Tube/projectile interaction modeling using finite element simulation

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Introduction: Industrial context

- Manage the loading/unloading cycle of the artillery projectile:

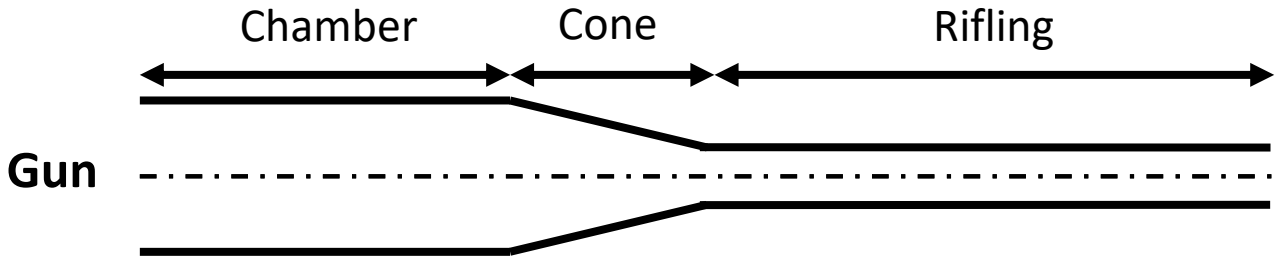


Fig. 1. Gun barrel.

Fig. 2. Projectile.

Gun loaded:

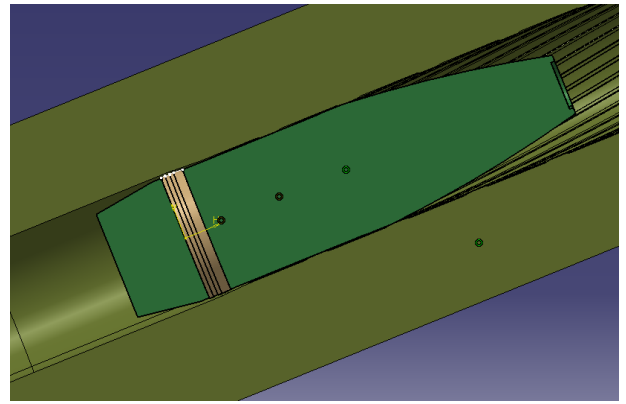


Fig. 3. Loaded projectile.

➔ Conical shrink fit assembly

- Objective: Focus on shrink fit assembly

- Non-linearities to take into account:

Elastic-plastic material

Complex geometries

Contact + Friction

Finite strain (≈ 30% locally)

I.a) Analytical model – Rigid cone

- Cone to cone interaction with no strain:

Principles of statics:

- $E_{\mathrm{p}} = PS\left(\frac{\mu_{\mathrm{p}}}{\tan(\alpha/2)} + 1\right)$
- $E_{\mathrm{ex}} = -PS\left(\frac{\mu_{\mathrm{ex}}}{\tan(\alpha/2)} - 1\right)$

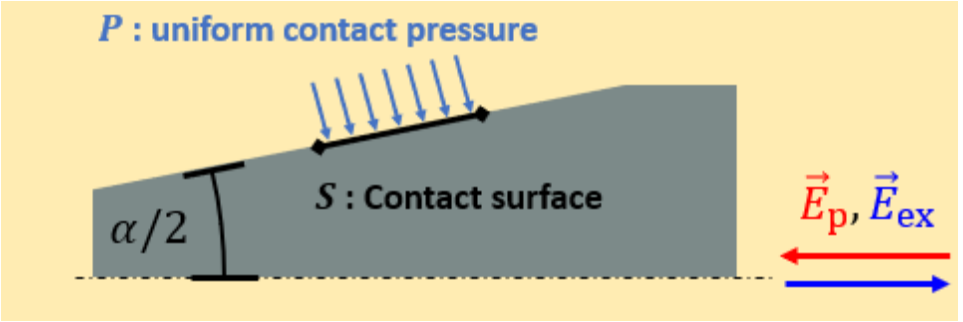


Fig. 4. Rigid cone model.

- "Reaction" factor:

$$r_{\mathrm{rigid}} = \frac{-E_{\mathrm{ex}}}{E_{\mathrm{p}}} = \frac{\mu_{\mathrm{ex}} - \tan(\alpha/2)}{\mu_{\mathrm{p}} + \tan(\alpha/2)}$$

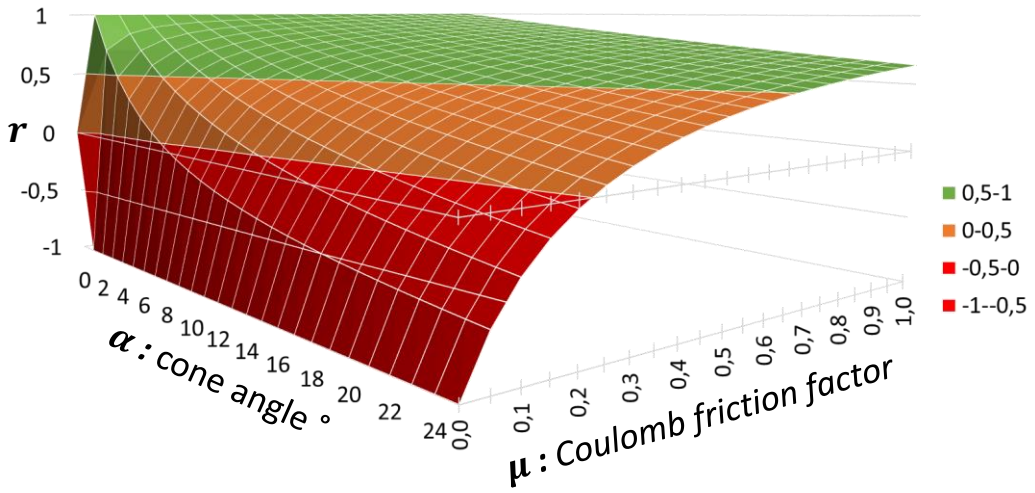


Fig. 5. r response.

- Extraction force is lower than penetration force.

I.b) Analytical model – Elastic cone

- Adding an elastic behaviour:
  - Obtaining a 3 steps model:
    1. penetration: push into cone ;
    2. springback: partial relief of stress ;
    3. extraction: pull until contact loss.

  - 1. ➔ $\frac{F_{x,p}}{F_{y,p}} = \frac{1-\mu_p \tan(\alpha/2)}{\mu_p+\tan(\alpha/2)}$ et 3. ➔ $\frac{F_{x,ex}}{F_{y,ex}} = \frac{1+\mu_{ex} \tan(\alpha/2)}{-\mu_{ex}+\tan(\alpha/2)}$
  - Leads to: $r_{elastic} = \frac{-E_{ex}}{E_p} = r_{rigid} \frac{1-\mu_p \tan(\alpha/2)}{1+\mu_{ex} \tan(\alpha/2)}$

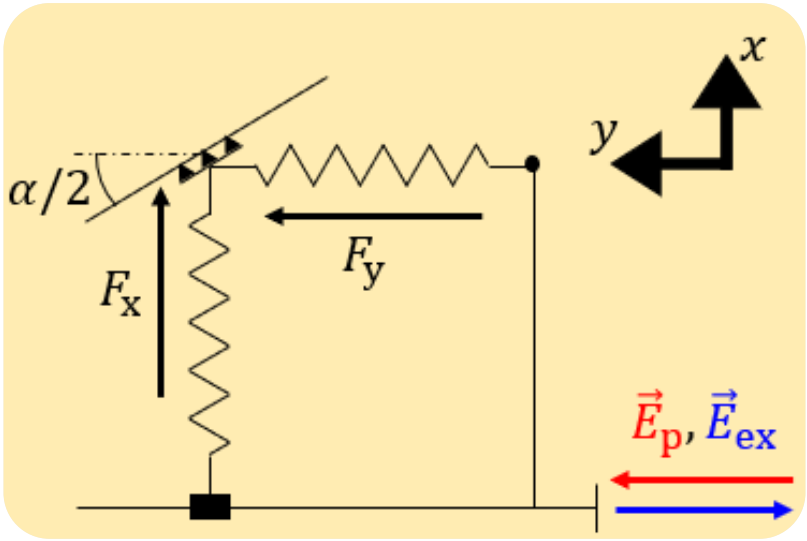


Fig. 6. Elastic cone model.

- « Inversion » factor :

$$f_{inv} = \frac{1-\mu_p \tan(\alpha/2)}{1+\mu_{ex} \tan(\alpha/2)}$$

- New factor describing the evolution of loading direction.

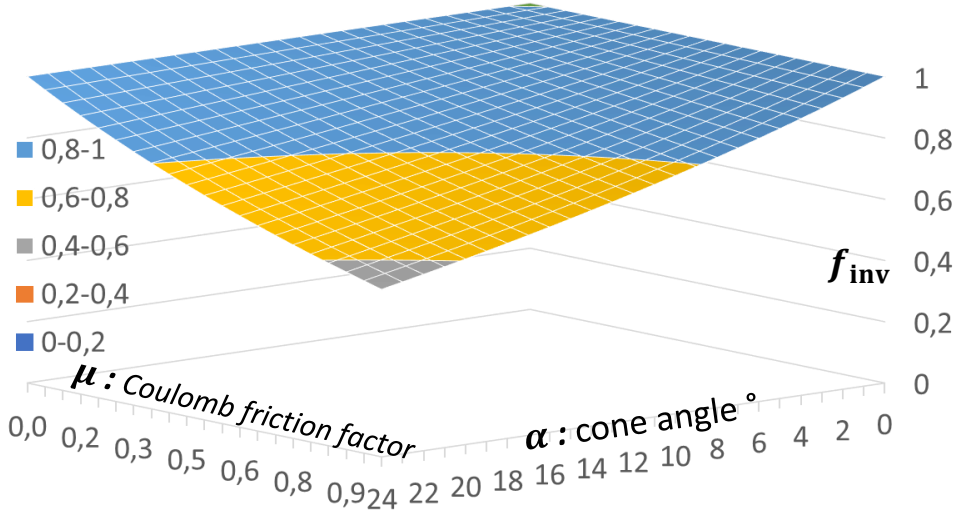


Fig. 7. f_{inv} response surface.

II.a) Finite element models – Quasi-statics

- Axisymmetric numerical model:

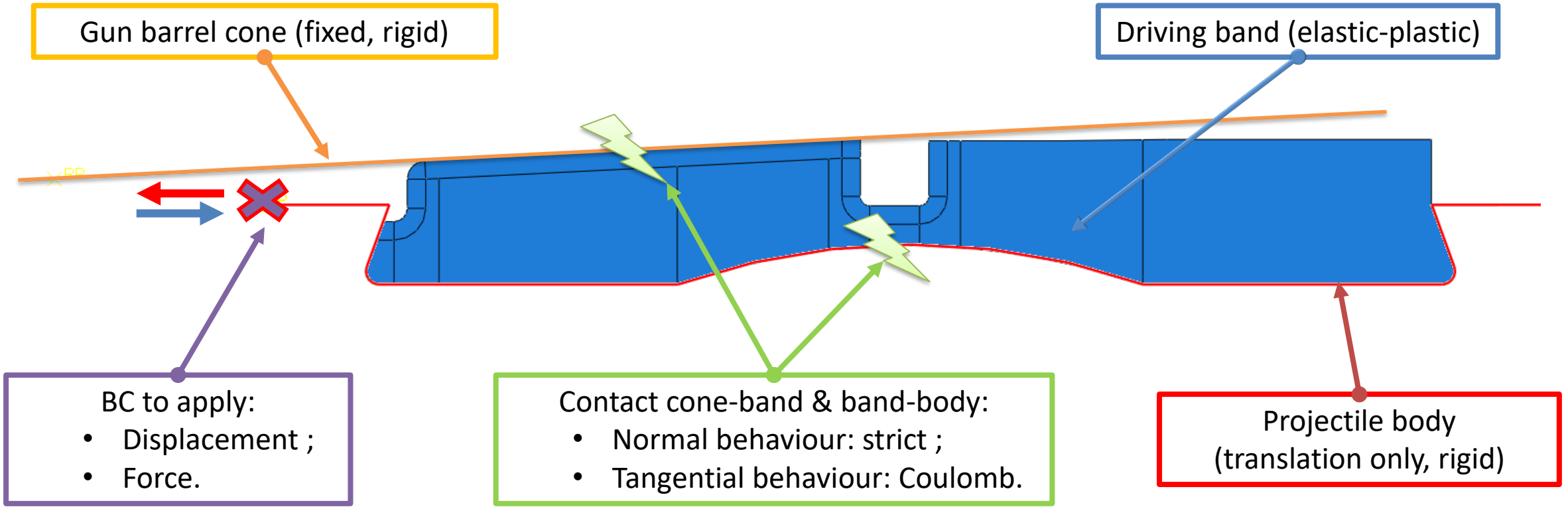


Fig. 8. Quasi-static model formulation.

- Simulation in three steps :

1) Penetration 2) Springback 3) Extraction

II.a) Finite element models – Quasi-statics

- von Mises stress during the three steps:

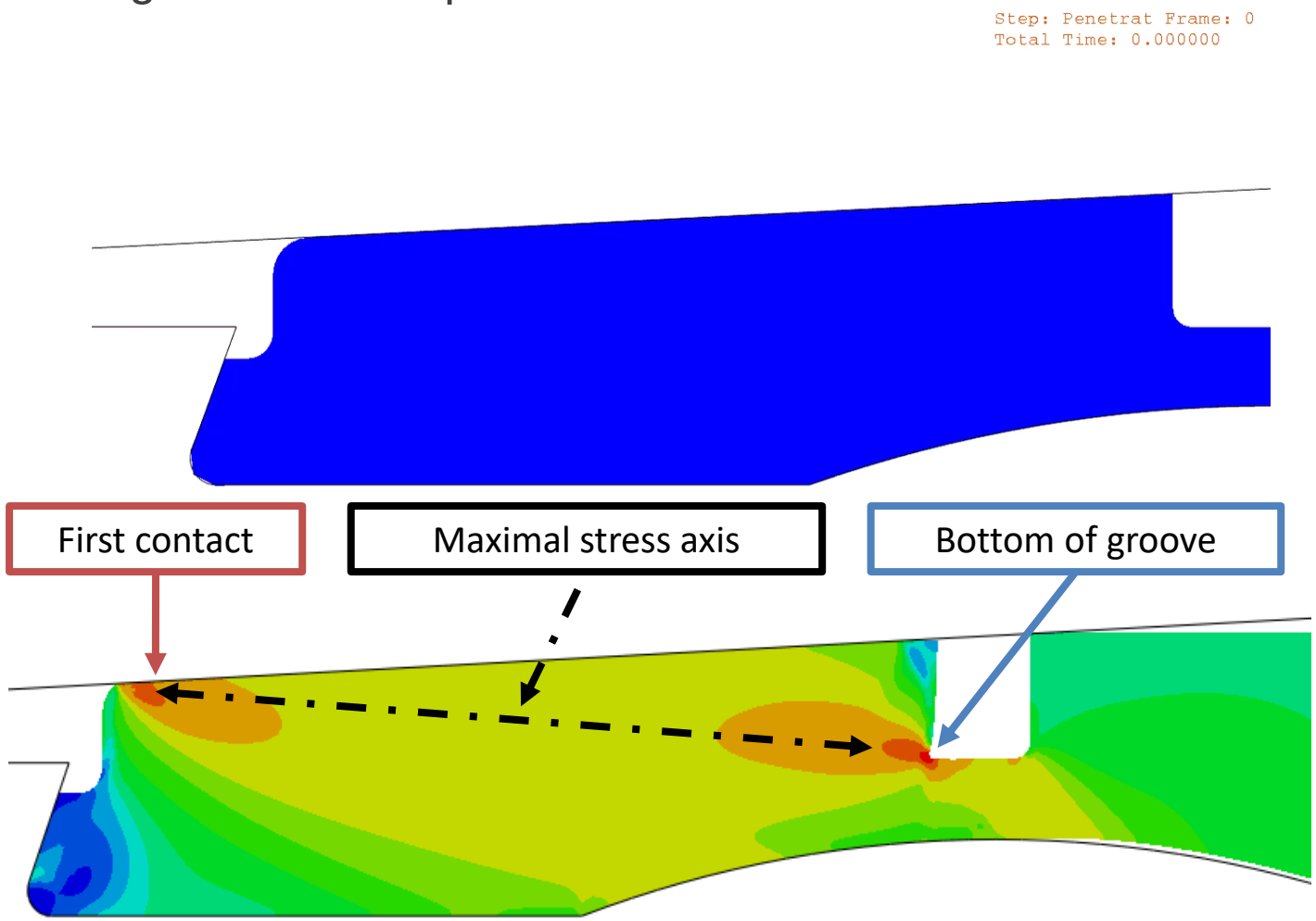


Fig. 11. von Mises stress color map.

Stress distribution at the end of the penetration phase

- Typical stress repartition due to geometry. I obtain: $r_{\mathbf{simulated}} = \frac{-E_{\mathbf{ex}}}{E_{\mathbf{p}}}$

II.a) Finite element models – Quasi-statics

- Mesh optimisation on extraction force:

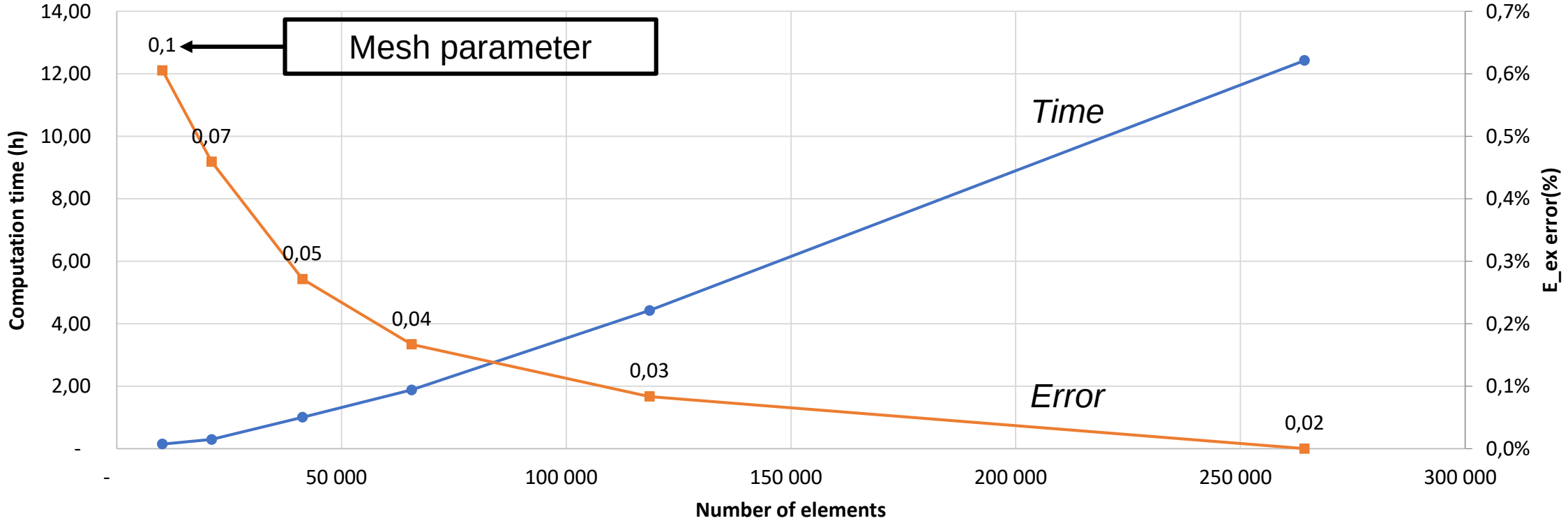


Fig. 12. Performances of an homogeneously meshed band.

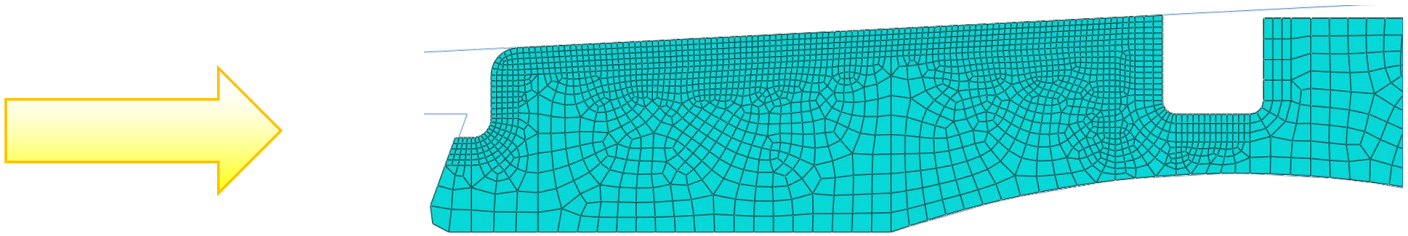


Fig. 13. Axisymmetric adapted mesh (2868 elements).

II.a) Finite element models – Quasi-statics

- Pressure – Overclosure ($P - o$) relationships for normal contact:
  - Strict : “hard contact”
    - $\forall P,\ o \leq 0$;
  - Linear :
    - $P = \mathrm{K}_0 * o$;
  - Exponential :
    - $P = \frac{\mathrm{P}_0}{\exp(1)-1}\left(\frac{o}{\mathrm{C}_0}+1\right)\left(\exp\left(\frac{o}{\mathrm{C}_0}+1\right)-1\right)$.

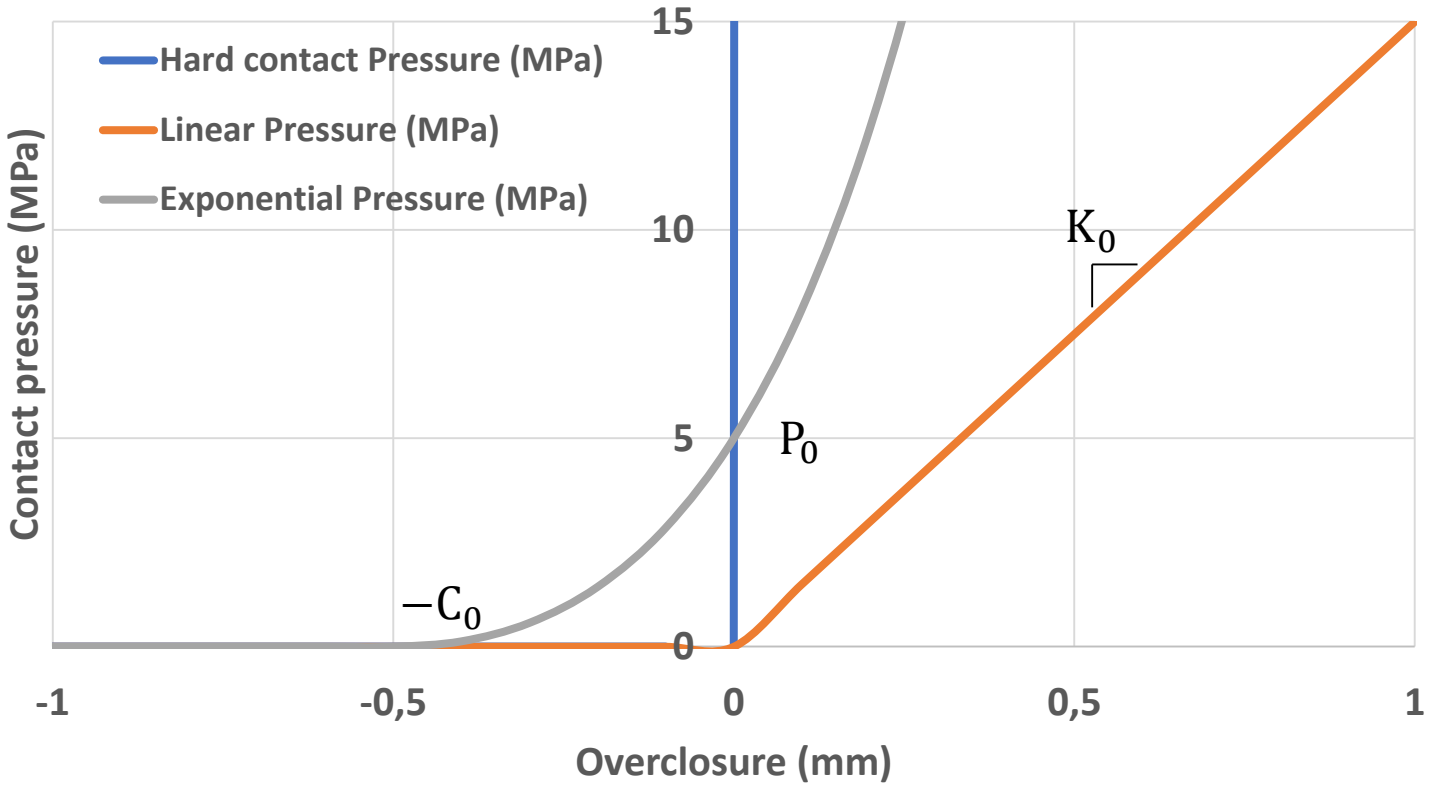


Fig. 14. Normal contact laws.

II.a) Finite element models – Quasi-statics

- Comparison of soft and hard contact laws:

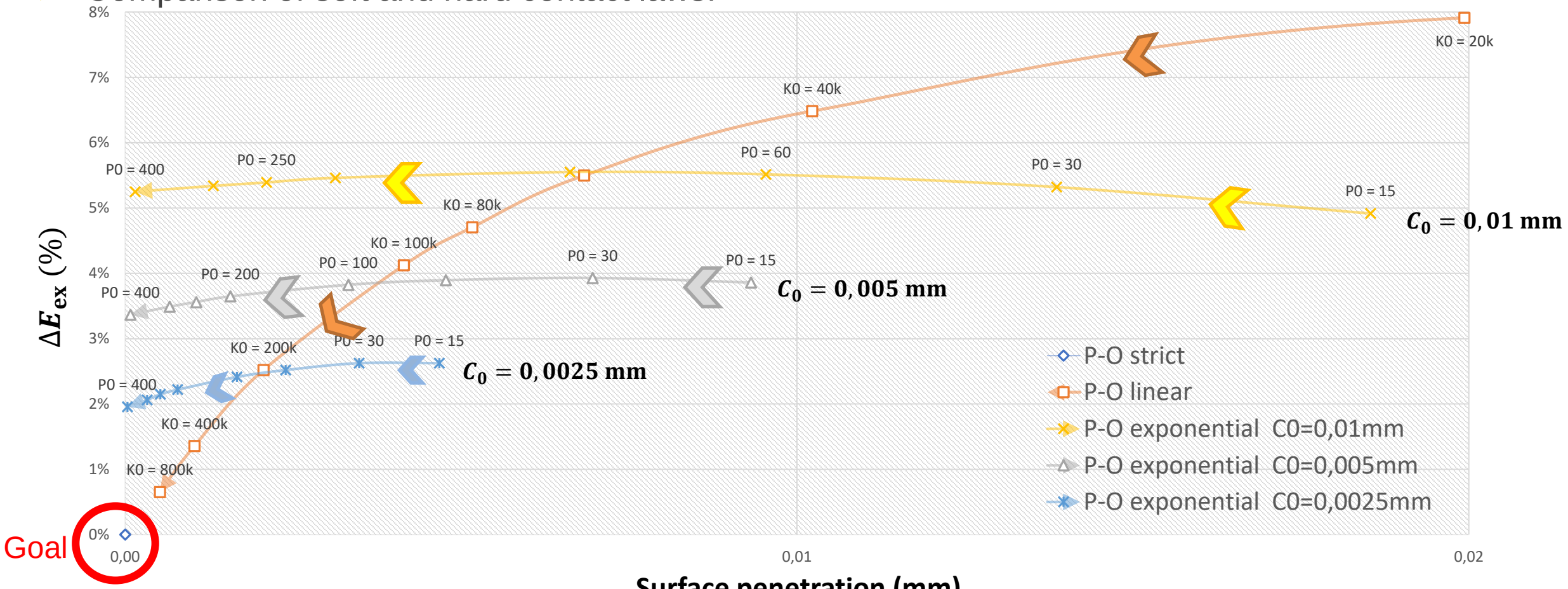


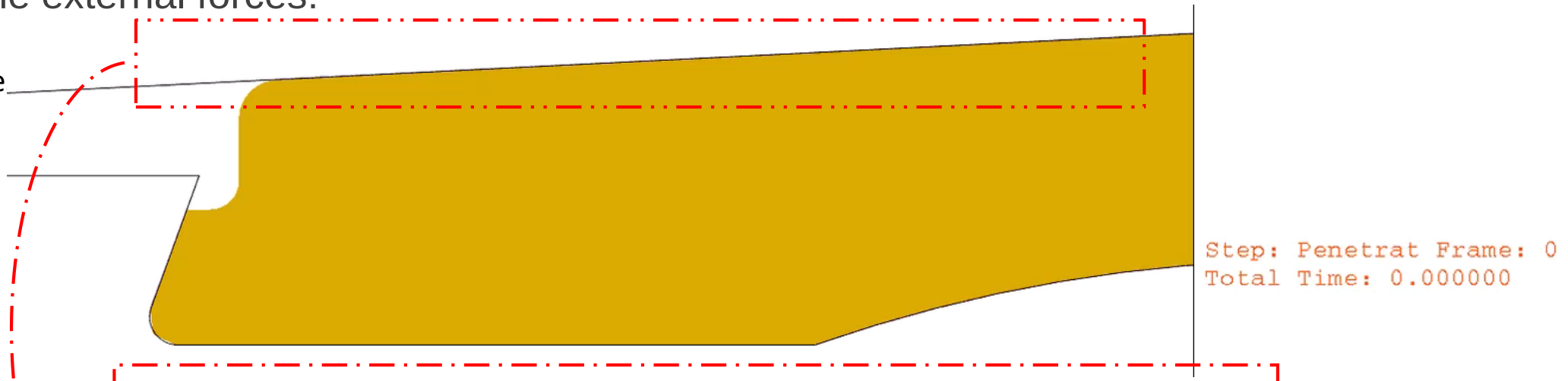
Fig. 15. Comparison of normal contact strategies accuracies.

- Bias can be reduced by "hardening" the law.

II.a) Finite element models – Quasi-statics

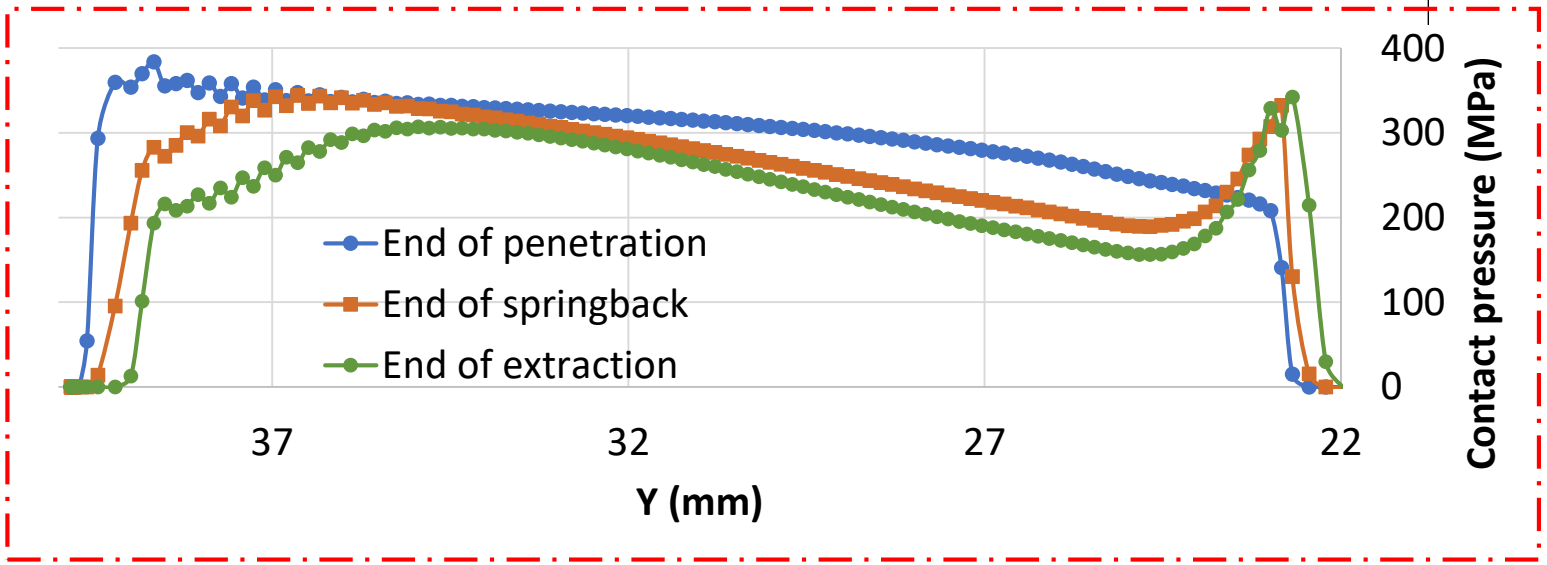
- Plotting the external forces:

Fig. 16. Nodal force evolution.



At the end of each step, we plot the pressure distribution.

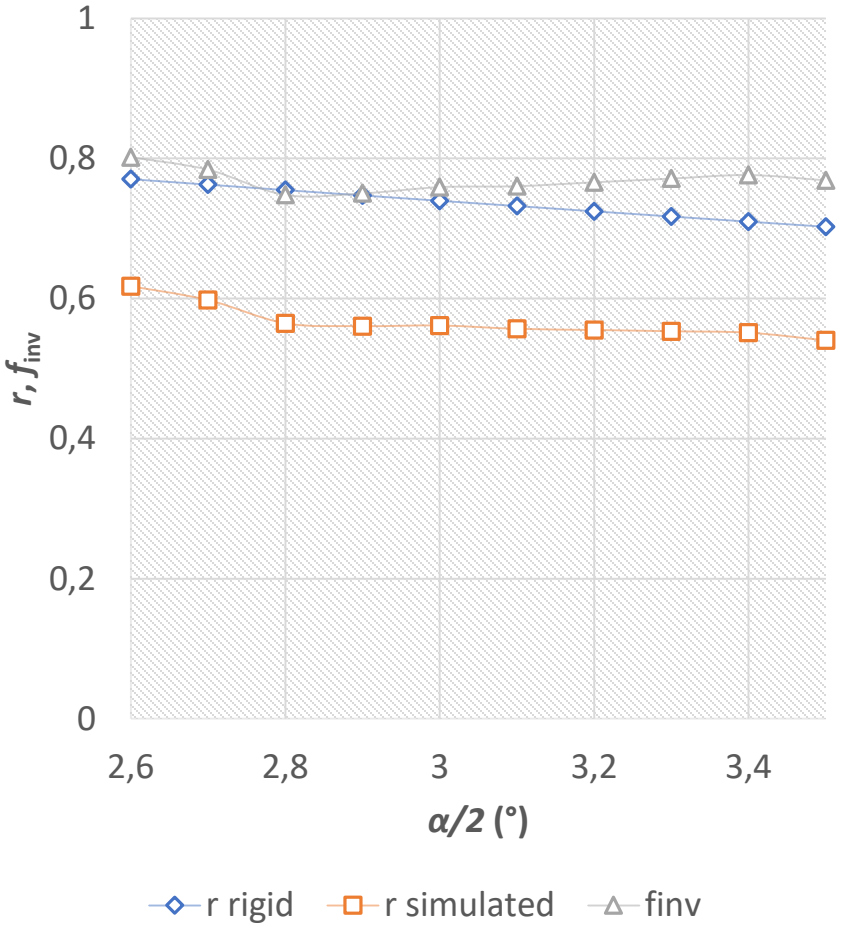
Fig. 17. Pressure evolution at the interface.

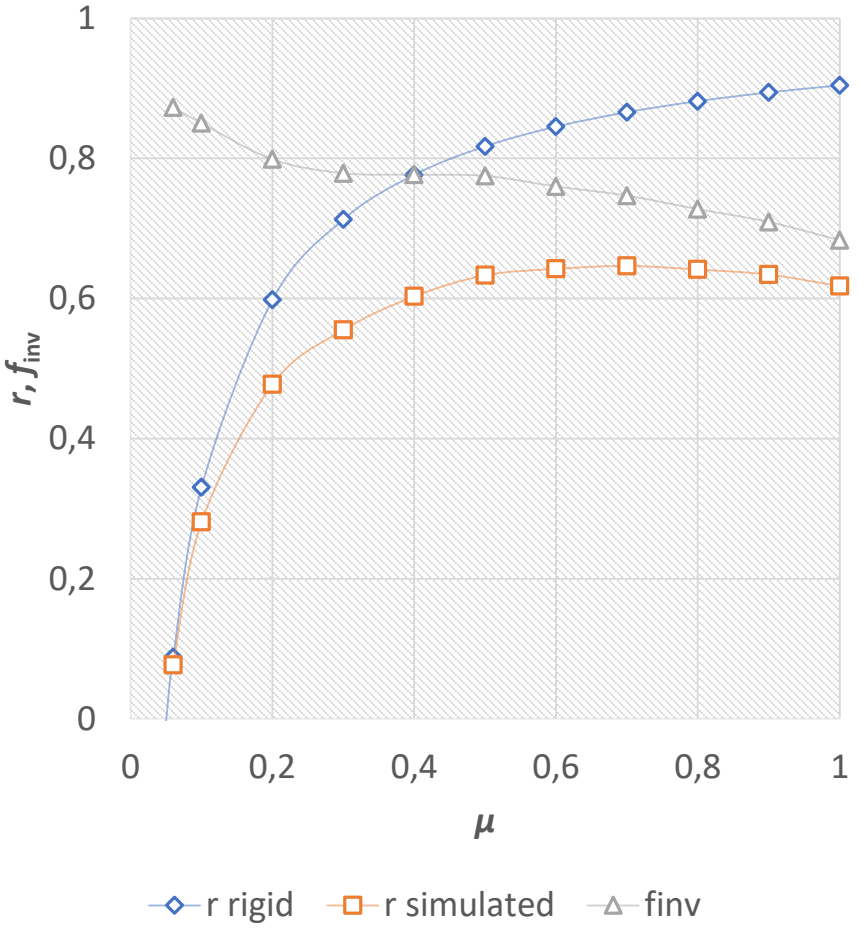


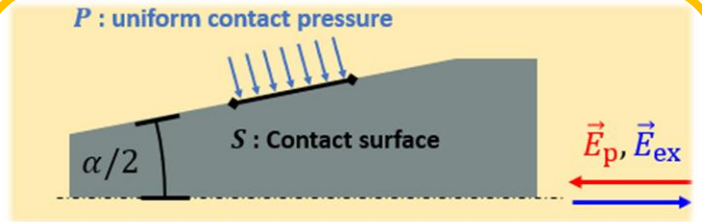
- Heterogeneous contact pressure evolving with loading.

II.a) Finite element models – Quasi-statics

- Input parameters sensitivity:







$$r_{rigid} = \frac{\mu_{ex} - \tan(\alpha/2)}{\mu_p + \tan(\alpha/2)}$$

Rigid hypothesis

$$r_{simulated} = \frac{-E_{ex}}{E_p}$$

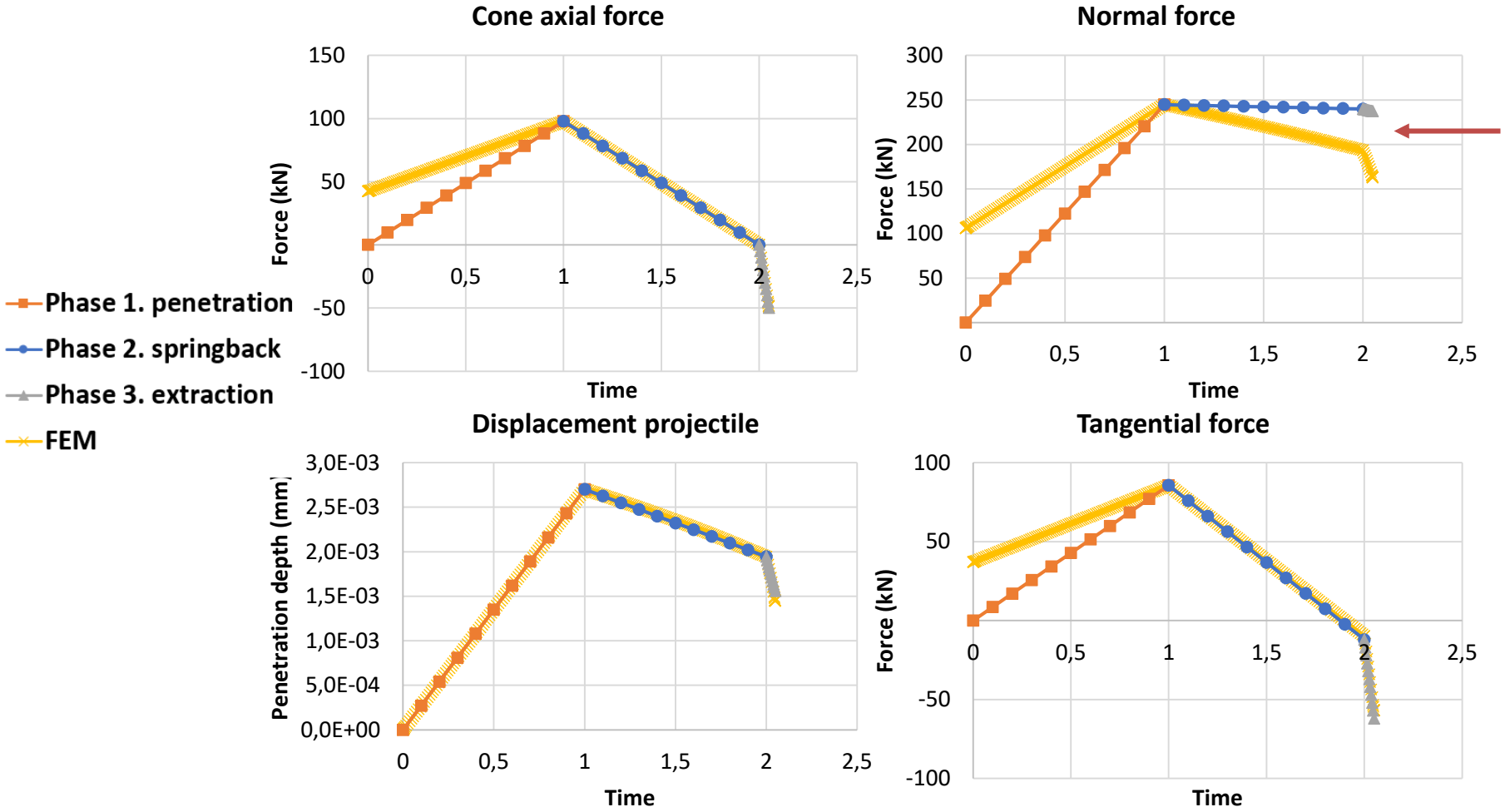
$$f_{inv} = \frac{r_{simulated}}{r_{rigid}}$$

Fig. 18. Influence of cone angle α and friction coefficient μ on r and f_{inv}.

- For typical cone angles, μ is more impactful than α.

II.a) Finite element models – Quasi-statics

- Comparison between FEM and analytical model. Temporals of the elastic model:



Discrepancies in the evolution of normal force.

Analytical/FEM error	
Position	**Force**
0,05%-0,6%	**20%-40%**

Fig. 19. Comparison between FEM and elastic model for interface variables.

- Elastic model qualitatively describes the phenomena.

II.b) Finite element models – Dynamics

- Axisymmetric numerical model:

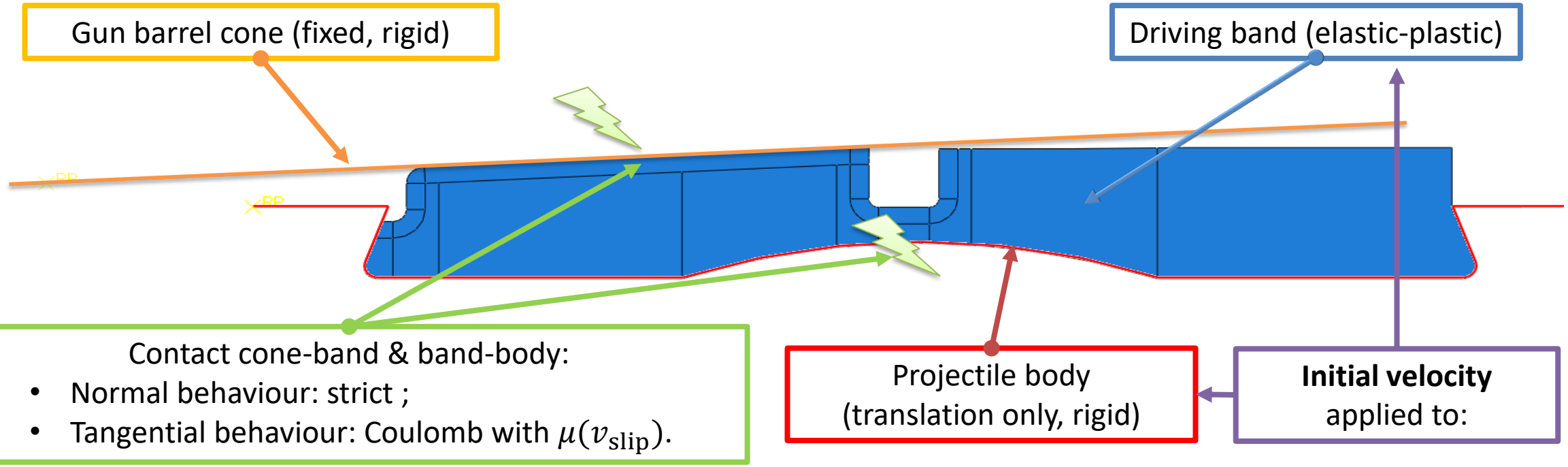


Fig. 20. Dynamic model formulation.

- Simulation in two steps :

  1) & 2) Penetration & springback c) Extraction

- Using same mesh than quasi-statics.

II.b) Finite element models – Dynamics

- Dynamic implicit results for $v_{\text{ini}} = 1\ \text{m.s}^{-1}$:

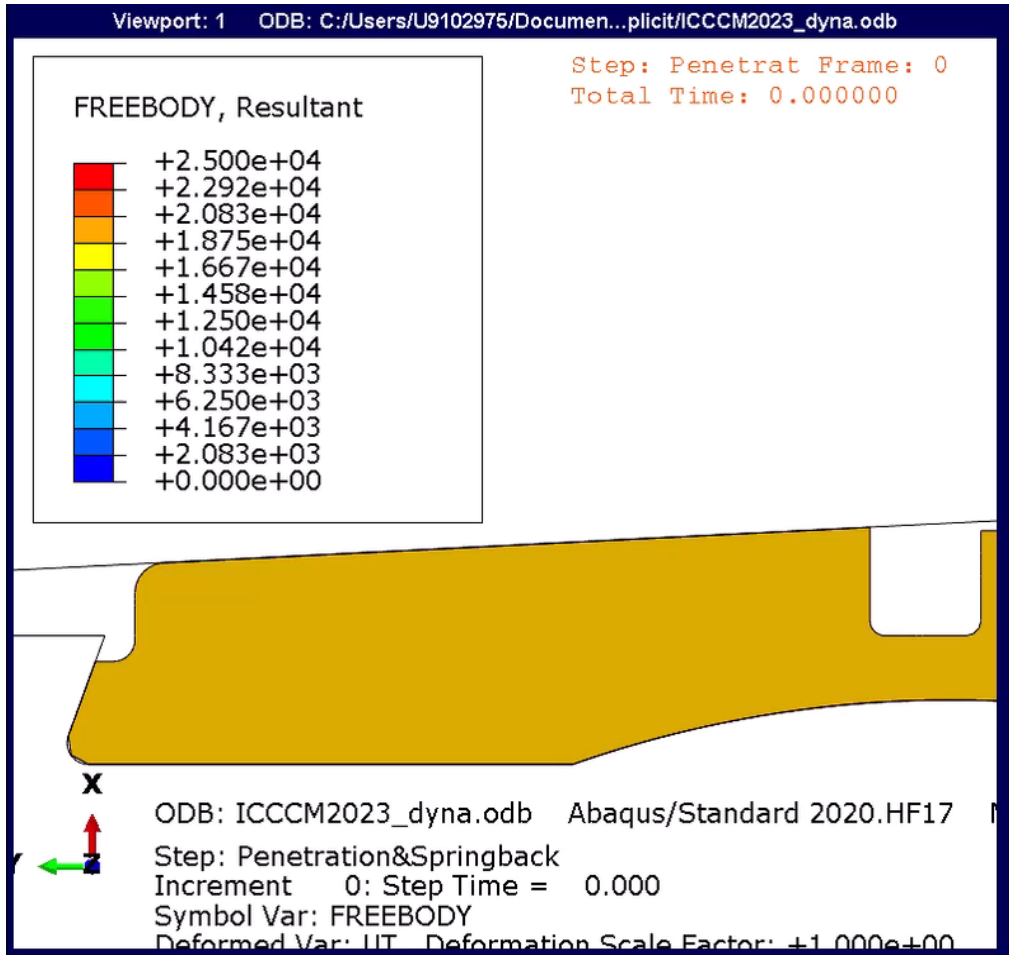


Fig. 21. Nodal forces evolution.

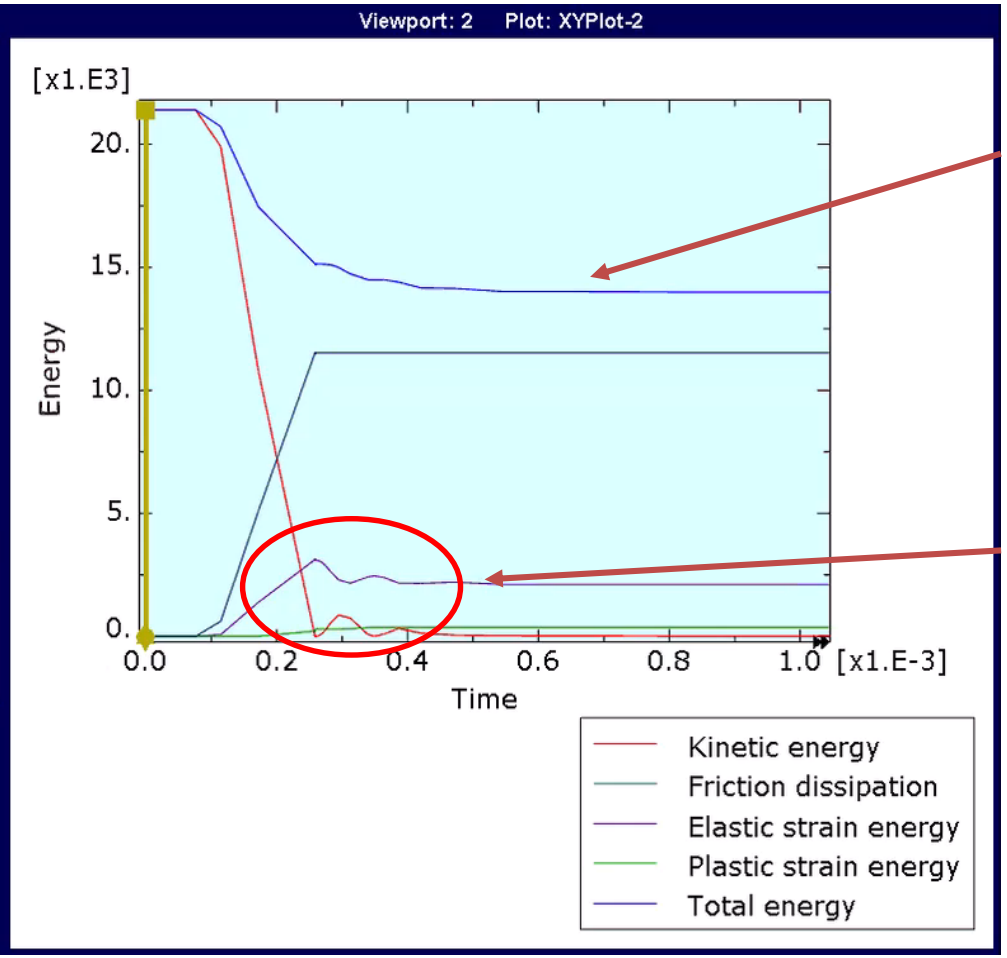


Fig. 22. Energies evolution.

Loss of energy due to the implicit scheme

Springback effect

- The elastic wave is quite costly in terms of computation time.

II.b) Finite element models – Dynamics

- Extraction force comparison for static and dynamic implicit simulations:

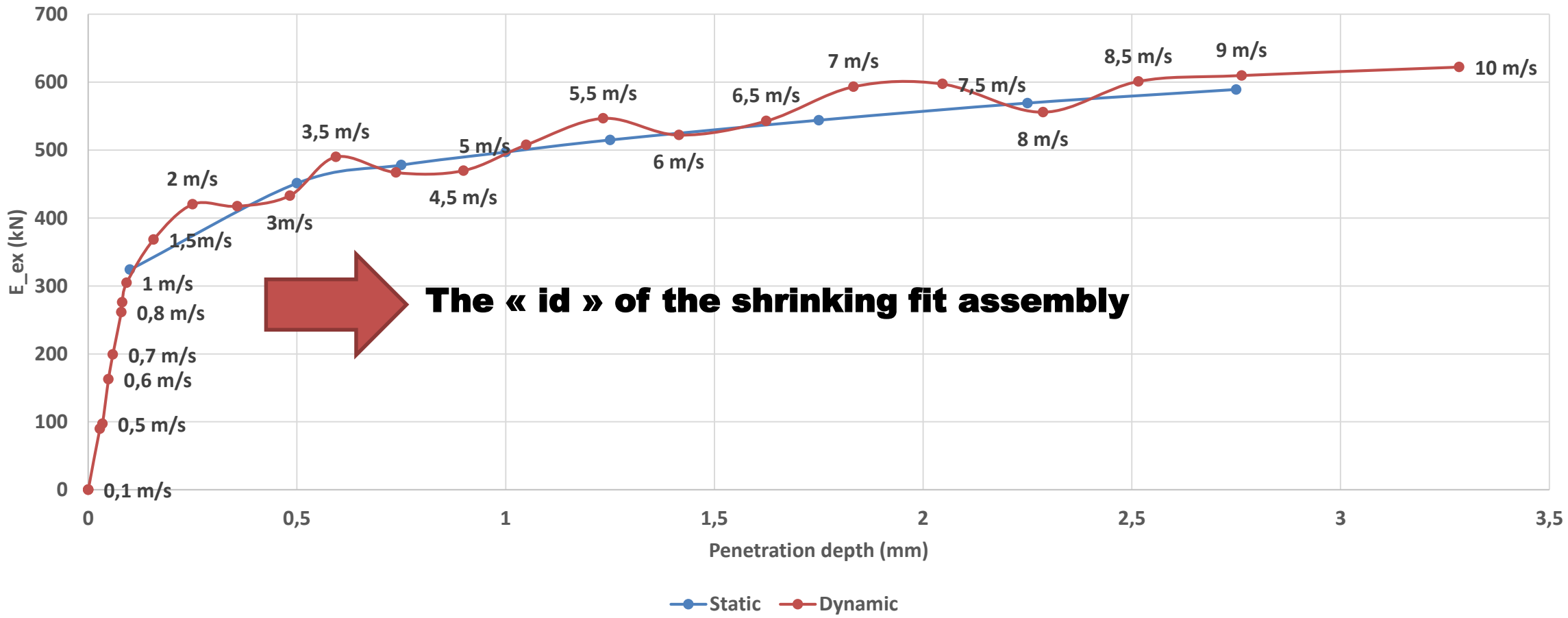


Fig. 23. E_{ex} (penetration depth) for quasi-statics and dynamics implicit models.

- Good tendency adequation but oscillations have to be managed.

Conclusion

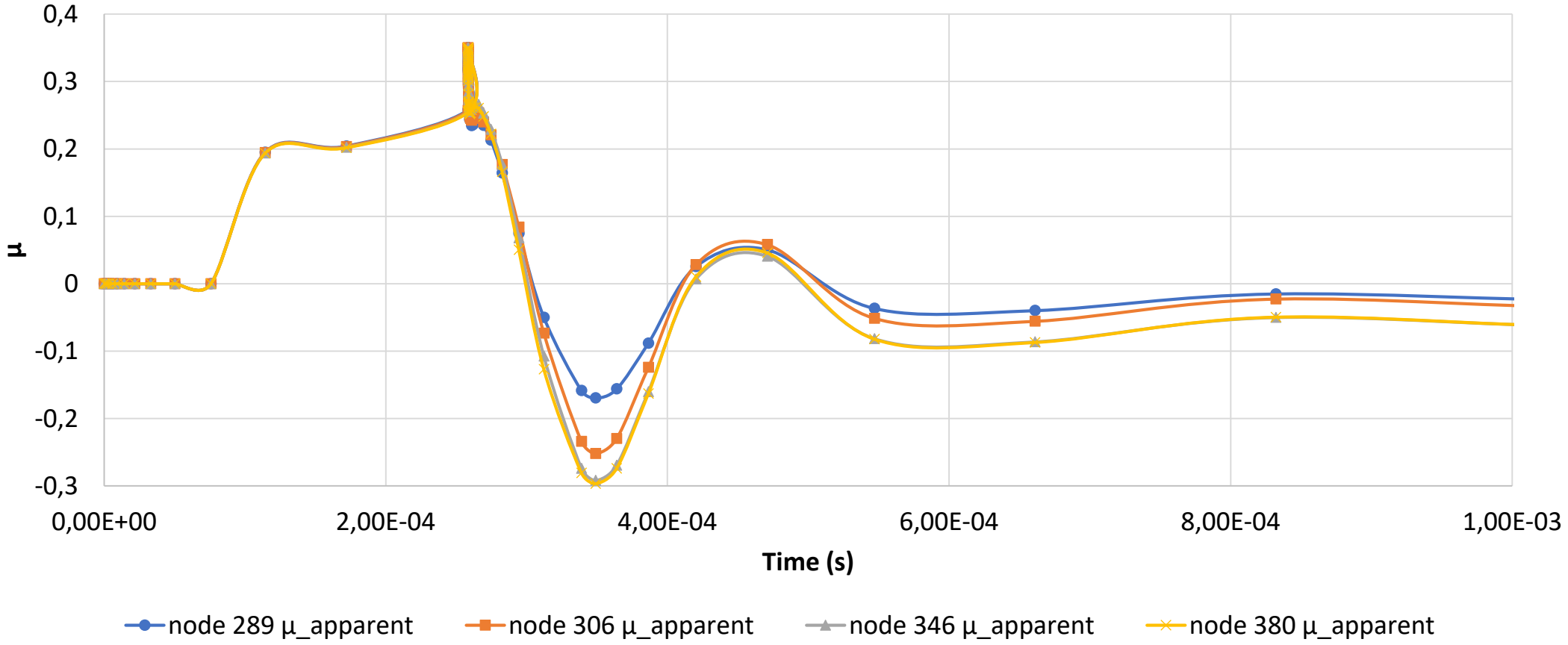
- FEM as a tool for research in difficult access area.
- No large discrepancy between analytical or FEM model identified ;
- Theoretical demonstration of $-E_{\mathrm{ex}} < E_{\mathrm{p}}$;
- μ is the most important parameter in a conical shrink fit assembly ;
- Further developments:
  - Experimental campaign to validate the numerical results ;
  - Analytical model have to be enhanced.

THANK YOU FOR LISTENING !

Now it is time for questions !

Appendix: Evolution of $\mu_{apparent}$

- Looking at some nodes at the interface (dynamic implicit simulation):



Appendix: FEM parameters

- Main simulation parameters:
  - materials:

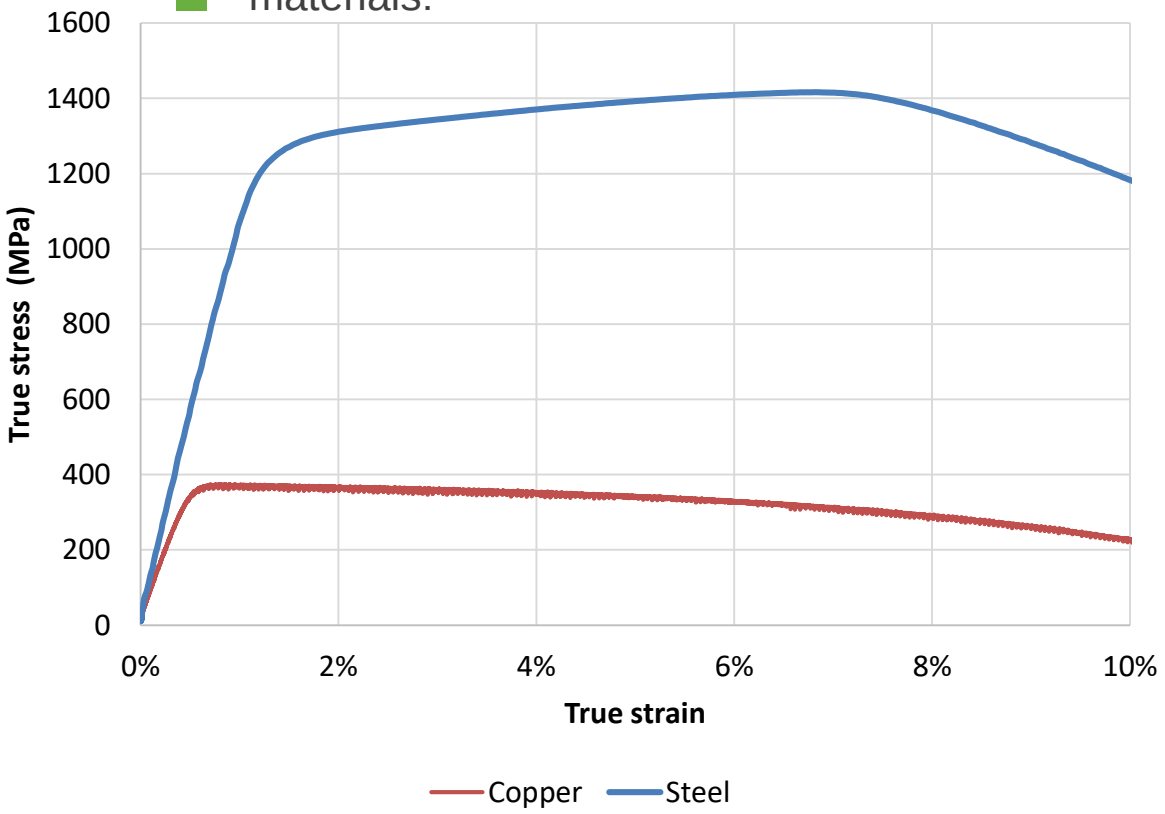


Fig. 9. Copper and steel stress-strain curves.

➔ The copper band will take most of the strain.

  - interface:

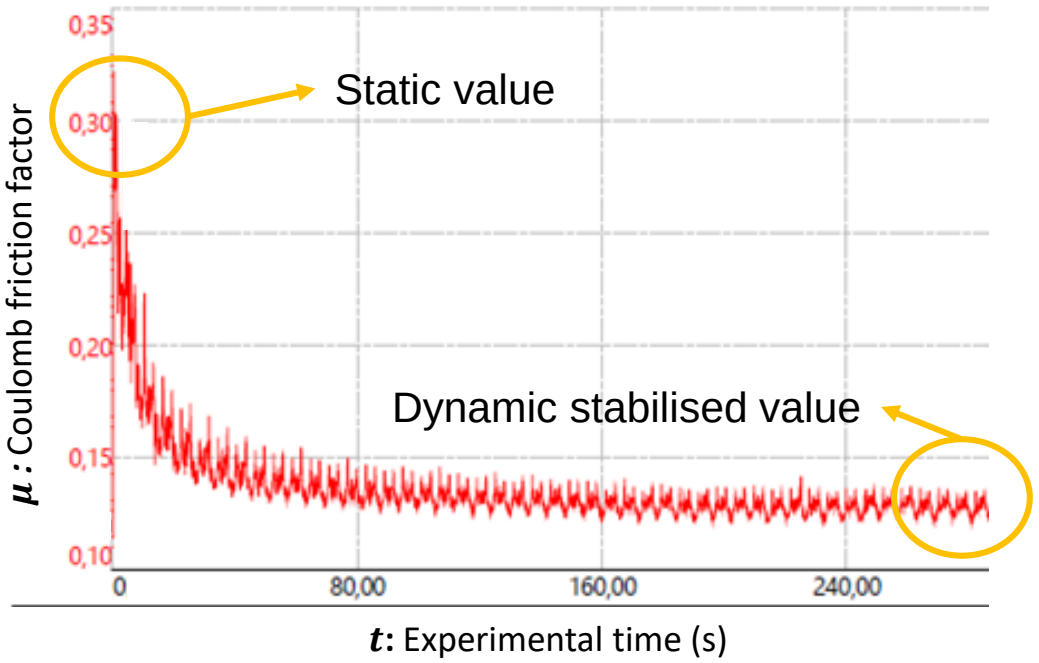


Fig. 10. Friction coefficient steel-copper on pin-disk tribometer.

➔ μ depends on materials and contact conditions.

- Characterisation campaign to obtain inputs for simulation.

Appendix: Implicit scheme instability

- Energy loss is due to the implicit scheme instability for contact pairs: