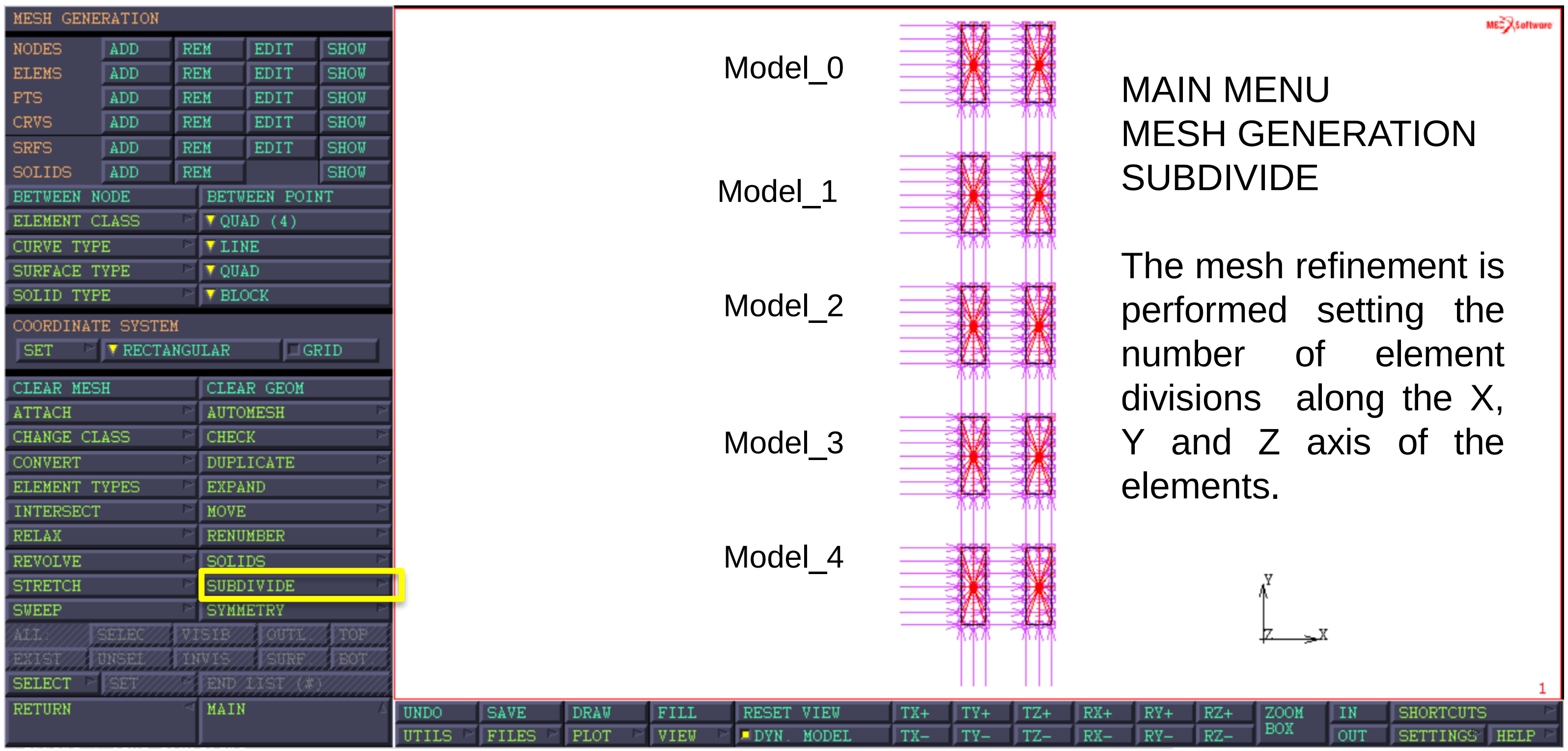
Duplicate Combined

```
|===================================
| Model_0: avg. element size = 20 mm (reference mesh)  --> y-coordinate range [ -59, +59]
| Model_1: avg. element size = 10 mm   --> y-coordinate range [-259, -141]
| Model_2: avg. element size = 5 mm    --> y-coordinate range [-459, -341]
| Model_3: avg. element size = 2.5 mm  --> y-coordinate range [-659, -541]
| Model_4: avg. element size = 1.25 mm --> y-coordinate range [-859, -741]
|===================================
```



All the models are the same element size (20 mm), the elements size that we want to assess for the differente models is shown above.

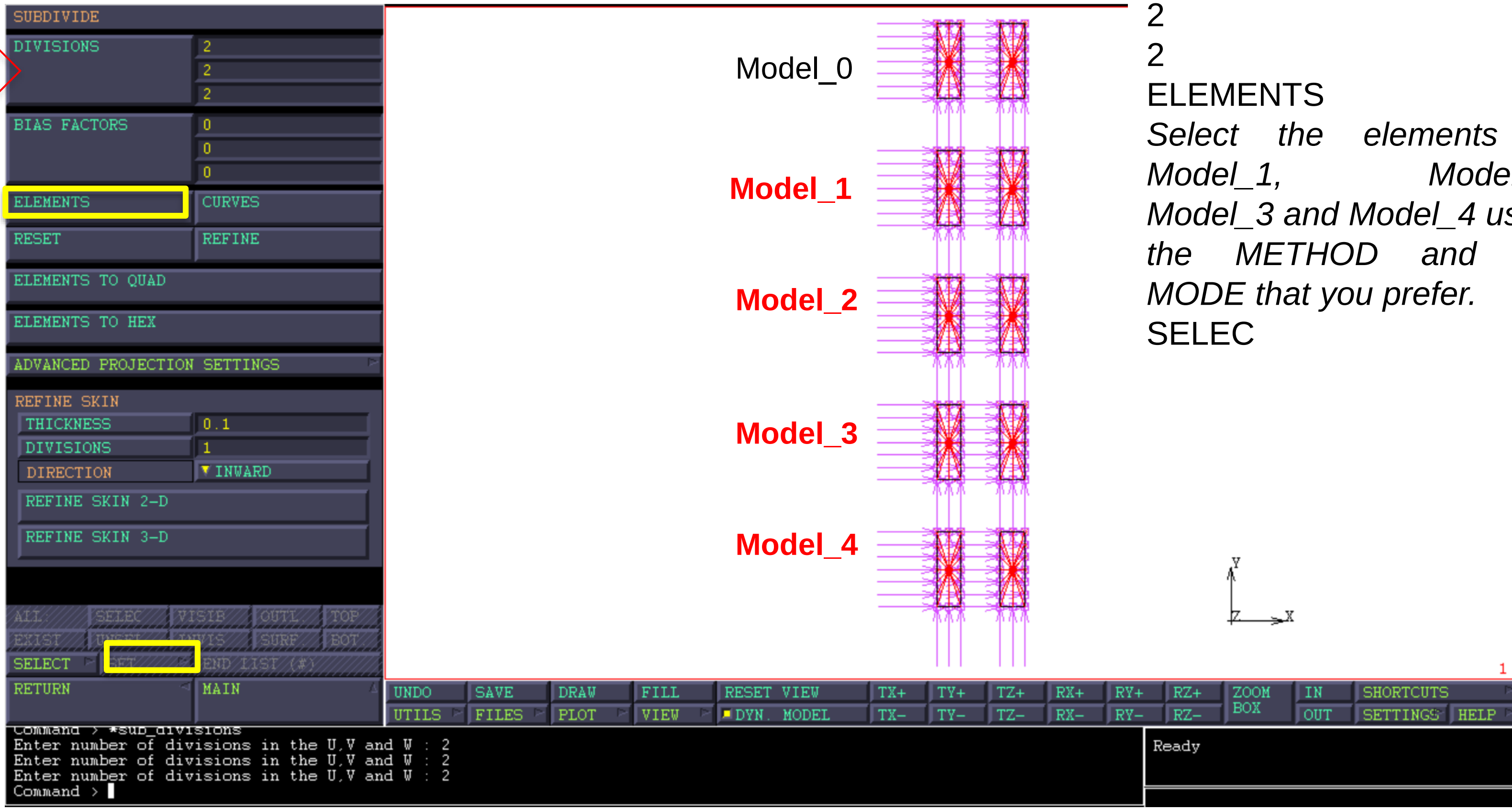
Thin-walled profile in torsion
Subdivide



MAIN MENU
MESH GENERATION
SUBDIVIDE

The mesh refinement is performed setting the number of element divisions along the X, Y and Z axis of the elements.

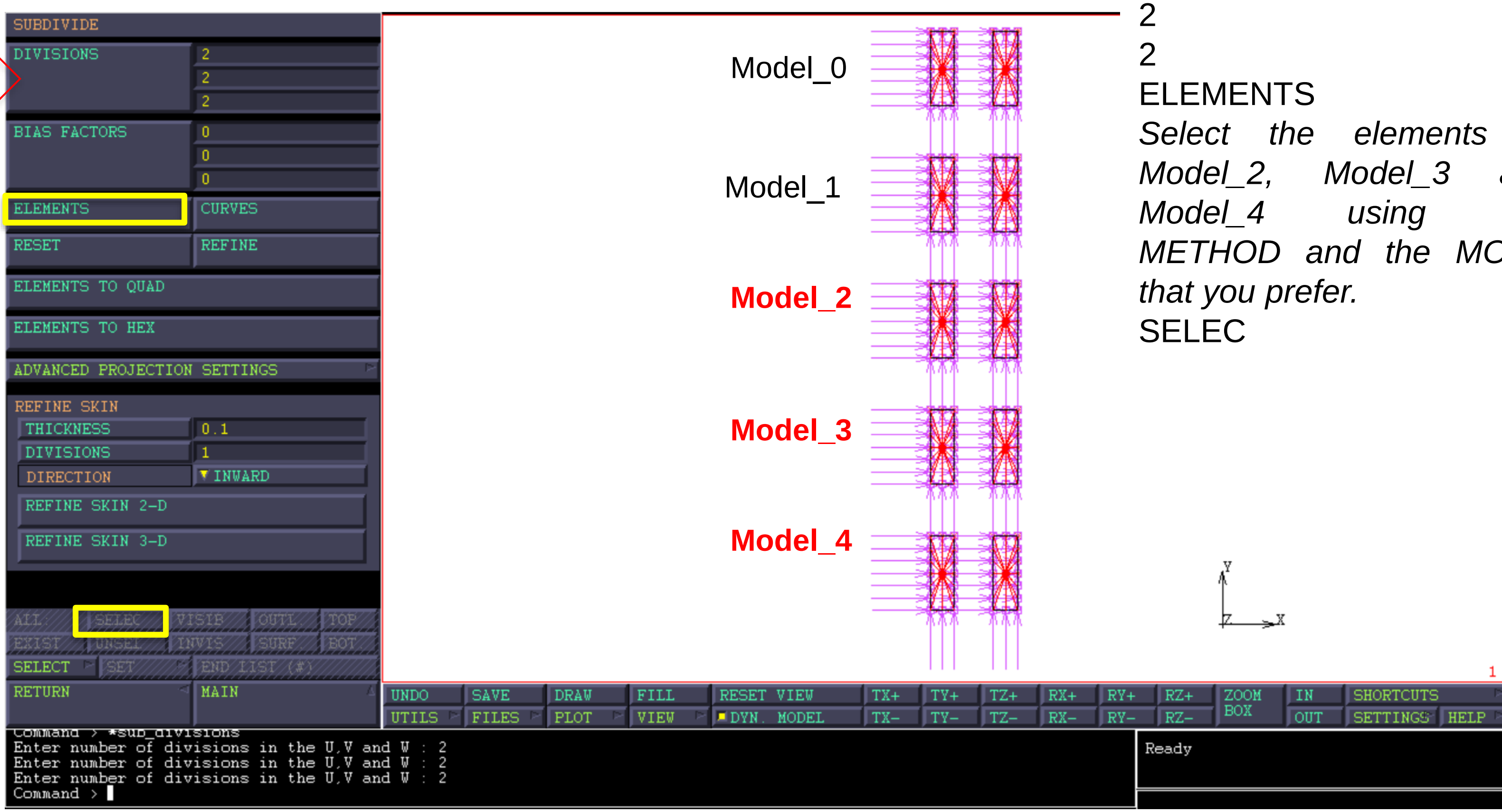
Thin-walled profile in torsion
Subdivide



DIVISIONS
2
2
2
ELEMENTS
Select the elements of Model_1, Model_2, Model_3 and Model_4 using the METHOD and the MODE that you prefer.
SELEC

Thin-walled profile in torsion

Subdivide



DIVISIONS
2
2
2
ELEMENTS
Select the elements of Model_2, Model_3 and Model_4 using the METHOD and the MODE that you prefer.
SELEC

Thin-walled profile in torsion

Subdivide

DIVISIONS
2
2
2
ELEMENTS
Select the elements of Model_3 and Model_4 using the METHOD and the MODE that you prefer.
SELEC

Thin-walled profile in torsion

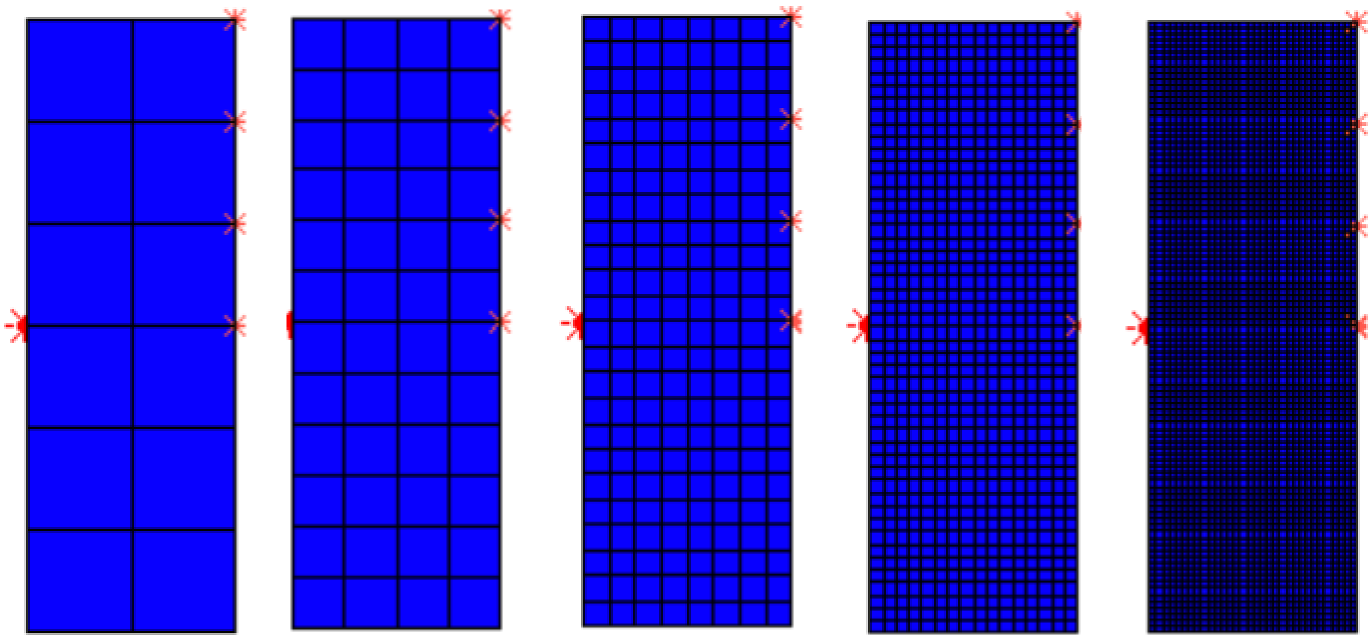
Subdivide

DIVISIONS
2
2
2
ELEMENTS
Select the elements of Model_4 using the METHOD and the MODE that you prefer.
SELEC

Thin-walled profile in torsion

Subdivide

Detailed view of the models



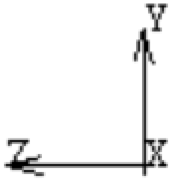
Model_0
20 mm

Model_1
10 mm

Model_2
5 mm

Model_3
2.5 mm

Model_4
1.25 mm



Thin-walled profile in torsion

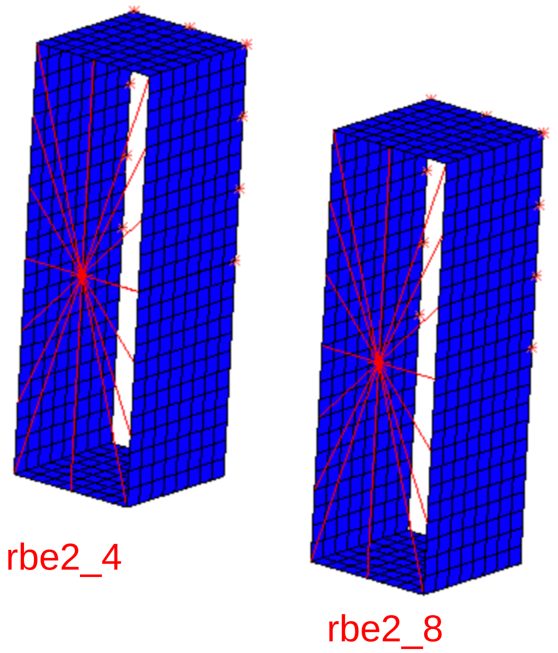
Sweep

```
|====================================
| SWEEP NODES - DUPLICATE DUE TO THE ELEMENTS SUBDIVIDE;
| WITHOUT REMOVING THE LATERAL CRACK OF THE OPENED SECTION (left-hand side models)
| the tolerance (t) must be:
| lower then the crack size (0.1);
| lower than the minimum elements size (1.25);
| therefore  t < 0.1
| I consider a tolerance value equal to 0.05
|====================================
*set_sweep_tolerance
0.05
*sweep_nodes
all_existing
*select_clear
|====================================
| CHECK THE COMMAND PROMPT
| Deleting 42191 duplicate nodes!
| Deleting 0 collapsed elements!
|====================================
```

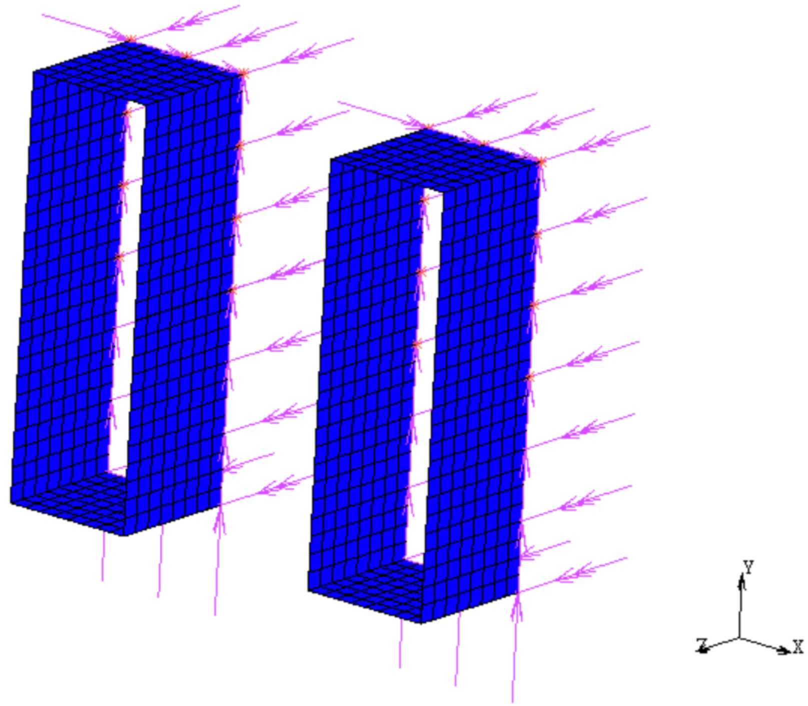
Thin-walled profile in torsion

Update Links (RBE2) and BCs

Detailed view of the Model_2: RBE2 tied nodes



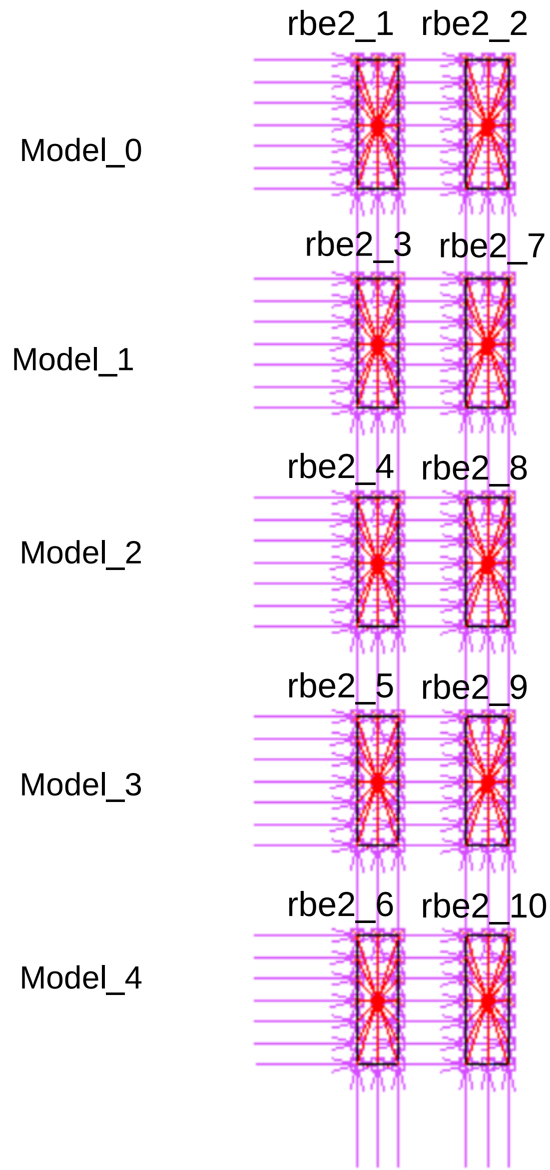
Detailed view of the Model_2: BCs skew-symm



The refinement of the mesh by subdividing the elements required that both the tied nodes of the RBE2, and the nodes involved in the skew-symmetry BCs must be updated.

Thin-walled profile in torsion

Update Links (RBE2) and BCs

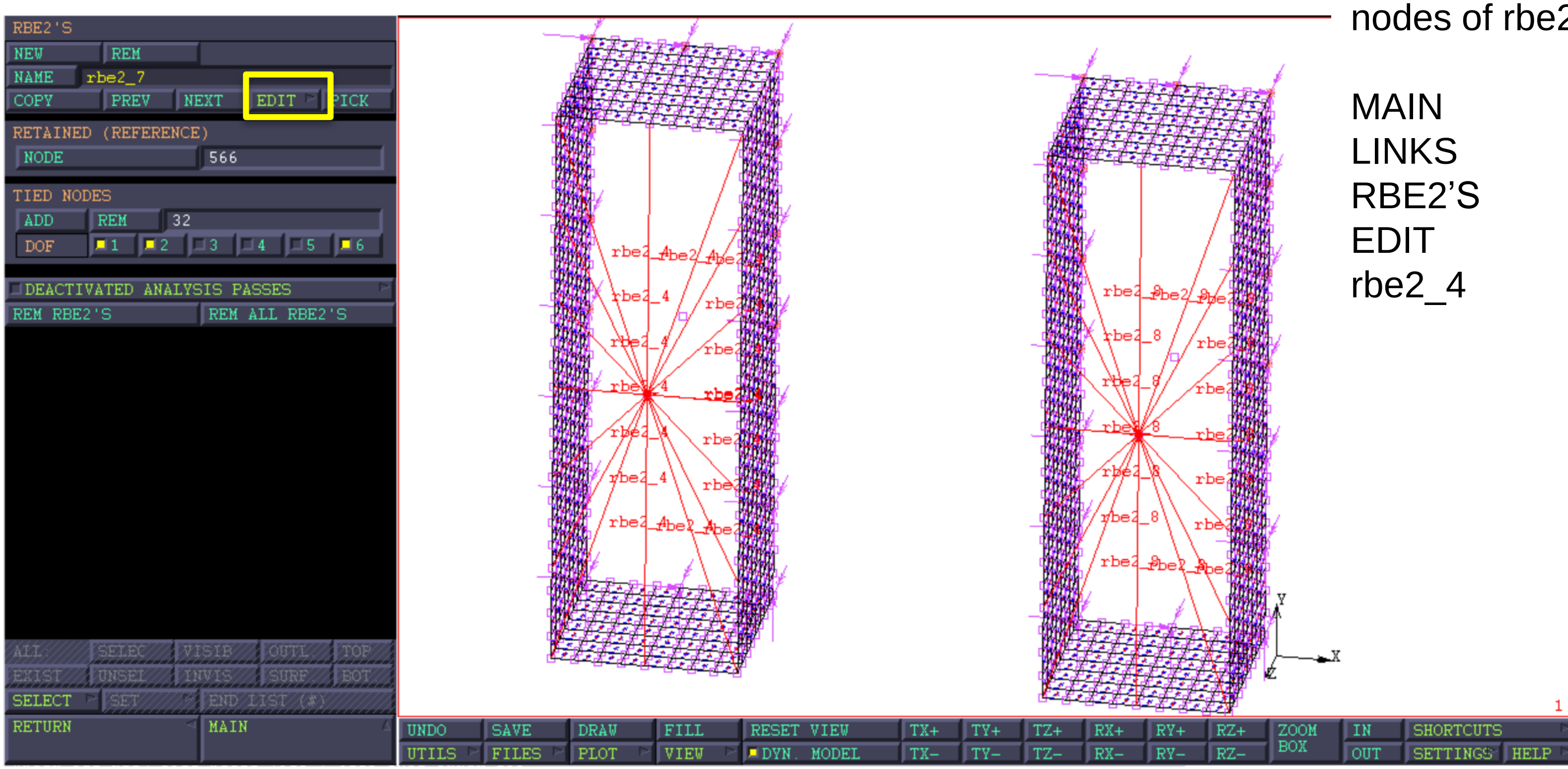


Make visibile the labels of the RBE2 on the screen, as follows:

PLOT
RBE2: SETTING
☒ LABELS
REGEN
RESET VIEW
FILL

Thin-walled profile in torsion

Update Links (RBE2) and BCs

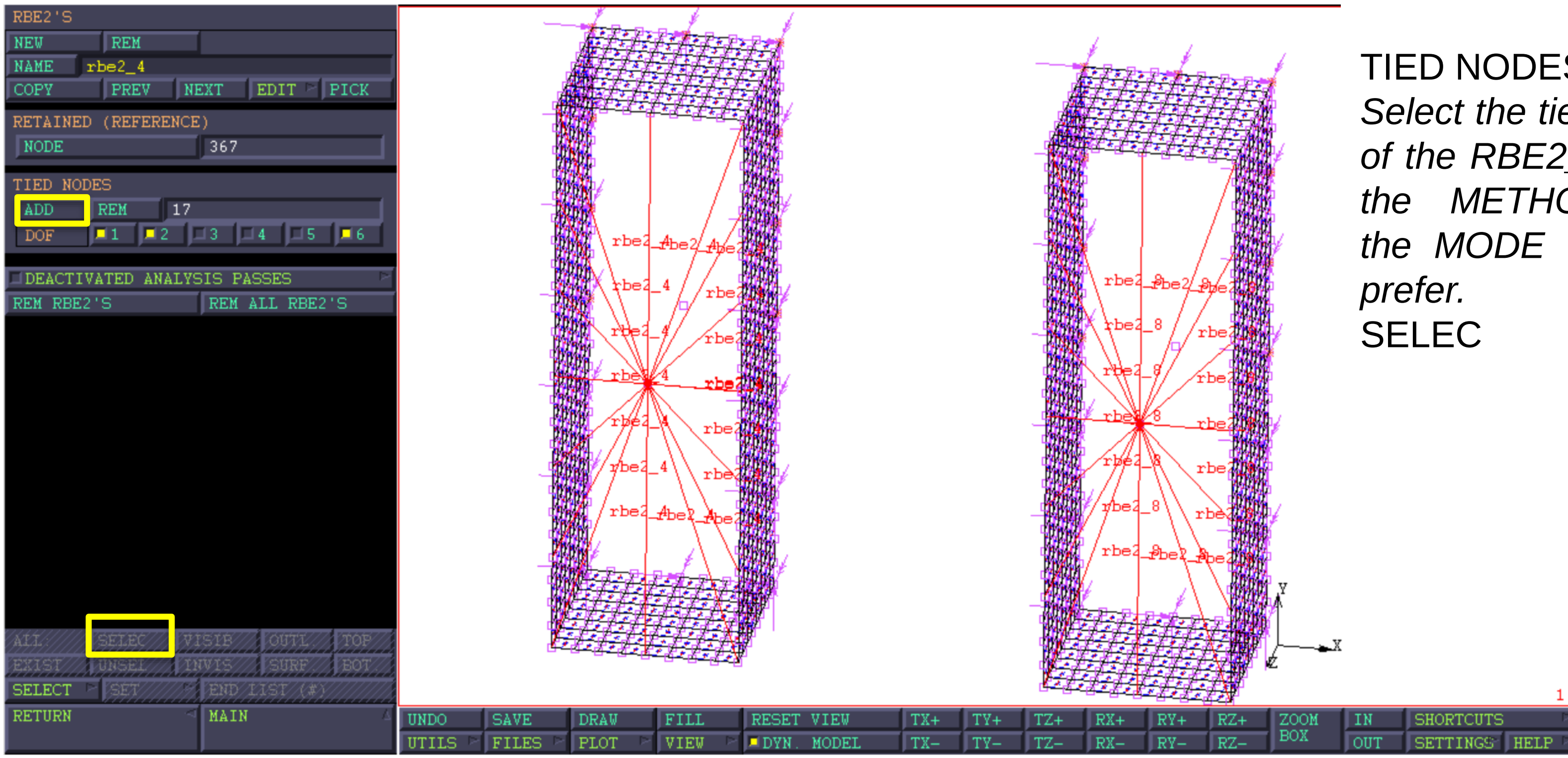


As an example, the upload procedure adopted for the tied nodes of rbe2_4 is:

MAIN
LINKS
RBE2'S
EDIT
rbe2_4

Thin-walled profile in torsion

Update Links (RBE2) and BCs



As an example, the upload procedure adopted for the tied nodes of rbe2_4 is:

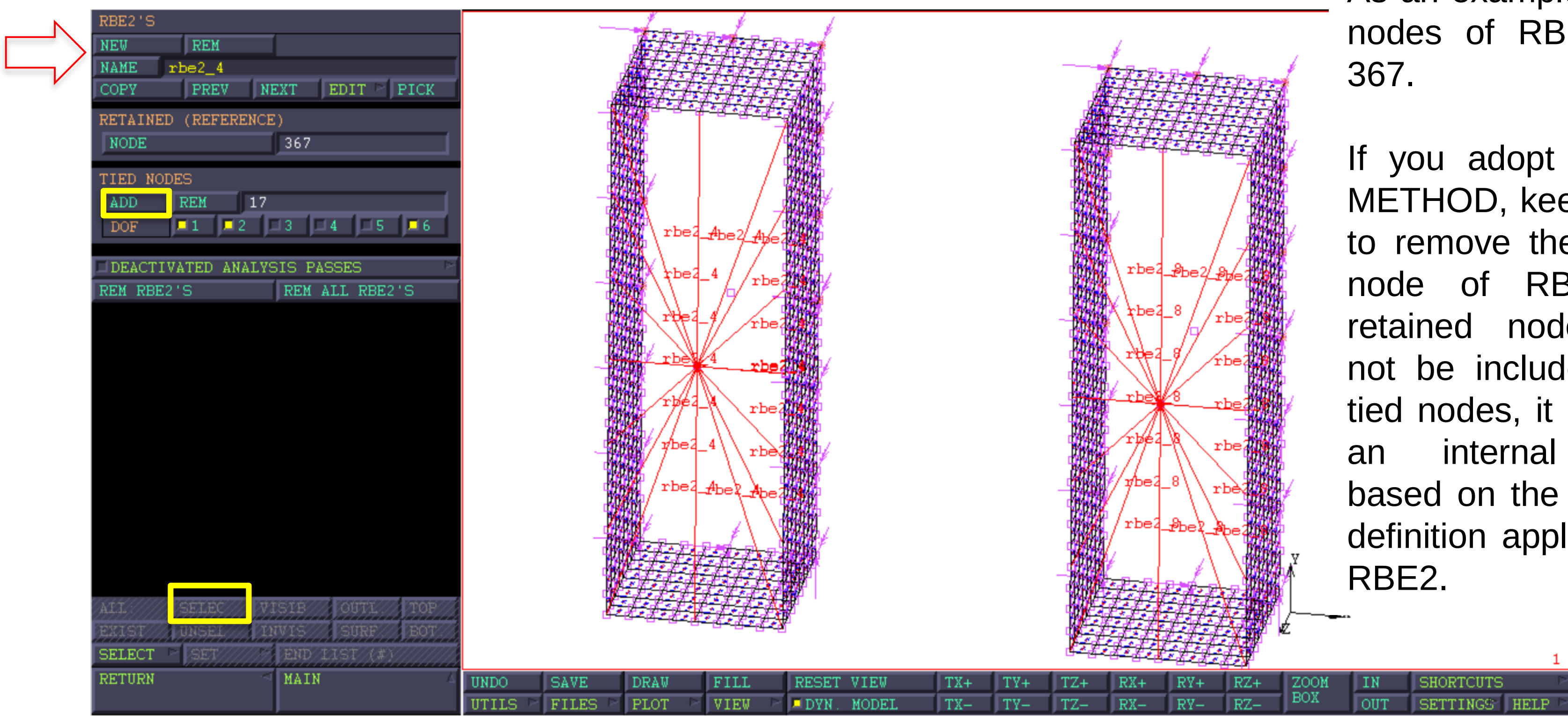
TIED NODES: ADD

Select the tied nodes of the RBE2_4 using the METHOD and the MODE that you prefer.

SELEC

Thin-walled profile in torsion

Update Links (RBE2) and BCs

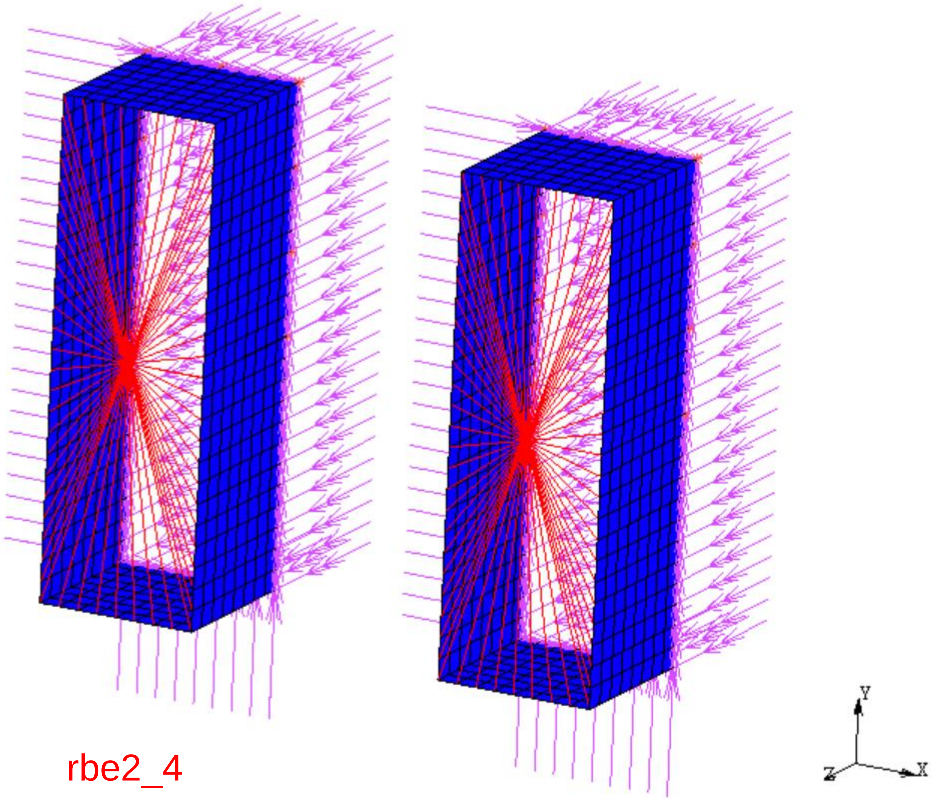


The number of tied nodes is function of the mesh refinement.

As an example, the tied nodes of RBE2_4 are 367.

If you adopt the BOX METHOD, keep in mind to remove the retained node of RBE2. The retained node should not be included in the tied nodes, it generates an internal conflict based on the kinematic definition applied to the RBE2.

Thin-walled profile in torsion
Update Links (RBE2) and BCs



rbe2_4

rbe2_8

Keep in mind also to update the skew-symmetry BCs.
After the update of RBE2 and BCs, the Models_2 becomes as shown here. Similarly, this procedure must be accomplished for any models.

The models are ready to be computed.

Thin-walled profile in torsion
Mesh Convergence: RESULTS

The stiffness (K_t) evaluated by FE and by the analytical solution are compared, and the relative error has been evaluated as follows:

$$\_Kt\_ratio = \frac{Kt\_Opened}{Kt\_Closed}.$$

	Element size [mm]	_Mt_ow_warp [Nmm]	_Mt_cw_warp [Nmm]	_Kt_ow_warp [mm^4]	_Kt_cw_warp [mm^4]	_Kt_ratio
Analytical*	/	/	/	832,0	515545,0	0,00161
Model_0	20,00	22351,9	1,39025E+07	830,2	516378,6	0,00161
Model_1	10,00	22309,4	1,39024E+07	828,6	516374,9	0,00160
Model_2	5,00	22234,7	1,39024E+07	825,9	516374,9	0,00160
Model_3	2,50	22129,0	1,39023E+07	821,9	516371,1	0,00159
Model_4	1,25	22038,4	1,39022E+07	818,6	516367,4	0,00159

* exact solution for profile with infinitesimal thickness (t → 0)

The influence of the mesh size on the torsional stiffness evalution for closed section is negligible, and it is of limited relevance for the opened section.

	Error_Kt_ow_warp [%]	Error_Kt_cw_warp [%]
Model_0	1,42%	0,0022%
Model_1	1,23%	0,0014%
Model_2	0,89%	0,0014%
Model_3	0,41%	0,0007%

Relative error evaluated for the FE models refering to the Model_4.

Agenda

MSC Marc Mentat: Select entities

- Method & Mode;
- Store;
- Identify set.

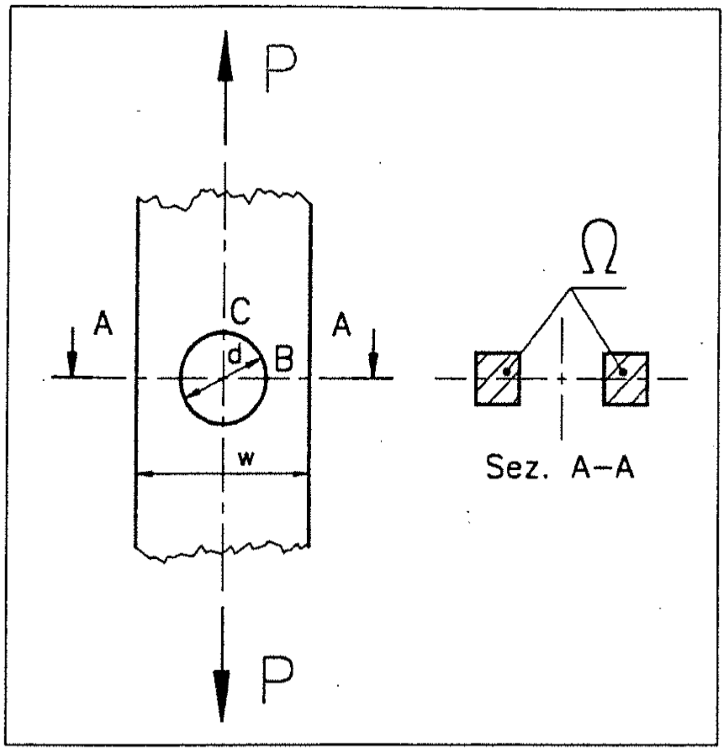
Thin-walled profile in torsion

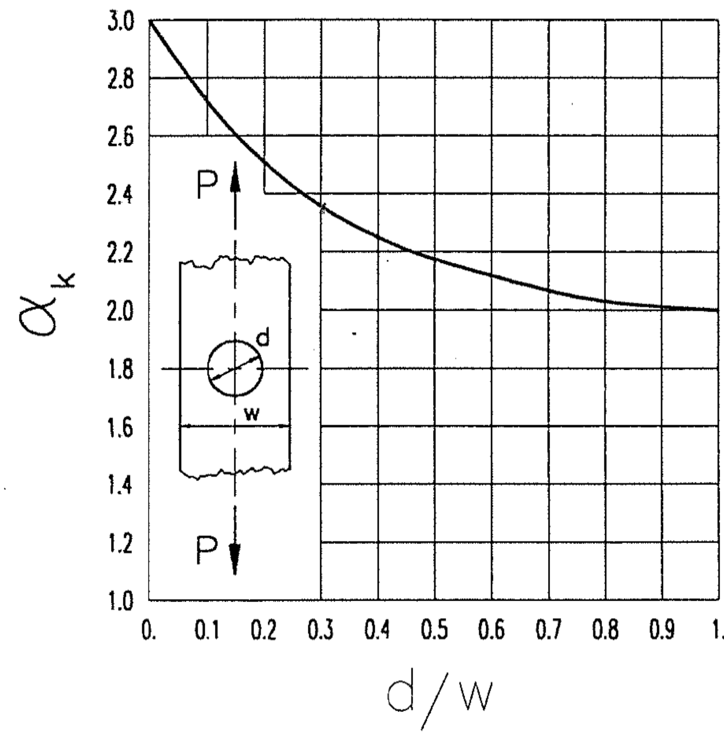
- Opened vs closed cross-section;
- Mesh convergence: Critical aspects

References

Mesh convergence

Critical Aspects: Case A

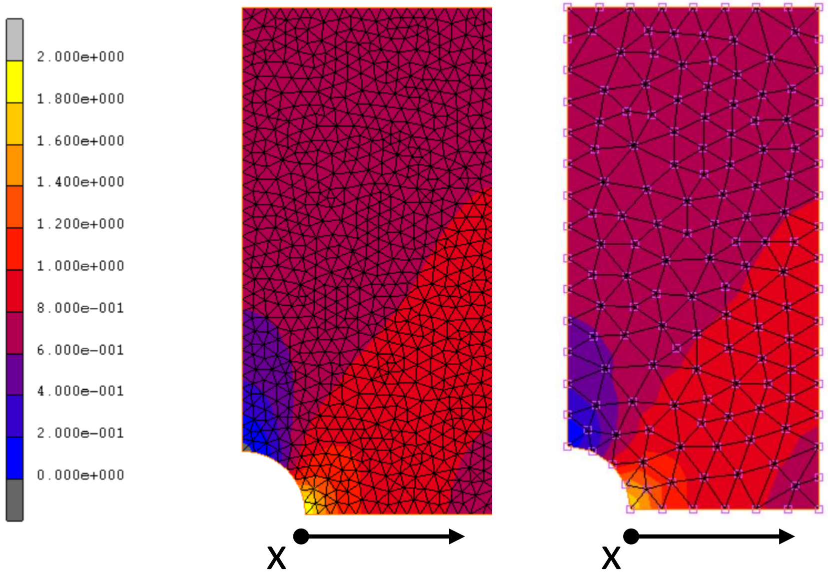


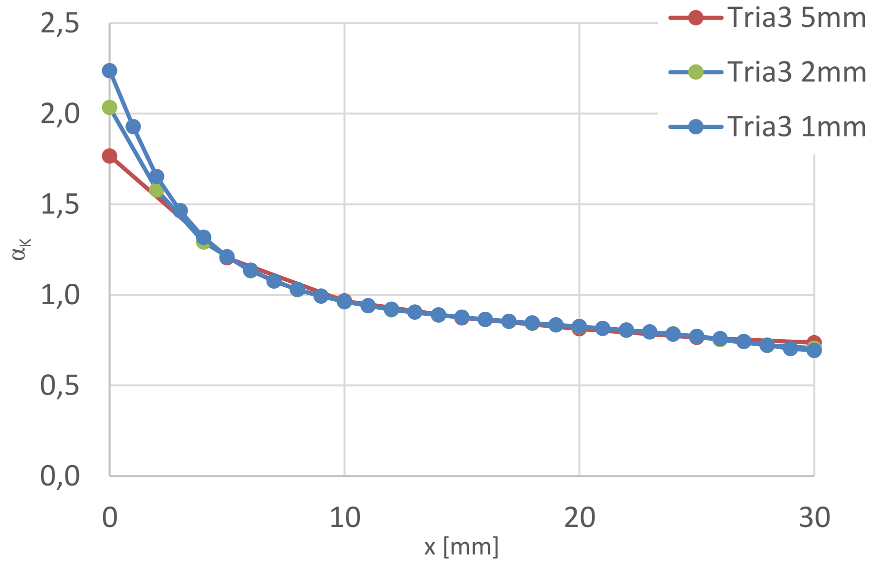


d/w = 0.25; $\alpha_k \approx$ 2,42 (theory),

Mesh Convergence

Critical Aspects: Case A

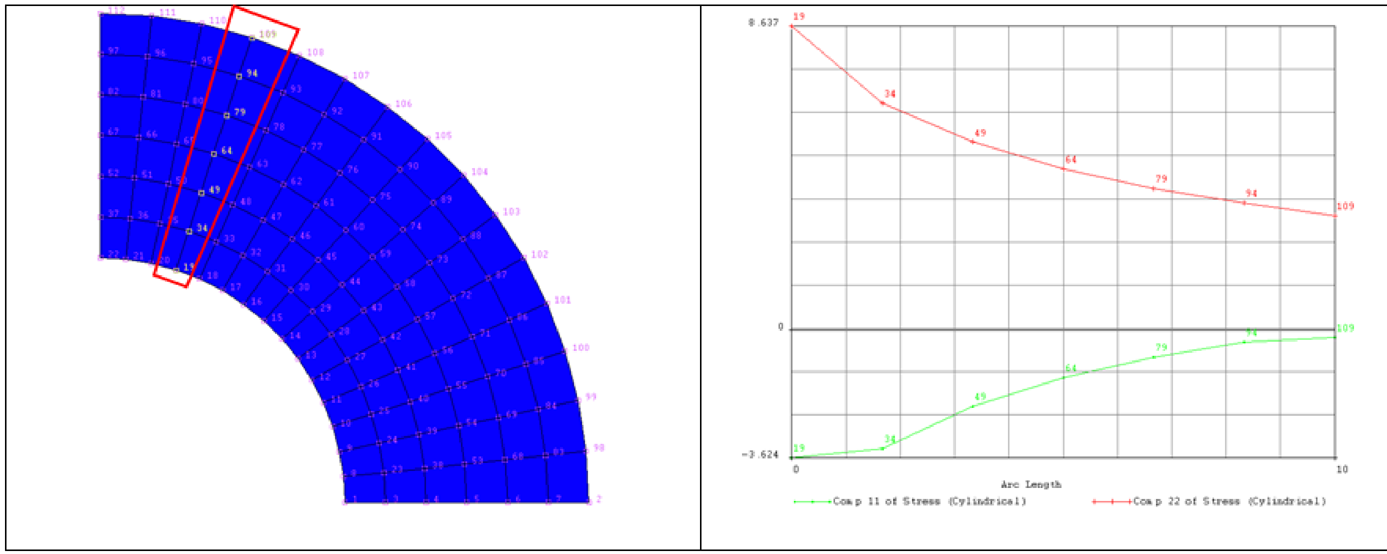




Mesh Convergence
Critical Aspects: Case B

Pressure Vessel
R_{int} = 10 mm
R_{est} = 20 mm
p_i = 5 MPa

MESH 1: *90 Elementi, 112 Nodi*



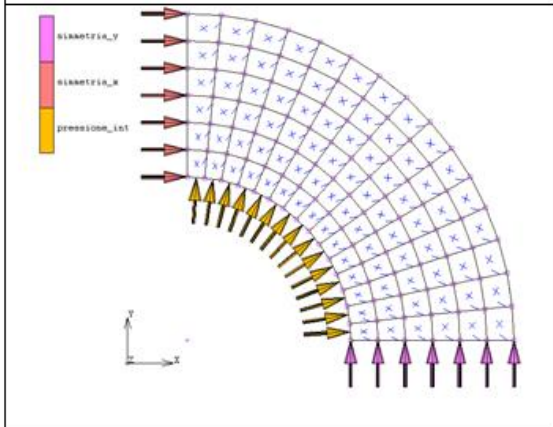
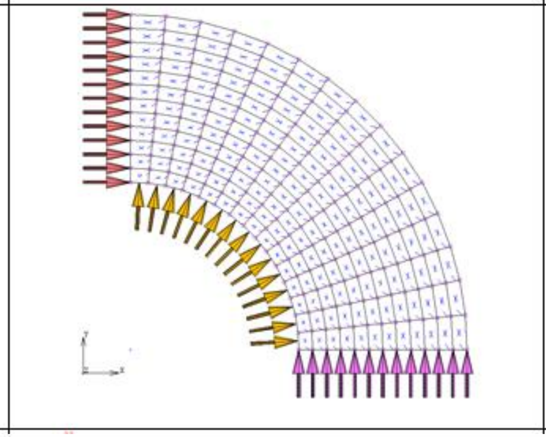
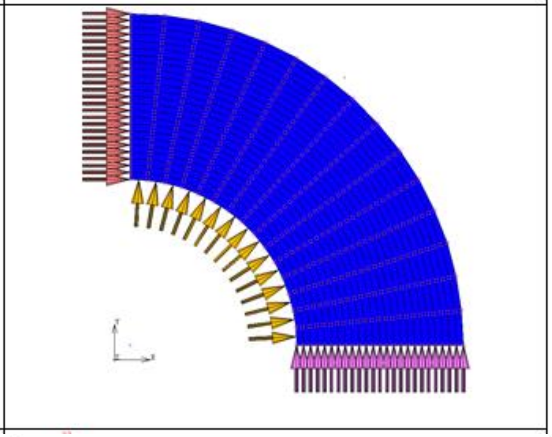
Lamè solution:
$\sigma_R|_{r = Ri}$ = - 5 MPa
$\sigma_C|_{r = Ri}$ = 8.33 MPa

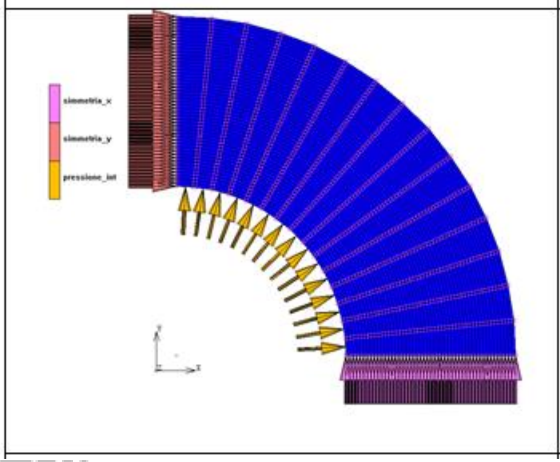
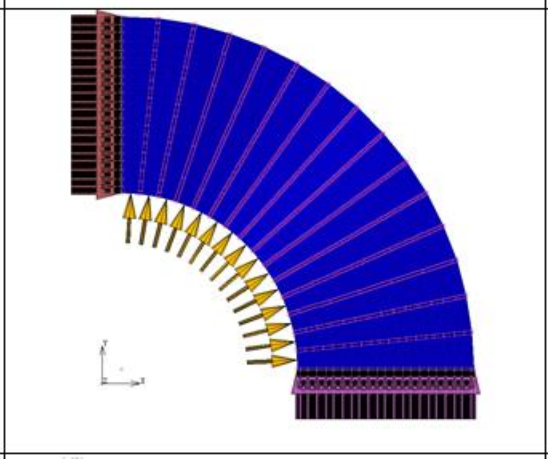
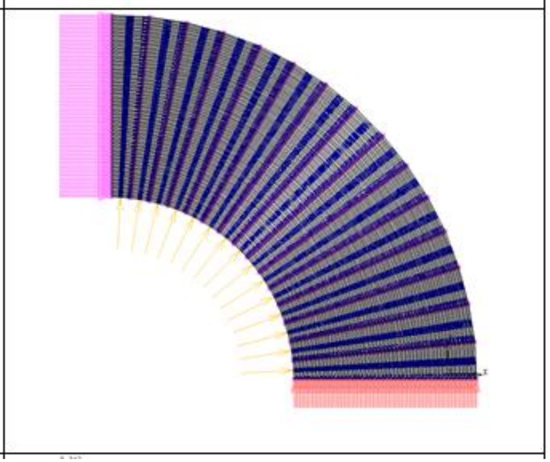
$$\sigma_r |_{R\,\mathrm{int}} = -p_{\mathrm{int}}$$

$$\sigma_c |_{R\,\mathrm{int}} = p_{\mathrm{int}} \frac{R_{est}^2 + R_{\mathrm{int}}^2}{R_{est}^2 - R_{\mathrm{int}}^2}$$

Mesh Convergence

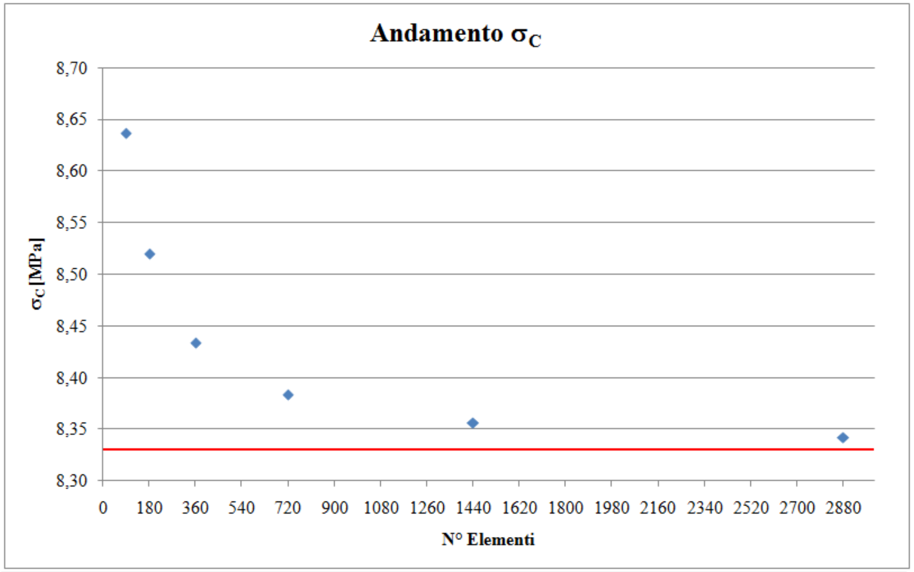
Critical Aspects: Case B

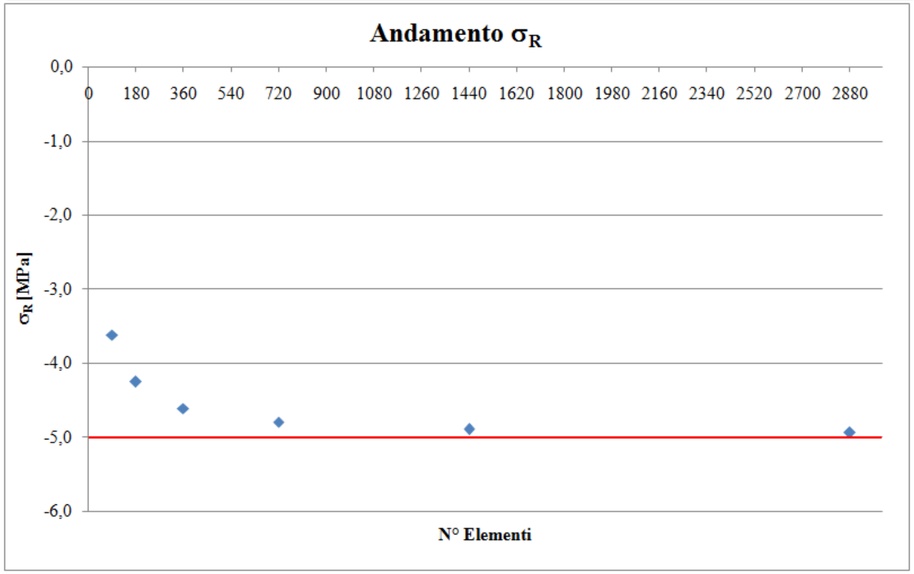
MESH 1: *90 Elementi, 112 Nodi*	***MESH 2:*** *180 Elementi,208 Nodi*	***MESH 3:*** *360 Elementi, 400 Nodi*
		

MESH 4: 720 Elementi, 784 Nodi	**MESH 5:** 1440 Elementi, 1552 Nodi	**MESH 6:** 2880 Elementi, 3088 Nodi
		

Mesh Convergence
Critical Aspects: Case B

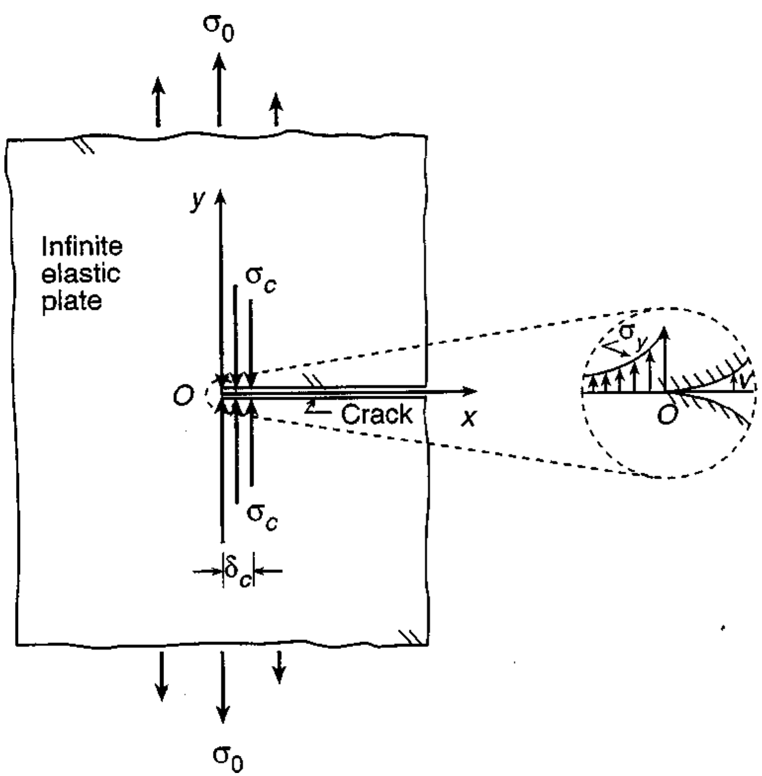
Asymptotic curve of the FE results with respect to the analytical solution.

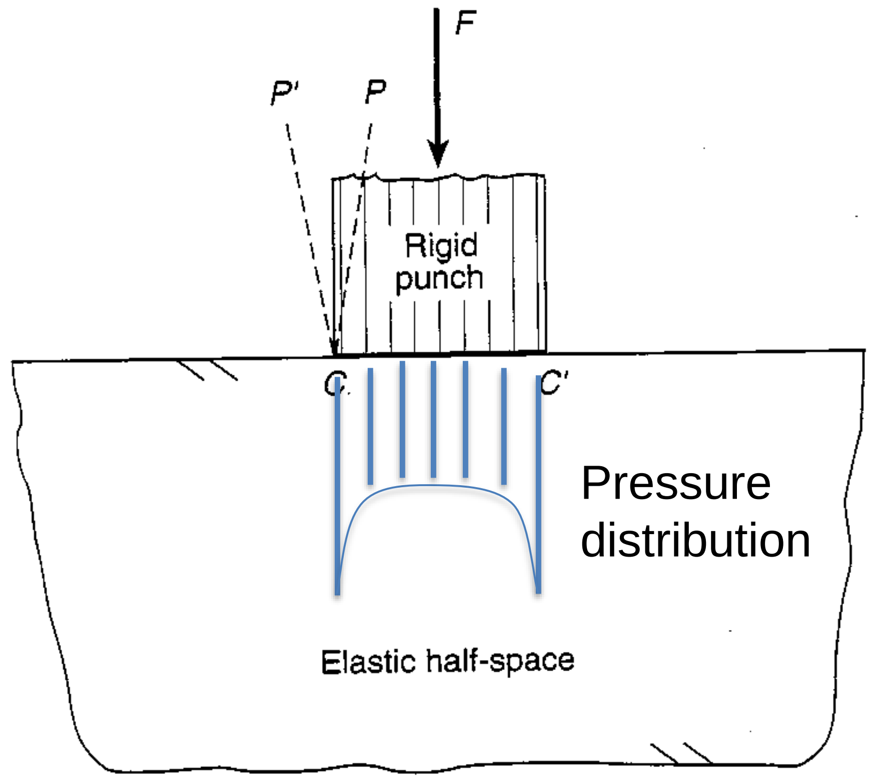




Mesh Convergence

Critical aspects: singularity occurrence





Agenda

MSC Marc Mentat: Select entities

- Method & Mode;
- Store;
- Identify set.

Thin-walled profile in torsion

- Open vs close cross-section;
- Mesh convergence.

References

References

LAB Marc Mentat files saved as:

```
torsione_rev01_nolabile.mud
torsione_rev01_nolabile_open_vs_close.mud
torsione_rev01_nolabile_open_vs_close_mesh_convergence.mud

thin_walled_profile_in_torsion_open_vs_close.proc
thin_walled_profile_in_torsion_open_vs_close_mesh_convergence.proc
torsional_stiffness_evaluation_paom2019_v001.ods
```

Books and papers:

Strozzi, A. (1998). Costruzione di Macchine, Pitagora Editrice, Bologna.

Sinclair, G. B. (2004). Stress singularities in classical elasticity-I: Removal, interpretation, and analysis. Applied Mechanics Reviews, 57(4), 251-298.

Sinclair, G. B. (2004). Stress singularities in classical elasticity—II: Asymptotic identification. Applied Mechanics Reviews, 57(5), 385-439.