LHC Collimators for Phase 1

Effects of the 450GeV accident case (TT40 experiment) on the jaw metal support (intermediate report)

LCWG meeting 12/09/2005

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Outline

- TT40 test results
- Preliminary interpretation
- Simplified “didactic” model
- Actual model
- Outlook and conclusions

Thermo-mechanical Analysis

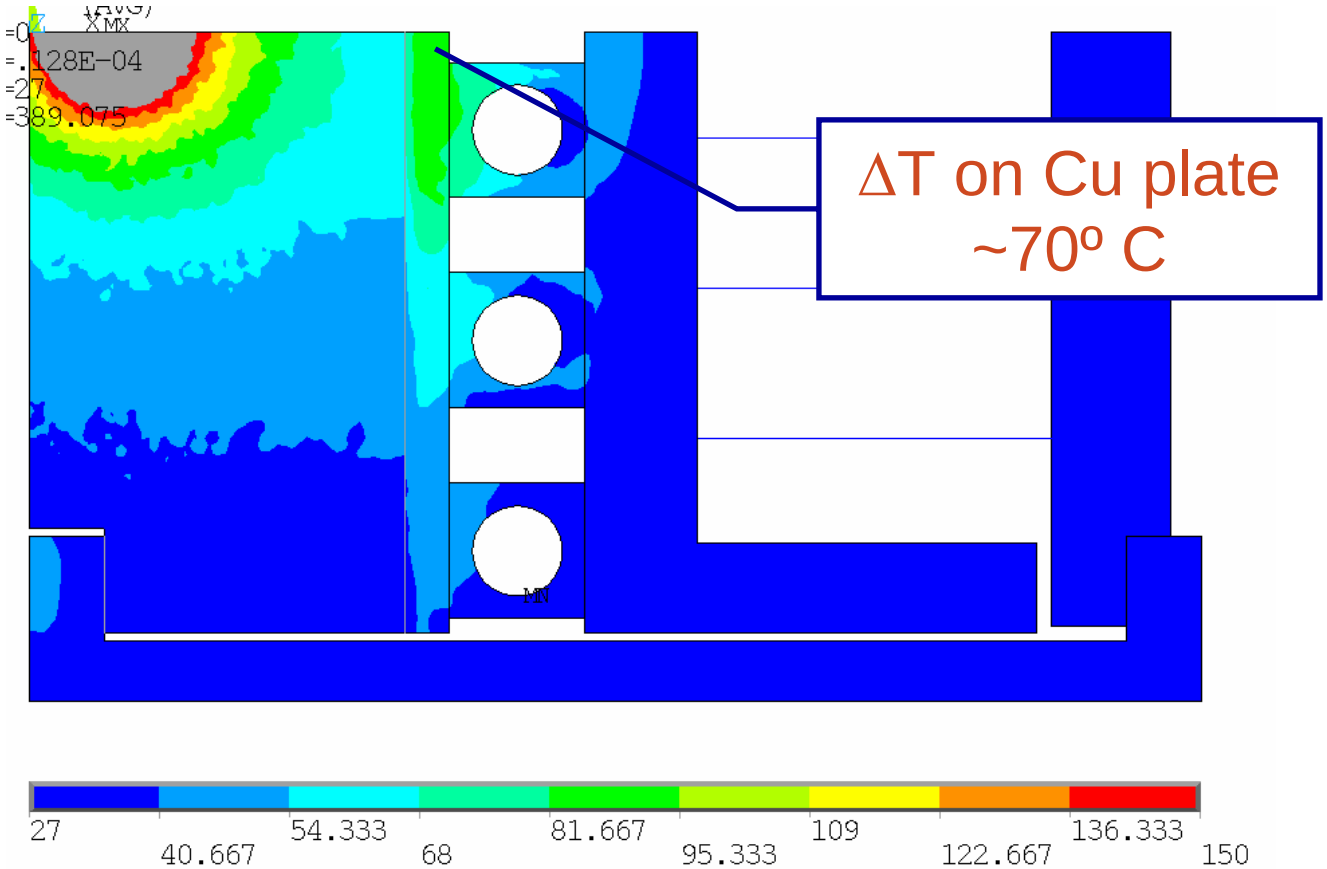
Controls on prototype #2 after TT40 test (5 3.2×10^{13} p shots plus many more at lower intensity) …

- **No sign of mechanical damage on both C/C and graphite jaw (in agreement with calculations).**
- **No permanent deformation of jaws.**
- **Permanent bending of metal support (~300÷350 μm)**

No in-depth calculations were done so far on the metal support for the accident cases (all focus on the jaws) … this has to be reconsidered!!

Thermo-mechanical Analysis

Temperature profile after 7.2 μs (5 mm offset) "hottest" cross-section



Thermo-mechanical Analysis

A simplified theory to justify permanent bending deformation … (1)

- The metal support is free to expand, but because of the rapidity of the thermal shock it acts "as if" no expansion is allowed ⇨ **compression stresses** arise …
- For copper a $\Delta T = 70°C$ with prevented expansion leads to $\sigma_z \div -E\alpha\Delta T \cong -140MPa$. This is well above yield strength of annealed OFE-Cu (**~50 MPa**) ⇨Plastic compressive deformation of 3mm Cu plate (and partially Cu pipes) ($\varepsilon_z < 0$) ⇨Bending of the support **away from the beam**!

Thermo-mechanical Analysis

A simplified theory to justify permanent bending deformation … (2)

- Vibrations are induced. Can successive tensile stresses lead to a "counter-plasticization" and positive permanent strains?
- An in-depth **coupled thermo-mechanical transient elasto-plastic** analysis is necessary!!
- Unfortunately such a non-linear analysis is very time-consuming
  - Shot duration 7 μs ⇨ calculation time-step ≤ 1 μs
  - Low flexural eigen-frequencies ⇨ ~ 15 ms
  - At least several periods must be studied ⇨ time-span > 0.1 s
  - Number of calculation substeps > 150000 ⇨ CPU time ~15 s/substep ⇨ > **25 days of calculation for a full model**

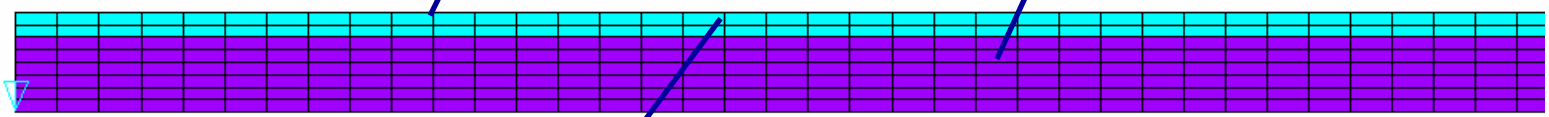
Thermo-mechanical Analysis

A simplified model is first used to understand the "basics" of the phenomenon and get results in a short time …

15 mm thick, 1 m long strip, bi-metal

3 mm elasto-plastic Cu (σ_o = 50 MPa)

12 mm fully elastic Glidcop (σ_o = 300 MPa)



Temperature increasing from 27ºC to 97º in 7 μs on all Cu strip

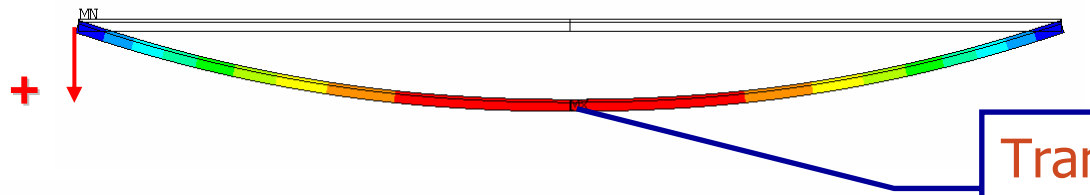
Heat diffusion taken into account

Density artificially reduced to "accelerate" the process

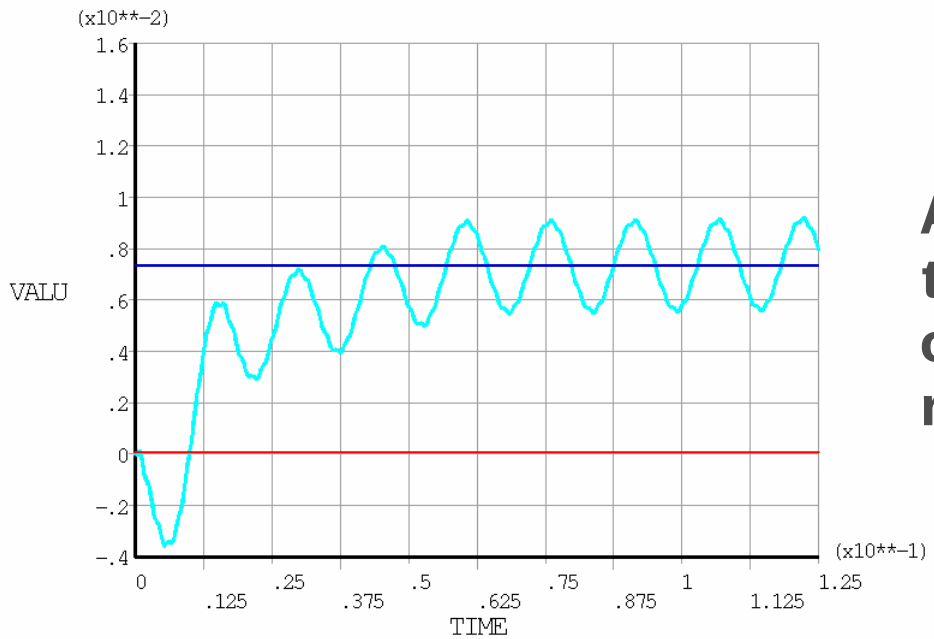
ν=0 to avoid mechanical coupling

Thermo-mechanical Analysis

Results for the simplified didactic model



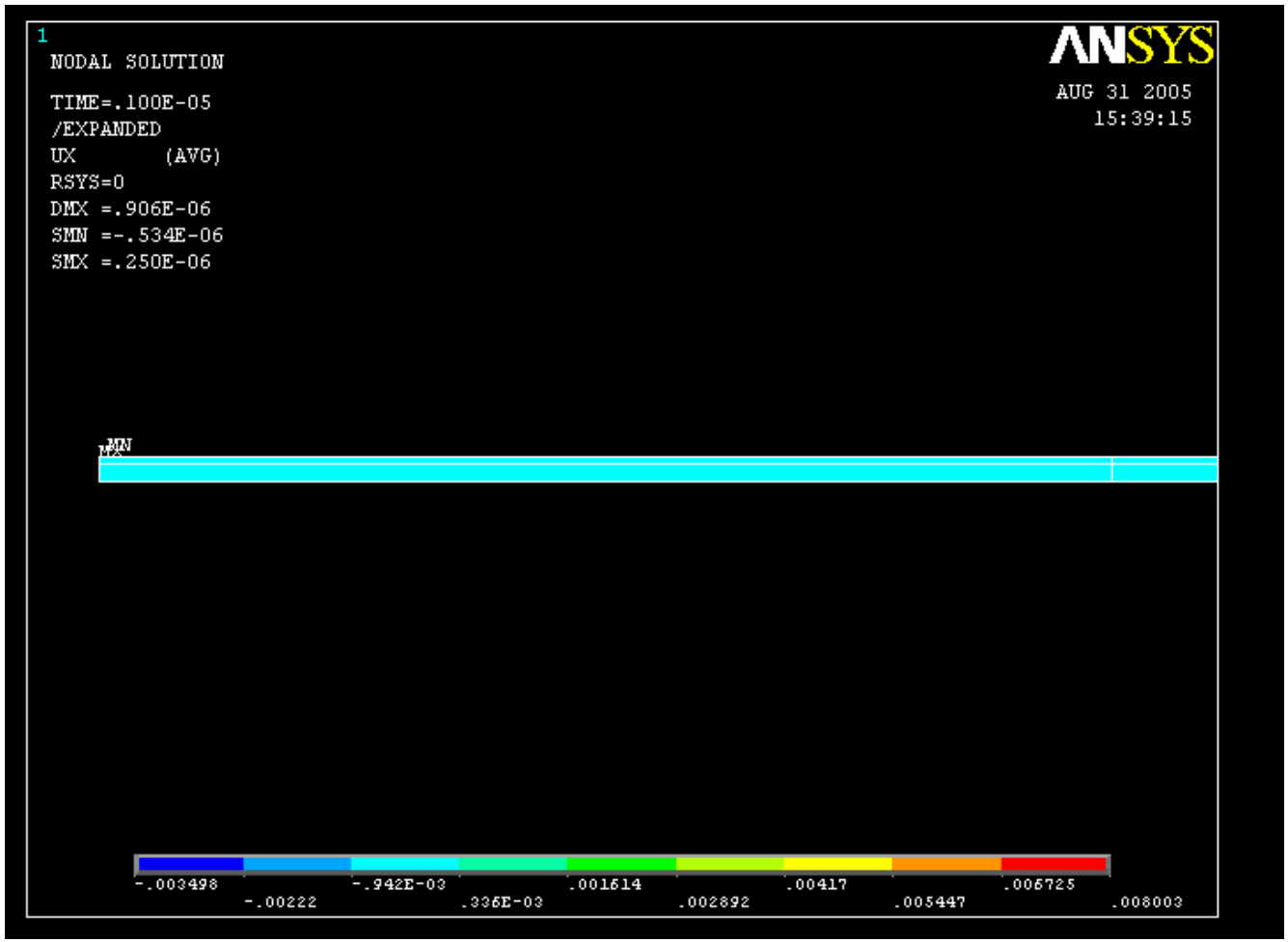
Transverse displacement at mid-span



After initially bending towards the beam, the strip oscillates about a "deformed" neutral position.

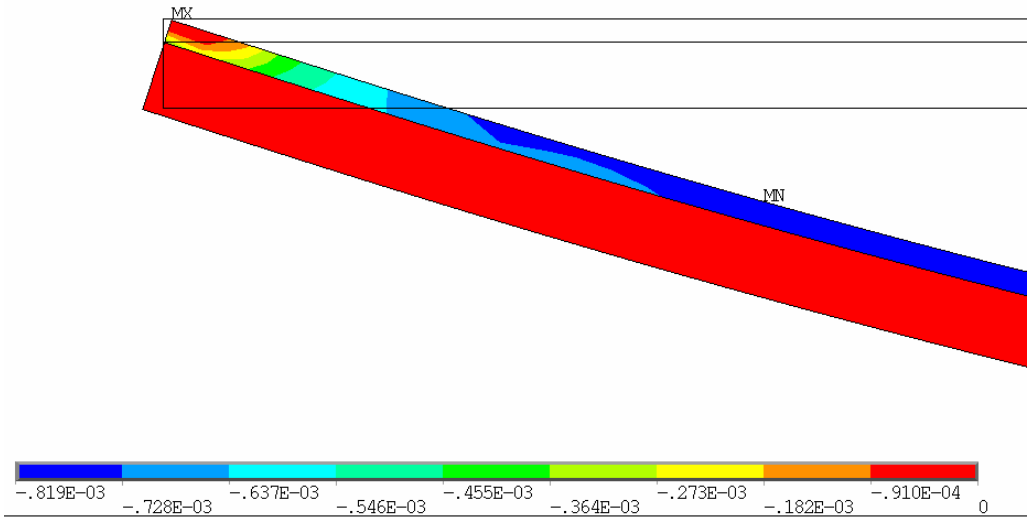
Thermo-mechanical Analysis

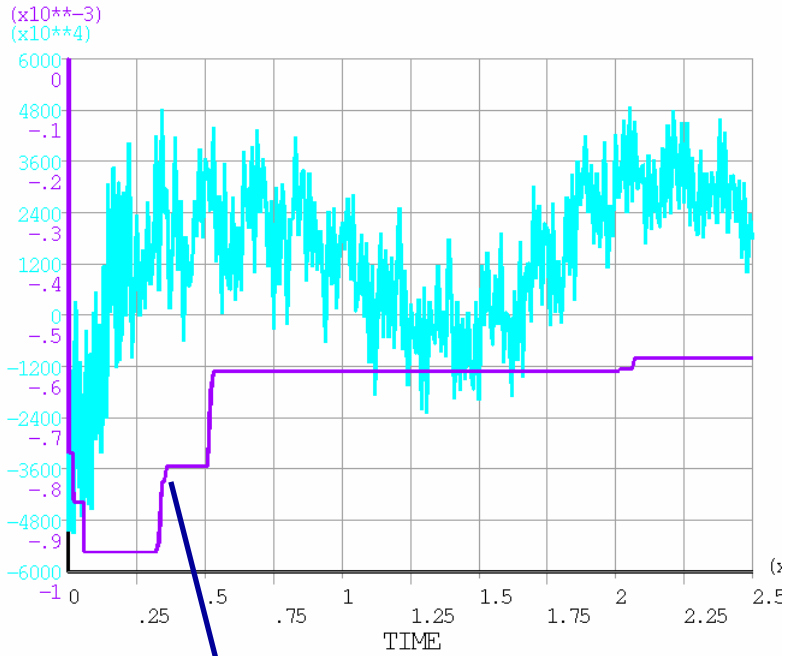
Results for the simplified didactic model



Thermo-mechanical Analysis

Results for the simplified didactic model (2)





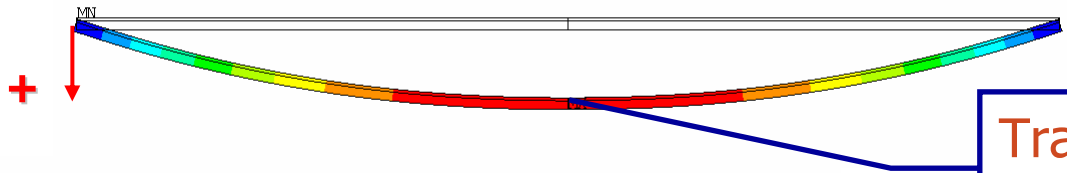
This is due to the fact that the permanent deformations on the Cu plate remain always negative

Longitudinal plastic strain on Cu-plate at mid span

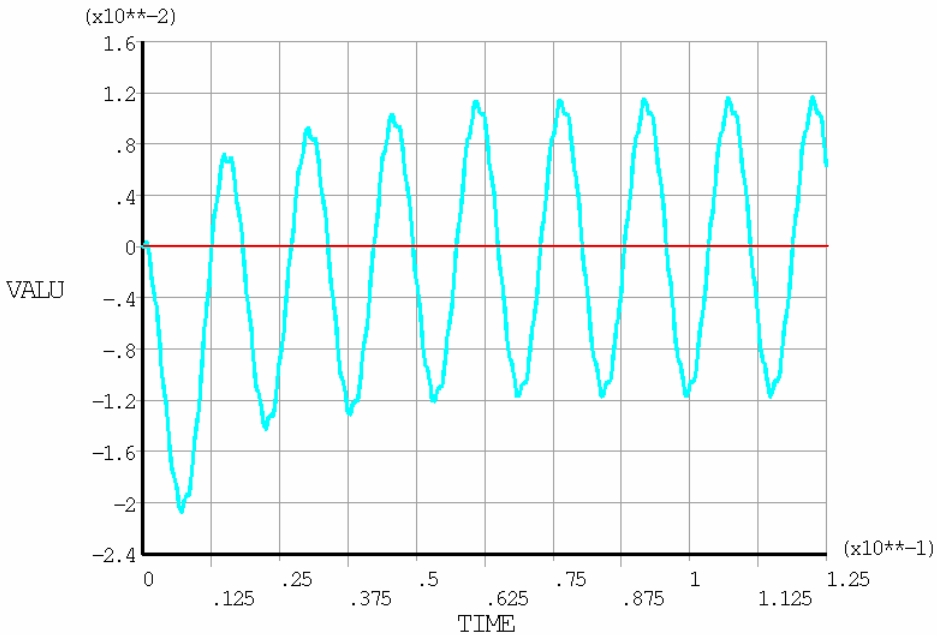
Thermo-mechanical Analysis

Results for the simplified didactic model (3)

What happens if a fully elastic model is used?



Transverse displacement at mid-span



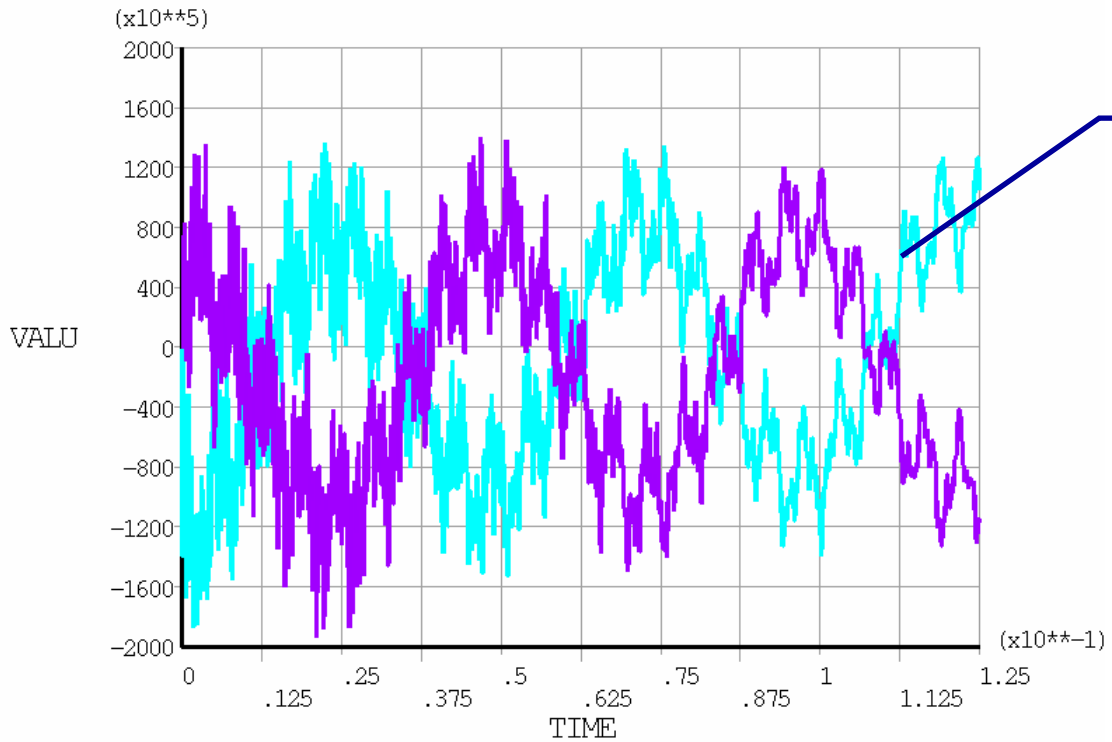
Differences in behavior:

- **Initial "positive" displacement is much larger.**
- **Strip returns to zero neutral position**

Thermo-mechanical Analysis

Results for the simplified didactic model (3)

What happens if a fully elastic model is used?



Bending stress at mid-span on Cu-strip face

Compressive stress on Cu-plate would reach 200MPa, because of dynamic effect

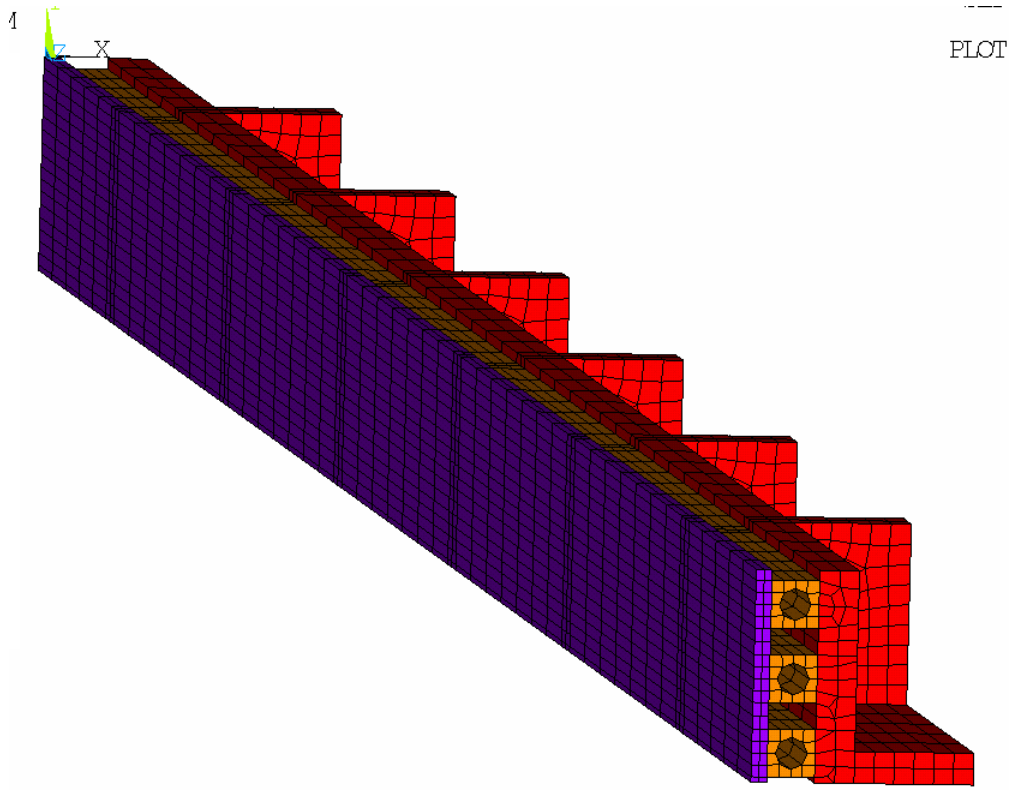
Thermo-mechanical Analysis

3-D full model of the metal support of TT40 prototype

TT40 prototype simulation (i.e. Cu-OFE for pipes and plate, Steel for C-bar)

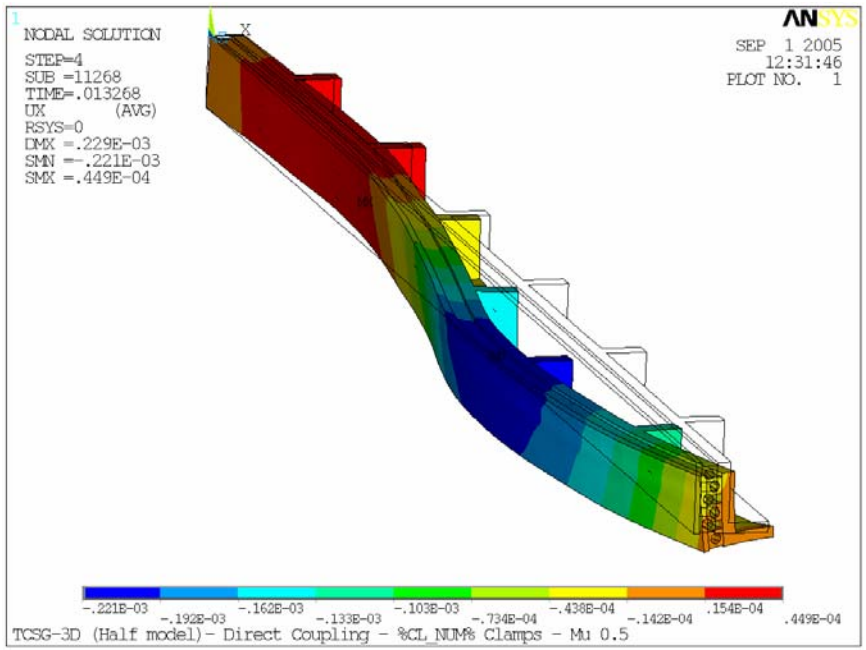
Actual energy distribution from FLUKA runs (linearly increasing during 7.2μs)

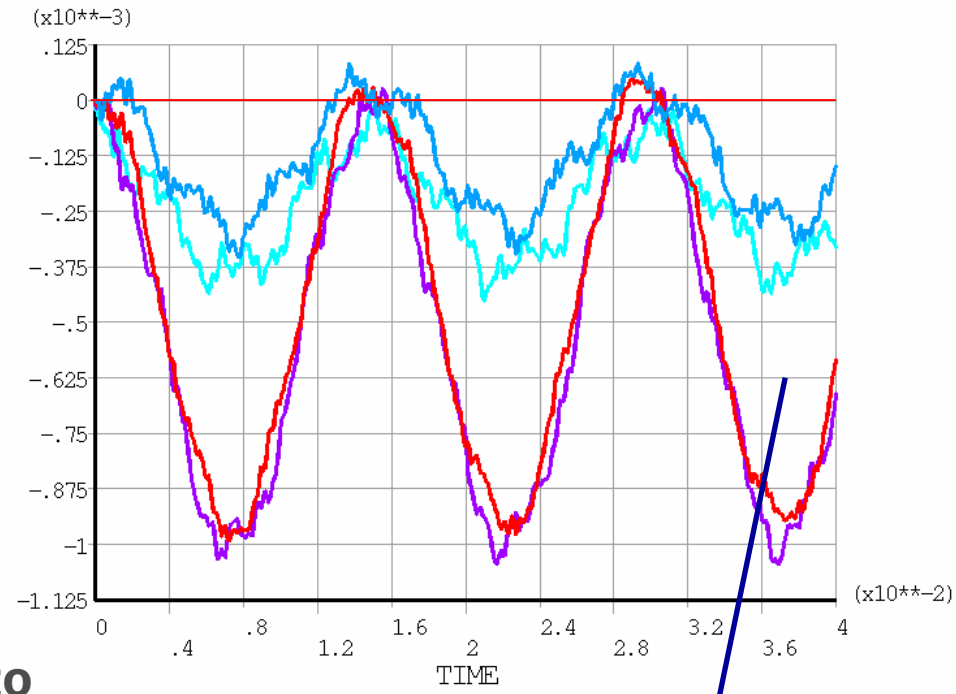
Elasto-plastic behavior for all materials



Thermo-mechanical Analysis

Results for the 3-D full model (analysis stopped at 40ms)



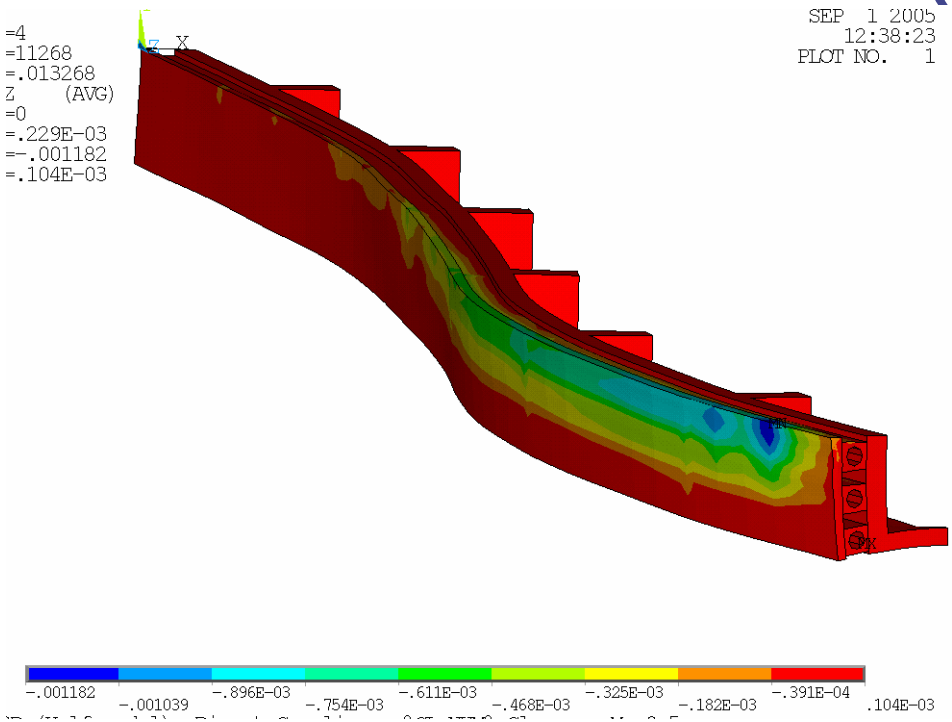


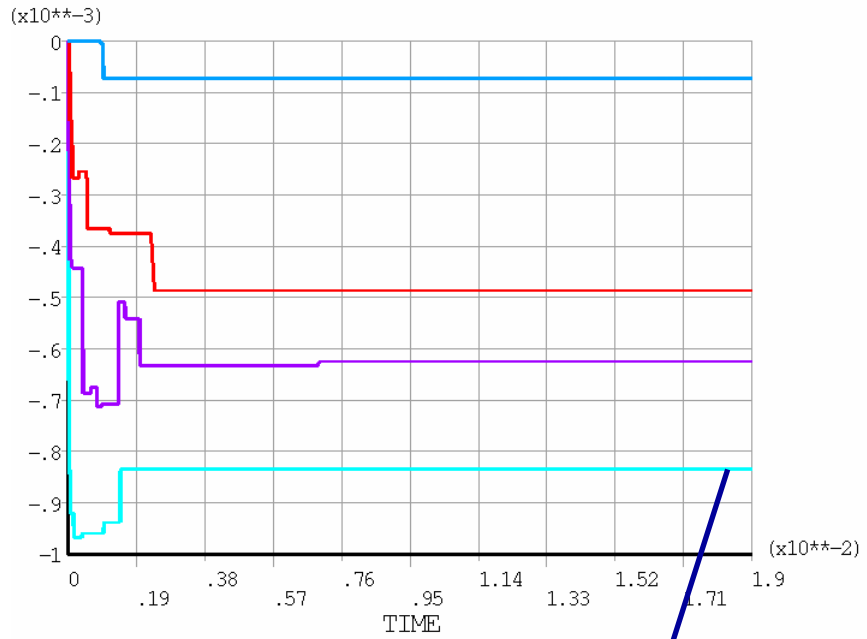
The displacement pattern seems to be the same as for simplified model, with a non-uniformity in z … unfortunately the drift is much slower ⇨ longer analysis time!!

Transverse displacement at circa mid-span

Thermo-mechanical Analysis

Results for the 3-D full model (analysis stopped at 40ms)





Longitudinal strains are always negative and seem to have stabilized after some millisec.

ε_z at 900 mm

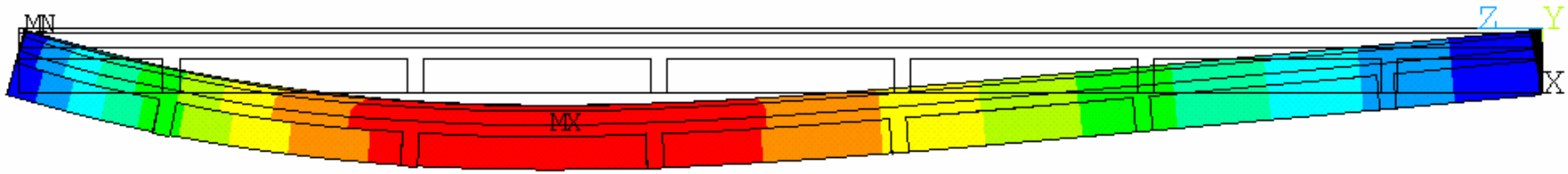
Thermo-mechanical Analysis

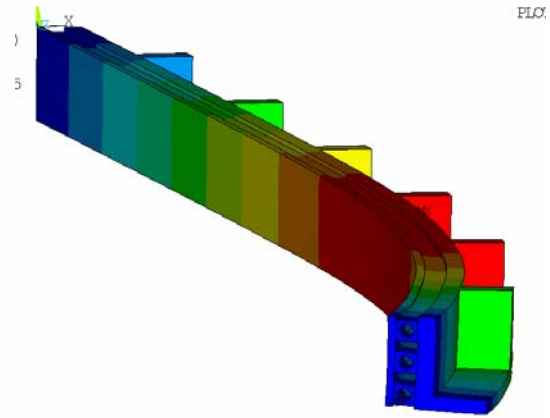
Results for the 3D model …

- Unfortunately after 40 ms (i.e. ~8 days CPU time) it is only possible to state that the permanent deformation is "qualitatively" similar to the measured one, but no prediction can be done on the quantity …
- But the permanent deformation has long been stabilized …
- We decided then to force the system to converge to its final static value by putting to zero the inertial term (time integration effects turned off)

Thermo-mechanical Analysis

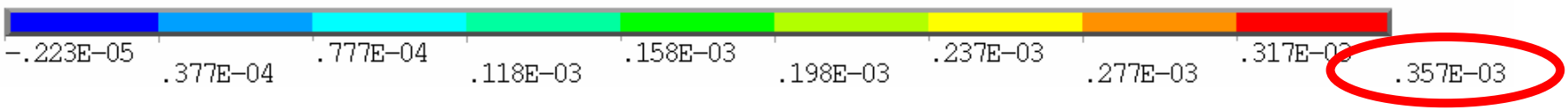
Results for the 3-D full model





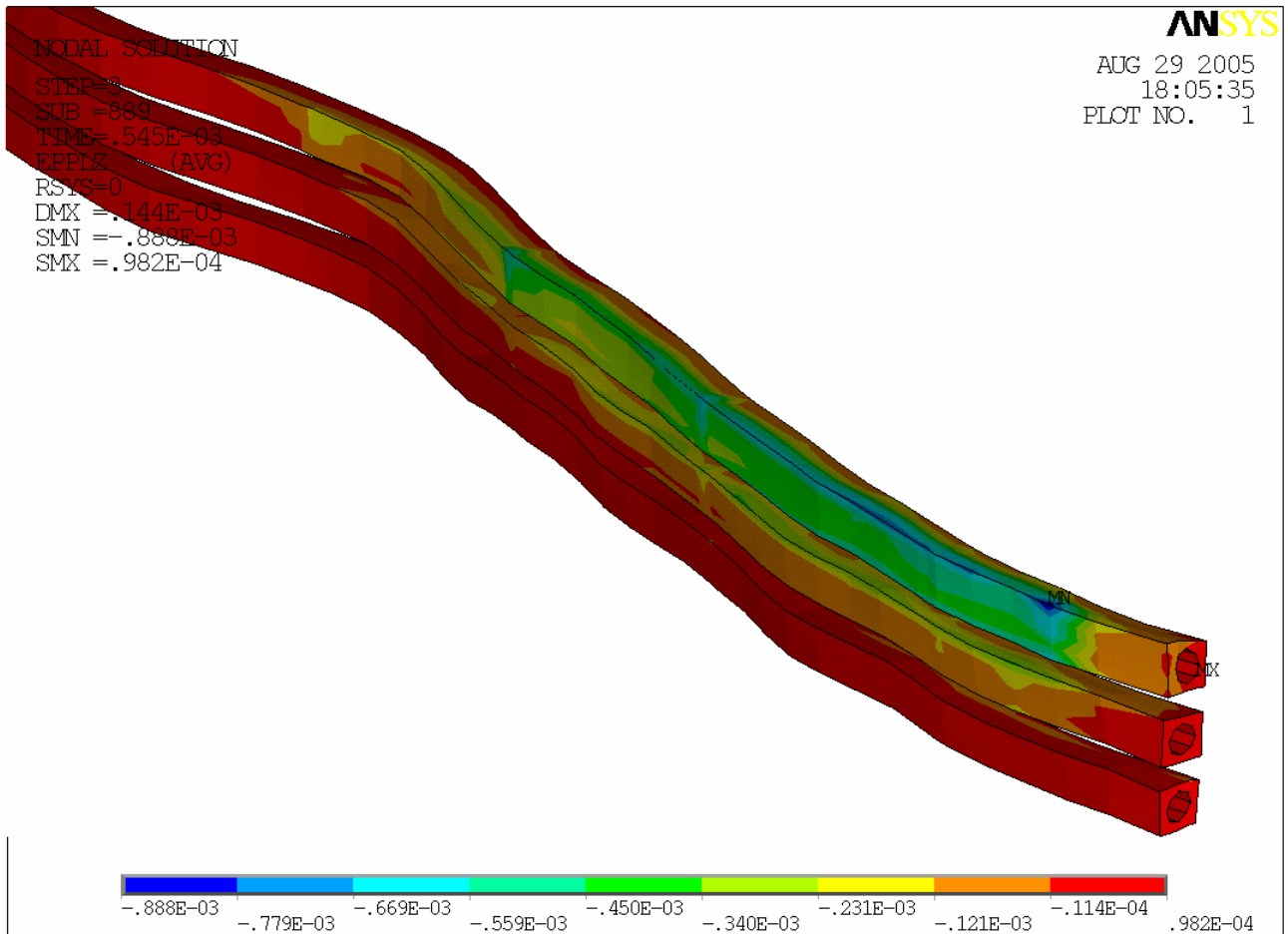
When the dynamics effects finally disappear ⇨ $F_{elast} = F_{plast}$

The calculated displacement well matches the measured deformations both in absolute value (357 μm) and in shape



Thermo-mechanical Analysis

Results for the 3-D full model (TT40 replica)



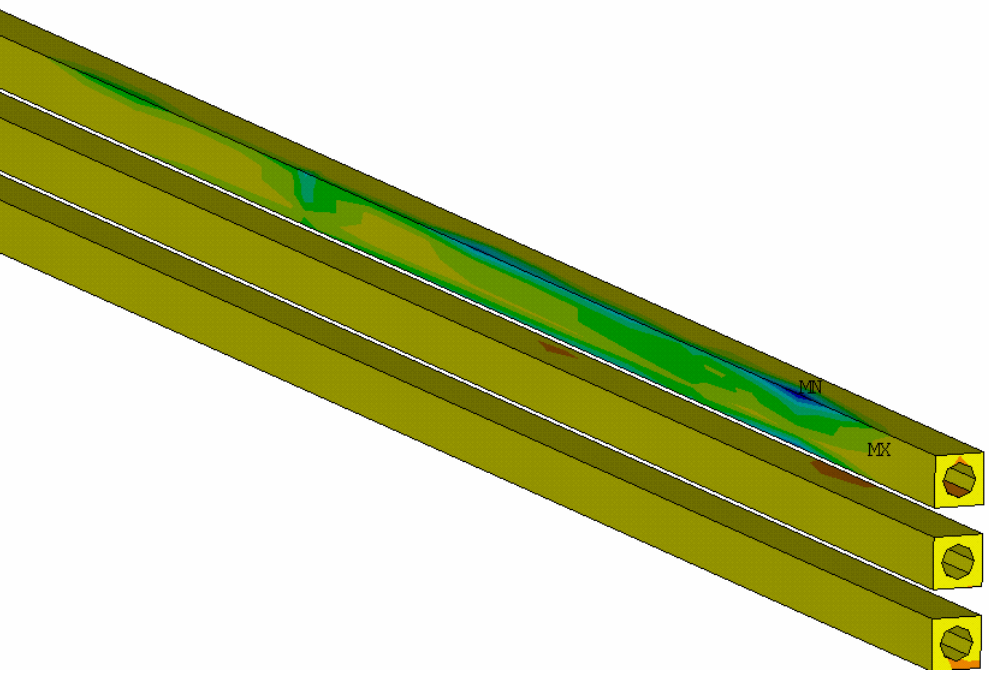
A certain degree of plasticization is found also on pipes (though here in Cu-OFE) ⇨

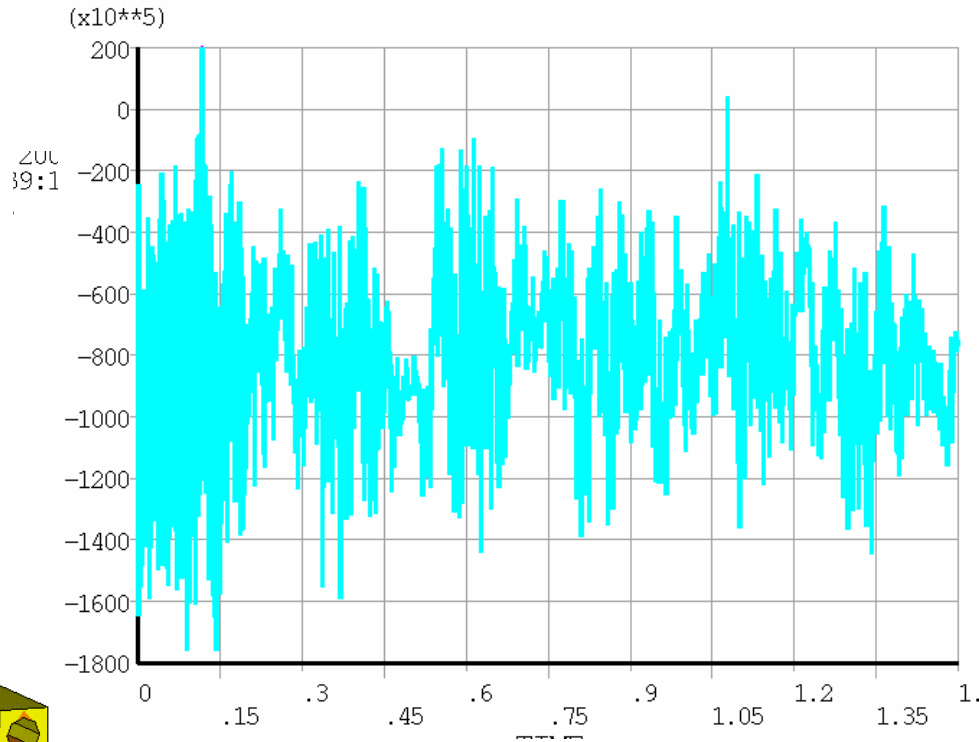
Analysis of new Glidcop/CuNi solution is necessary!

Thermo-mechanical Analysis

Results for the 3-D full model (Series production)

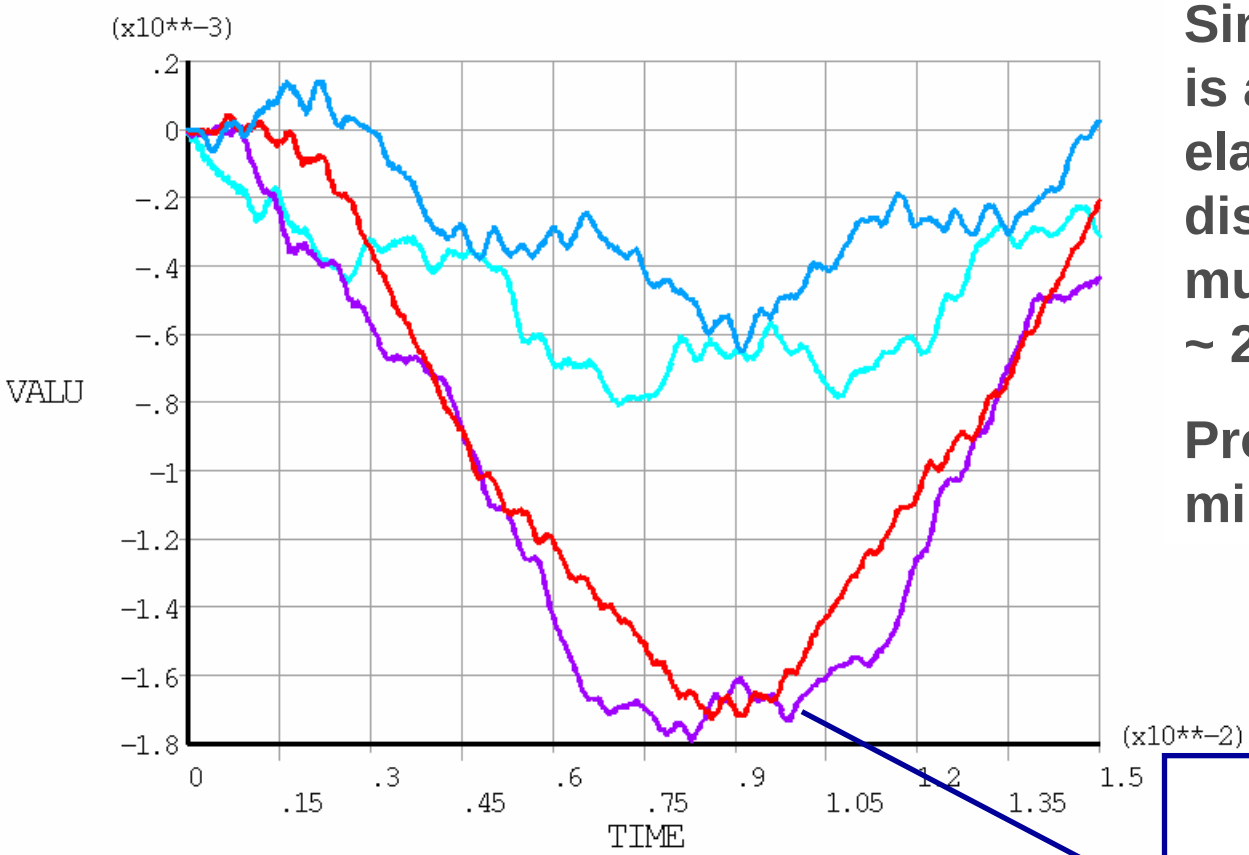
Plastic deformation is absent from Glidcop plates ($\sigma_{max} \cong 190$ MPa) and limited on CuNi pipes





Thermo-mechanical Analysis

Results for the 3-D full model (Series production)



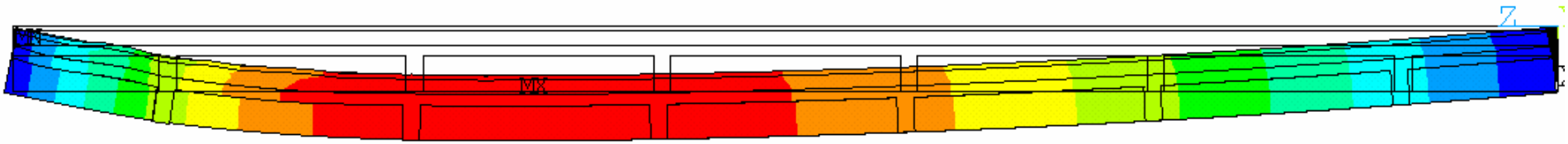
Since the behavior is almost fully elastic, displacements are much larger ⇨ up to ~ 2mm at jaw center.

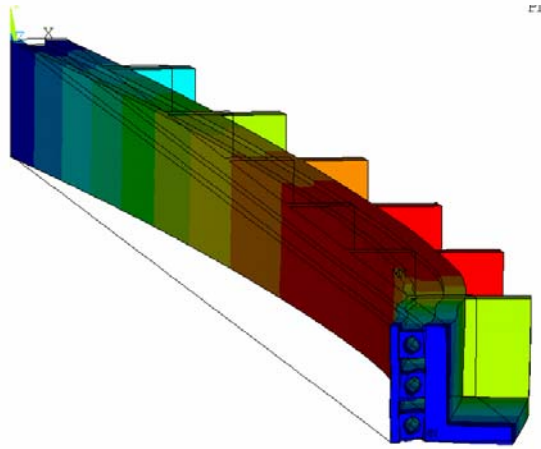
Problems with minimum gap?

Transverse displacement at circa mid-span

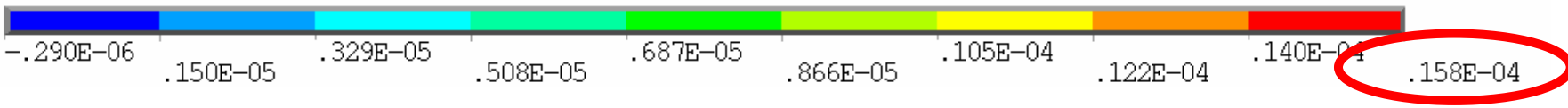
Thermo-mechanical Analysis

Results for the 3-D full model (Series production)





Permanent deformation is not zero but well within limits (16 μm)



Conclusions and outlook

- A preliminary “quasi-static” theory predicts a permanent bending away from the beam. Confirmed by a simplified model
- TT40 3D full model gives permanent deformations after 1 full shot (5mm i.p.) compatible with those measured (~350 μm).
- The substitution of OFE-Cu with Glidcop for the Cu-plate seems the best solution (higher elastic limit).
- Analysis of the series version shows a limited degree of plasticization on CuNi pipes.
- Large in-beam elastic deflection (2 mm) and permanent deformation of ~16 μm
- Cumulated damage not easy to assess. It should not increase linearly due to material strain-hardening.