Penstocks, pressure shafts
& pressure tunnels
workshop

4th November 2022

Numerical modelling of existing penstocks: from simple to advanced methods

Antonella Frigerio

Why reassess the safety of existing penstocks?

Material aging

Reduction of thickness beyond the design limit, occurrence of diffused or localized corrosion phenomena, manufacturing defects…

Anomalies in measurements

Occurrence of irreversible displacements, large strain-stress states, increasing shear slip and opening of cracks…

Geological phenomena

Presence of deep-seated gravitational slope deformations, high risk of landslides, misalignments due to the movements of supports…

Exceptional events

Impacts, water hammering, malfunctioning during operation…

Local or national Authority requirements

Due for instance to the updating of seismic and hydrologic hazards, the issue of local directives or new standards…

Past

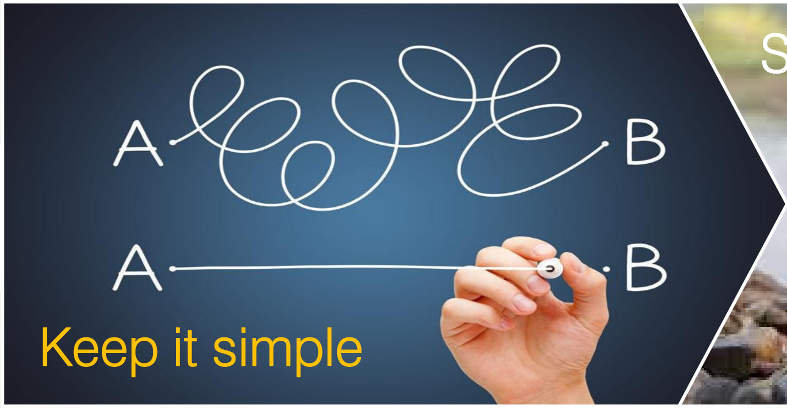
Gather **information** about the **structure design** (technical drawings, design calculations, properties of construction materials, geological data, etc.), and the **past operating conditions** (any occurred modifications in loading or boundary conditions, test, monitoring data, scheduled or unscheduled repairs, etc.)

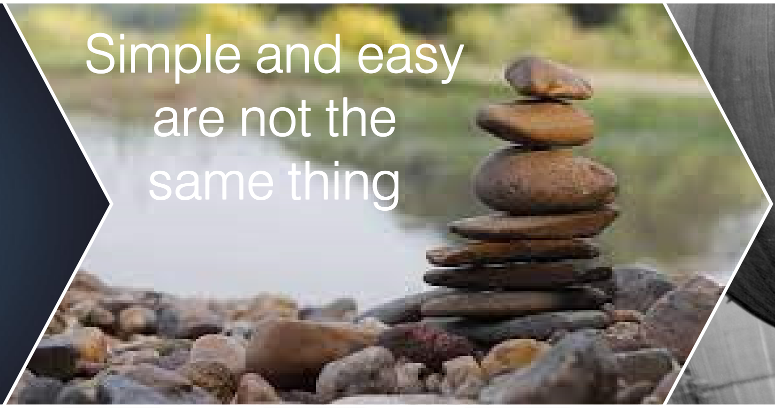
Present

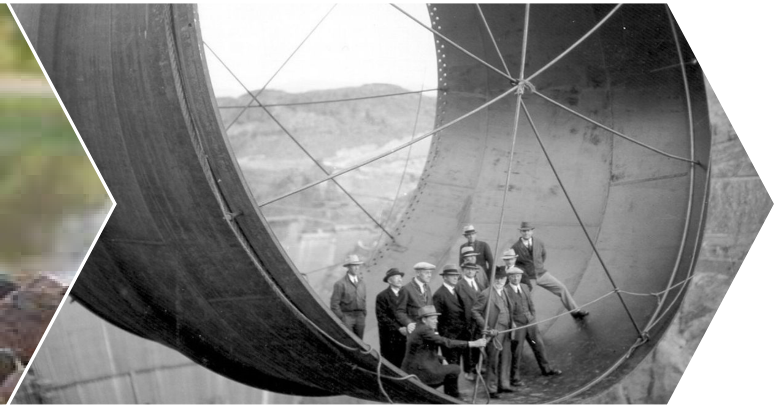
Assess the safety of the current state of the structure

Future

Evaluate possible rehabilitation solutions to guarantee/increase the level of safety of the structure in the medium-long term







The best practice is to start verifying the structure with **simple conceptual schemes** referring to analytical formulas or closed-form solutions

Simple schemes may be based on excessively **conservative hypotheses** and sometimes not representative of the real structural behavior

The **ultimate limit state verification** of **ancient existing structures**, designed with out-of-date standards, may be **critical** or even unsatisfied

When to use numerical modelling for the safety assessment?

From analytical formula or closed-form solutions…

… to complex and advanced finite element models

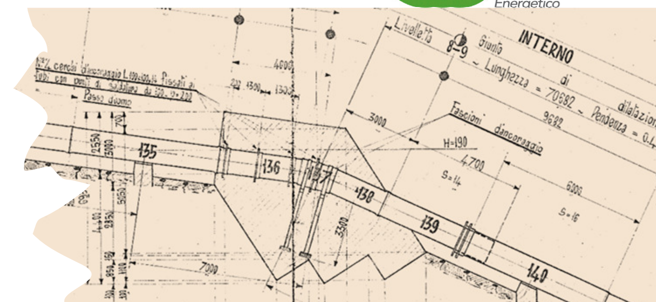
In case the safety assessment is not satisfied referring to simple schemes, conservative or unrealistic assumptions must be gradually removed

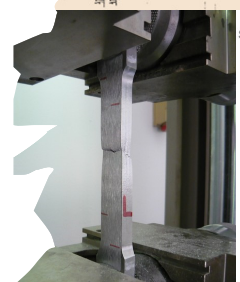
Numerical modelling, based on the Finite Element Method, can describe more accurately the geometry and the real operating conditions of existing structures

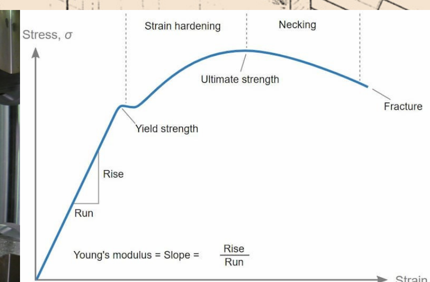
WARNING: the most advanced finite element methods can be used only if the quality of available data allow the set up and validation of the numerical model

Which data are necessary to set up finite element models?

- ✓ Design technical drawing and calculations
- ✓ Current status of the alignments, topographic mapping
- ✓ Geological site investigation (photogeological maps, lithology, seismicity, ground water conditions…)
- ✓ In situ inspections based on non-destructive testing techniques and/or laboratory testing on materials
- ✓ Hydraulic studies related to operational and accidental loading conditions (malfunctioning of safety devices, exceptional vibration, water hammering…)
- ✓ Data related to specific events occurred during the operational life (repair interventions, replacing or reinforcement of components...)
- ✓ Data provided by visual inspections, control and monitoring systems







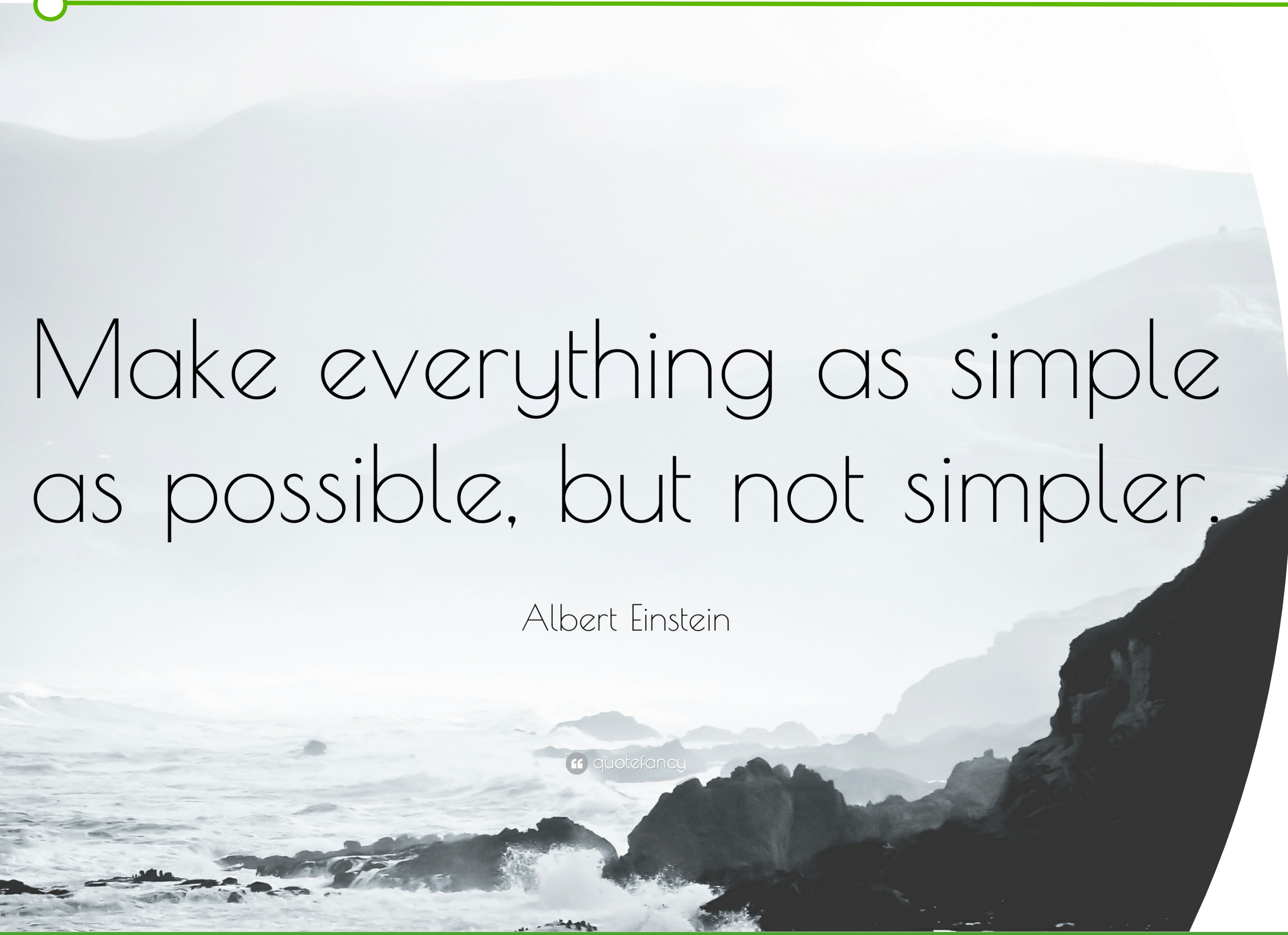
How can numerical modelling support engineers?

Assess which physical phenomena are in progress and how their evolution can affect the structural behavior

Evaluate how past events or changes in operating conditions have affected the structure’s current behaviour

Choose which rehabilitation solution can guarantee the long term safety operation and functionality of the structure

Numerical modelling: verification and validation



Verification

The implemented **numerical methods and algorithms** must properly approximate the **mathematical solution** of the investigated physical phenomena

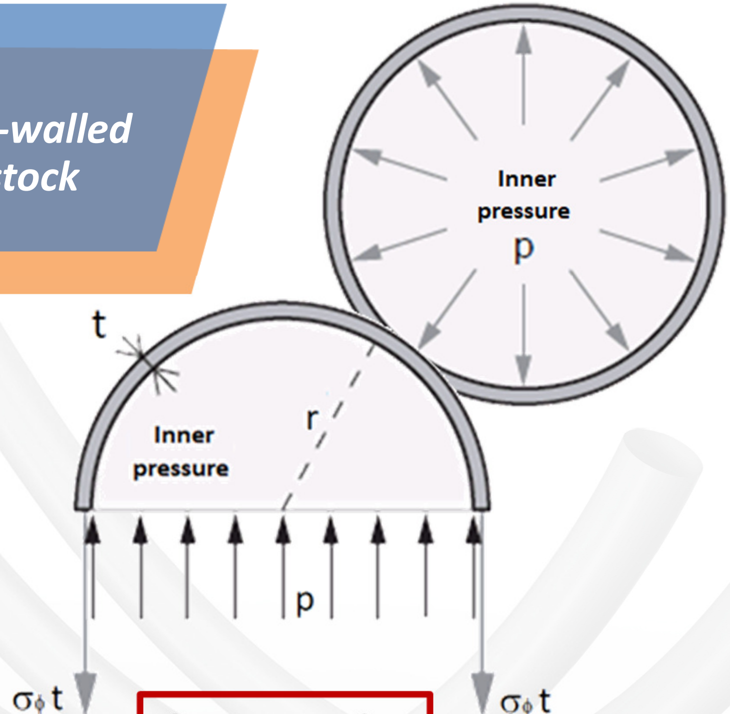
Validation

The **numerical model** must be representative of the **real physical behavior** of the structure under examination; i.e., numerical results should best match the measured data

Simple numerical models can facilitate the stress evaluation and remove conservative assumption

Open air steel penstocks: analytical formulation

Thin-walled penstock



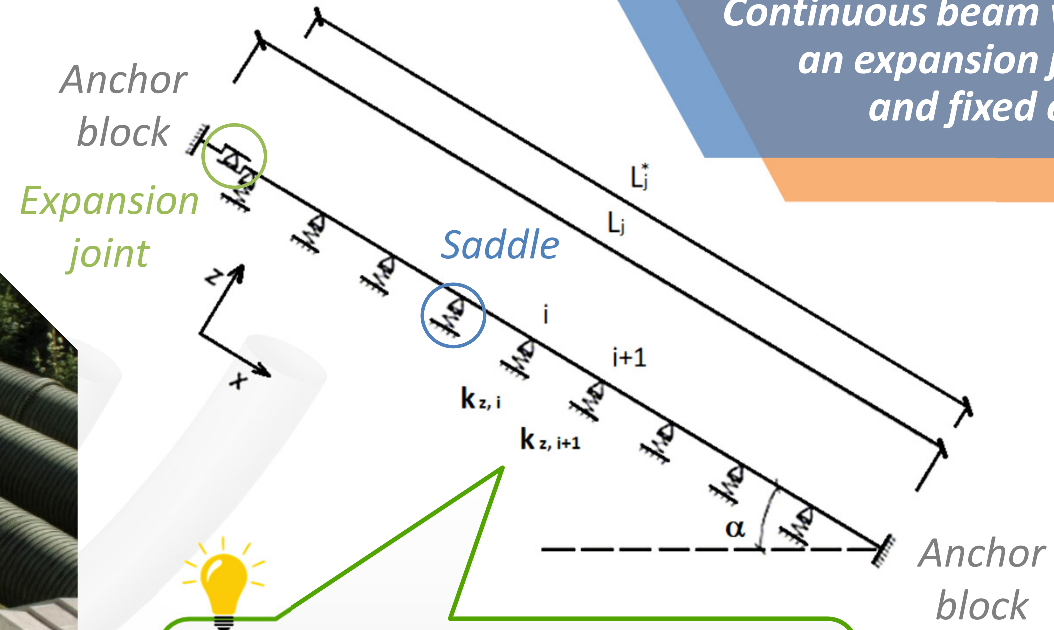
$$\boxed{2\,\sigma_{\phi} t = p\,2\,r}$$

Hoop stress σ_ϕ

Barlow/Mariotte's formula

Open air steel penstocks: 1D beam scheme

Longitudinal stress σ_x



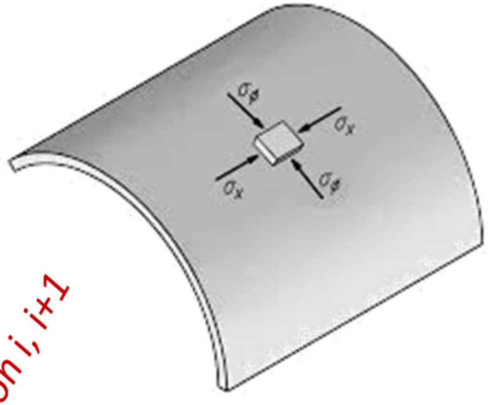
Continuous beam with an expansion joint and fixed ends

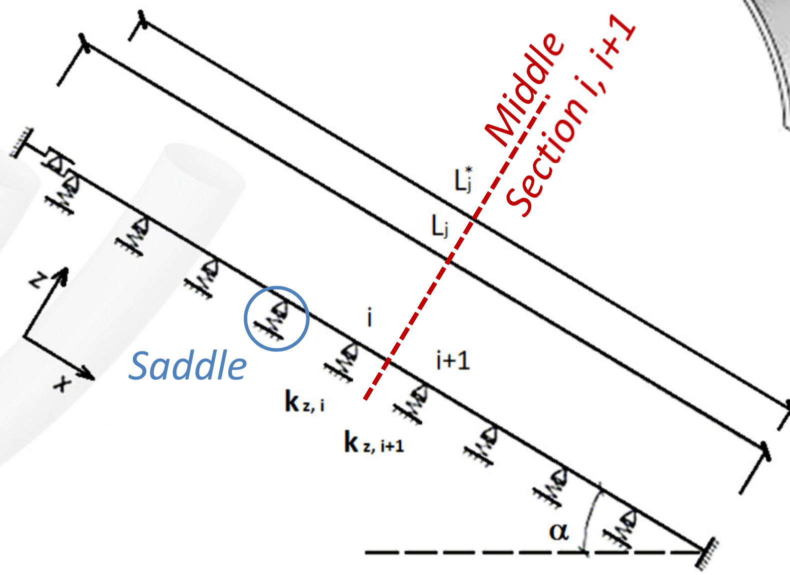
1D beam elements can be used to easily compute longitudinal stresses

Combined stresses

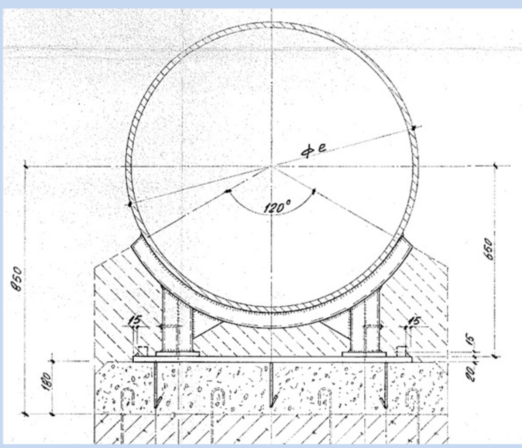
Von Mises criteria

$$\boxed{\sigma_{von\ Mises} = \sqrt{\sigma_{\phi}^{2} + \sigma_{x}^{2} - \sigma_{\phi}\sigma_{x}} \leq \frac{f_{yk}}{\gamma_{M0}}}$$





What about local stresses close to saddles?



Semi-empirical approaches

Hoop stress σ_ϕ

Roarck's formula

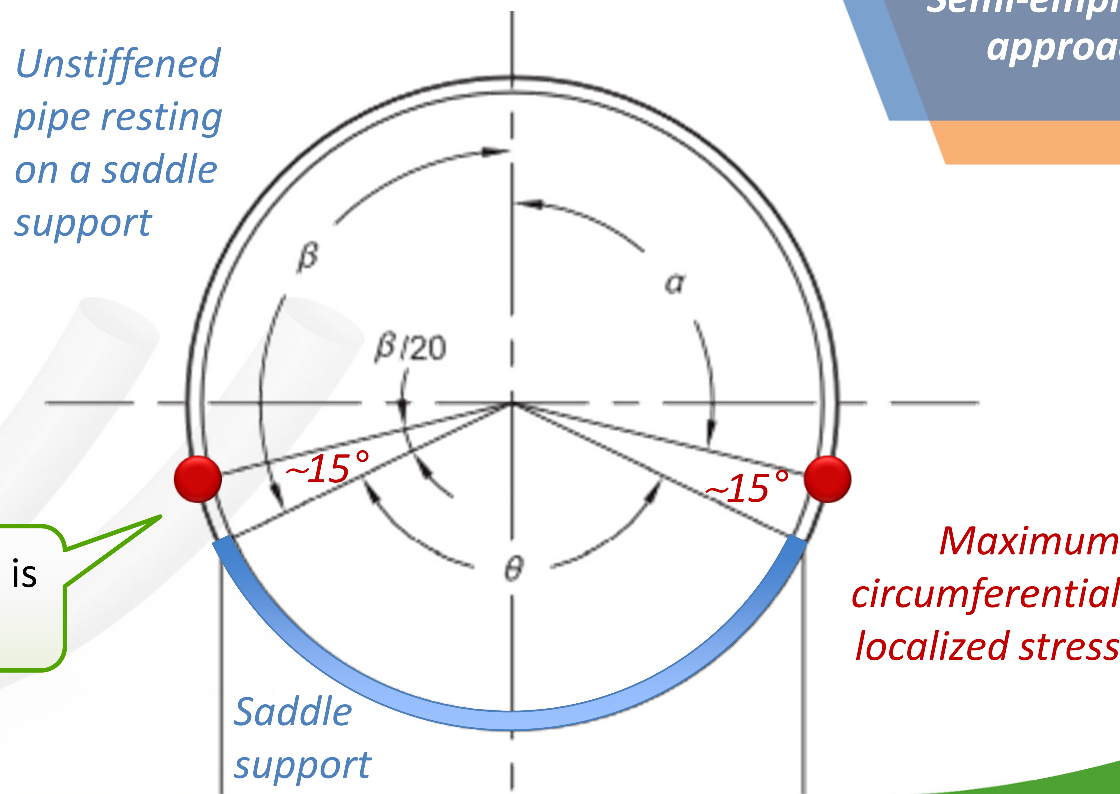
$$\boxed{\sigma_{max} = k\frac{Q}{t^2}ln\left(\frac{r}{t}\right)}$$

$Q = total\ saddle\ reaction$

$k = 0.02 - 0.00012\ (\theta - 90)$, r/t > 50

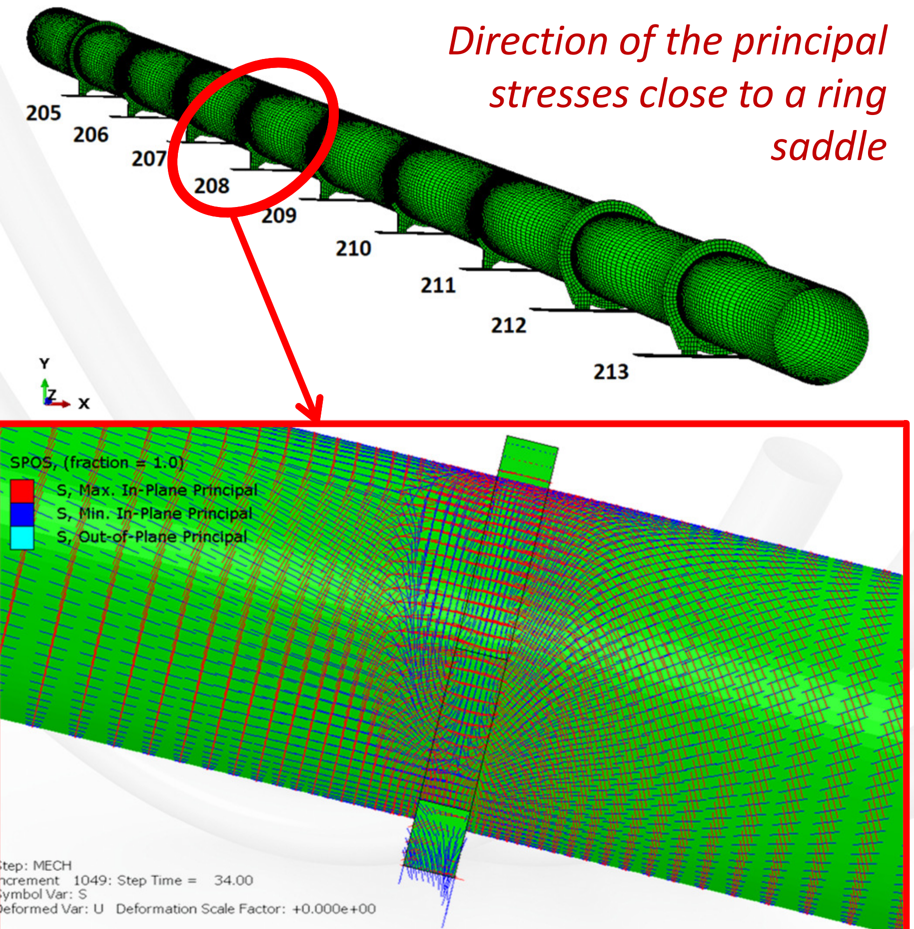
$k = 0.03 - 0.00017\ (\theta - 90)$, 28 < r/t < 50

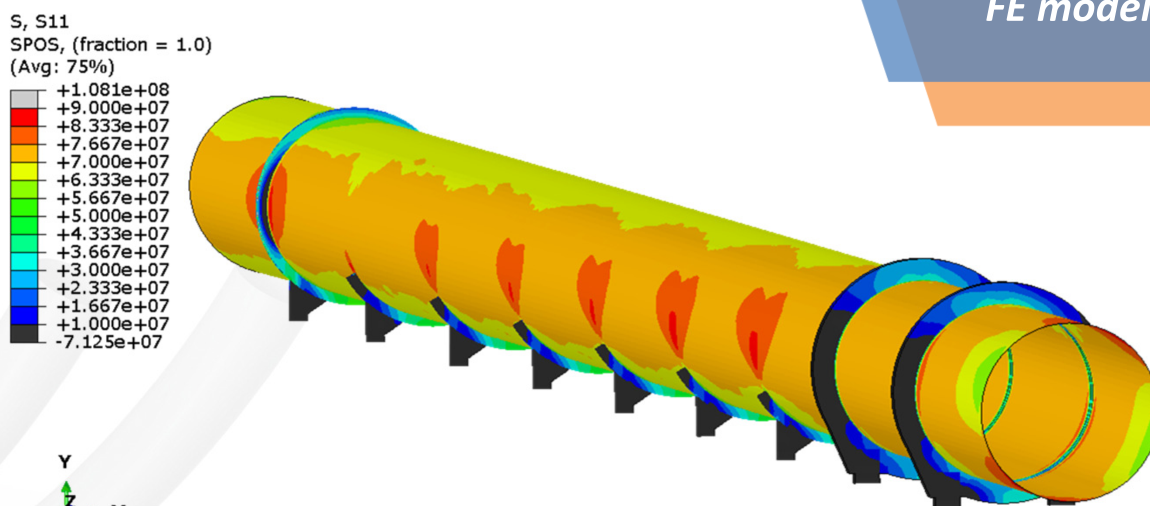
The maximum circumferential stress is located at 15° from the saddle tip



Open air steel penstocks: local stresses evaluation

3D numerical FE model

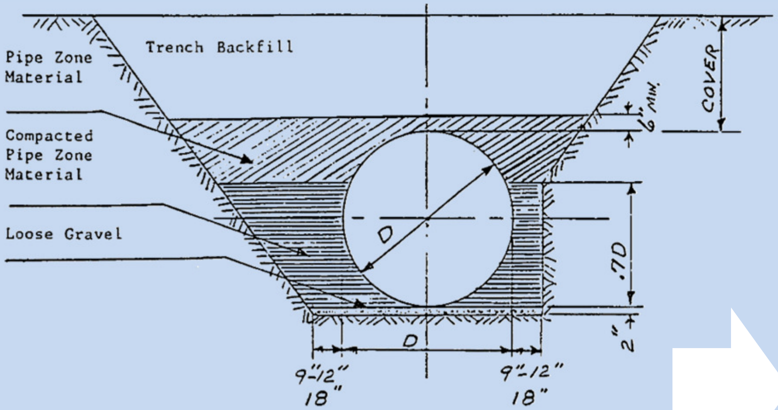




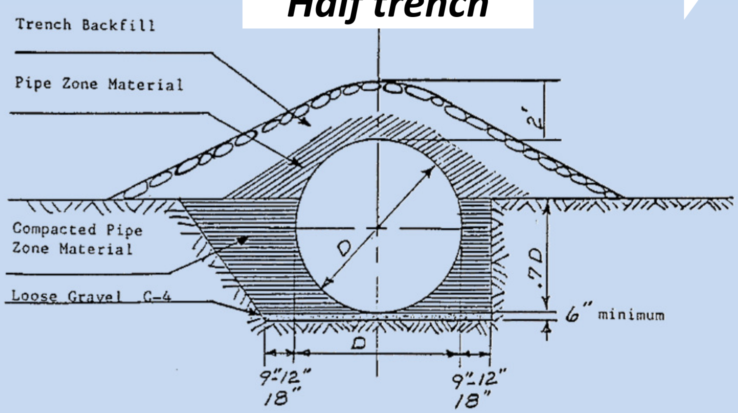
Circumferential stress (S11) distribution along the penstock

Buried penstocks: analytical formulation

Normal trench

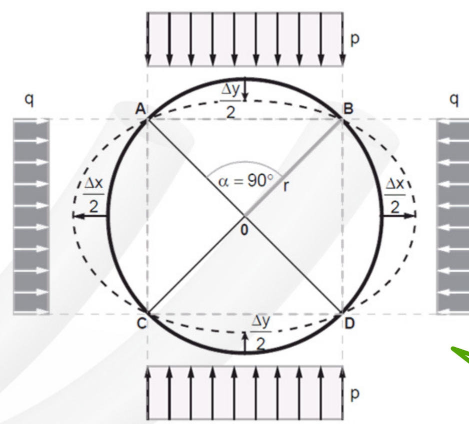


Half trench



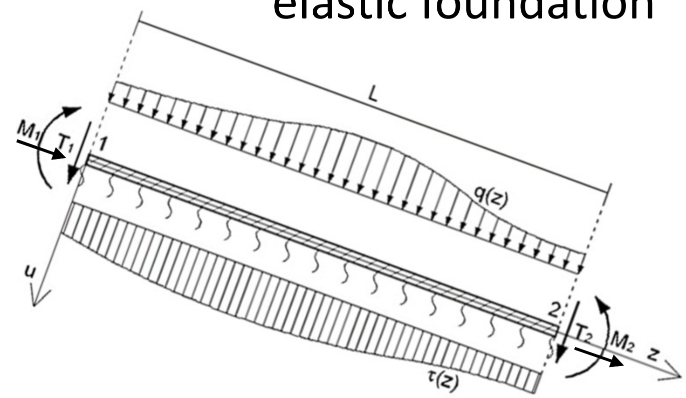
Hoop stress σ_ϕ

Marston & De Saedeleer theory



Longitudinal stress σ_x

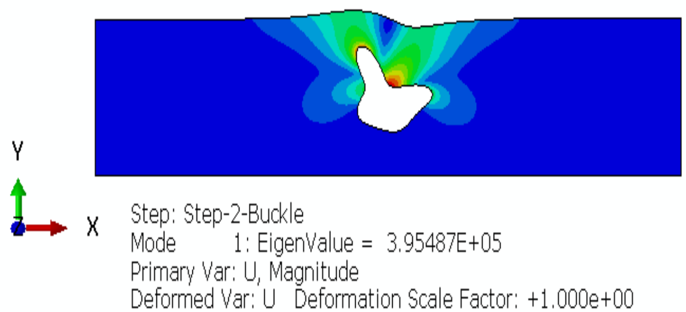
Theory of beam on elastic foundation

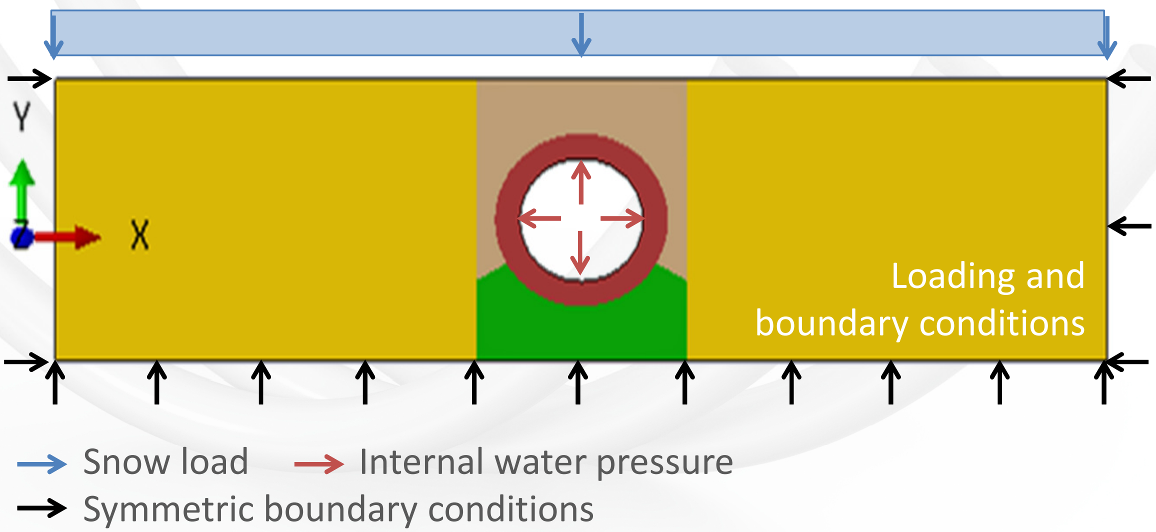


Simplified scheme to model the interaction between soil and penstock

Buried penstocks: 2D FE modelling

Simplified 2D numerical FE model

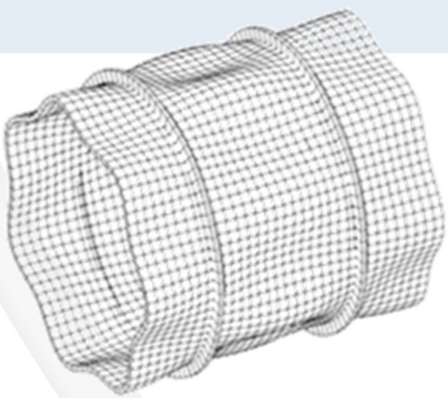




- Circumferential stresses are computed assuming a **plane strain condition**
- Possibility to assign accurately:
  - the appropriate material parameters to each foundation area (e.g., compacted zone and trench backfill)
  - the loading and boundary conditions
- Possibility to accurately compute the pressure distribution between the penstock and the foundation, taking into account the proper stiffness of each area
- The concrete coating stiffness of steel penstock can be considered
- The same 2D model can be used to carry out buckling analyses

Buckling - Analytical formulas are not always intuitive

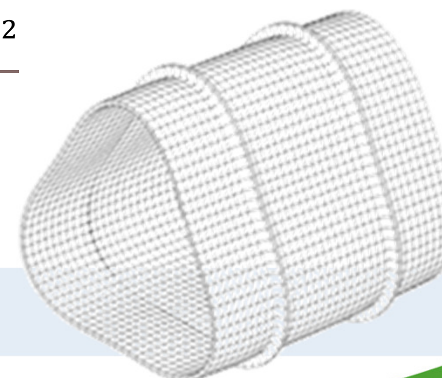
***Timoshenko e von Mises formula** - local buckling of the inner stiffener shell*



$$q_a = \frac{2Et}{D}\frac{1}{(n^2-1)\left(\frac{n^2}{\left(\frac{\pi D}{2s}\right)^2}+1\right)} + \frac{Et^3}{12(1-v^2)\left(\frac{D}{2}\right)^2}\left[(n^2-1)+\frac{2n^2-1-(n^2-1)v}{\frac{n^2}{\left(\frac{\pi D}{2s}\right)^2}+1}\right]$$

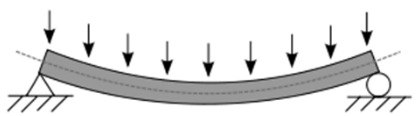
$$q_a = \frac{2Et}{D}\frac{\left(\frac{\pi D}{2s}\right)^4}{\left(n^2+\frac{\left(\frac{\pi D}{2s}\right)^2}{2}-1\right)\left(n^2+\left(\frac{\pi D}{2s}\right)^2\right)^2} + \frac{I(n^2-1)^2}{\left(\frac{D}{2}\right)^2 S}$$

***Kendrick formula** - general buckling*



Simplified scheme

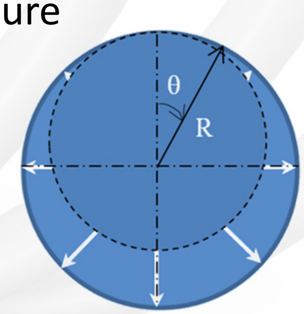
Dead water weight applied as a uniform distributed load with a uniform pressure distribution inside the penstock

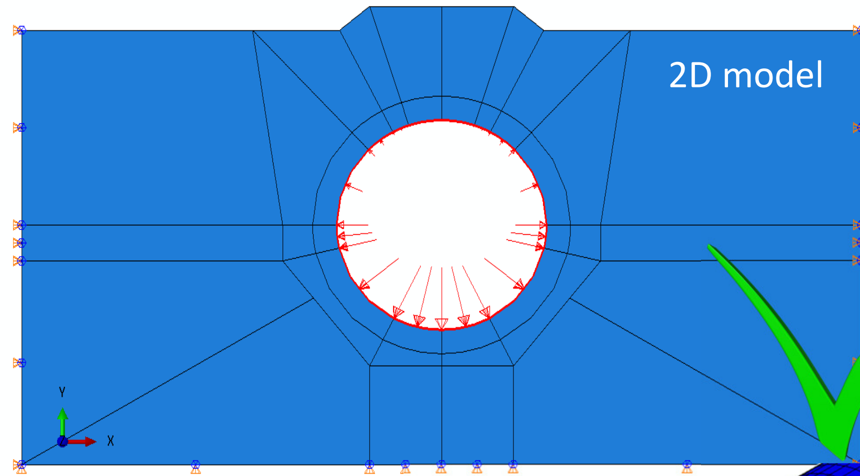


2D and 3D FE model

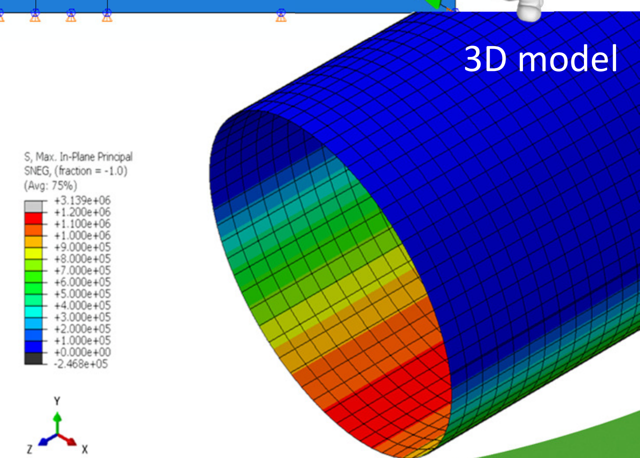
It's easy to apply an internal pressure varying with angle θ

$$dp = \rho_{H2O}\, g\, (1 - \cos\vartheta)\, dV$$
$$= \rho_{H2O}\, g\, (1 - \cos\vartheta)\, R\, d\vartheta$$





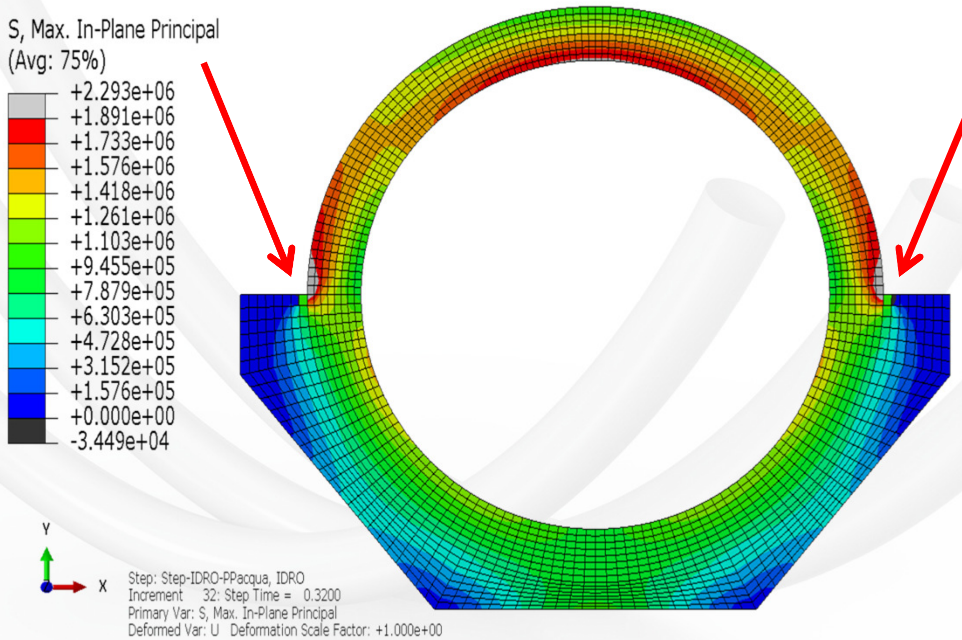
Realistic description of circumferential stresses



Old penstocks, designed according to the permissible stress approach, may not comply with the limit states verification

Buried concrete penstock, designed and built in the last century according to the **permissible stress approach**

- 2D finite element model of the variable thick-walled transverse cross section



Permissible stress verification

The stresses do not exceed the elastic limit even if the steel reinforcements are not considered

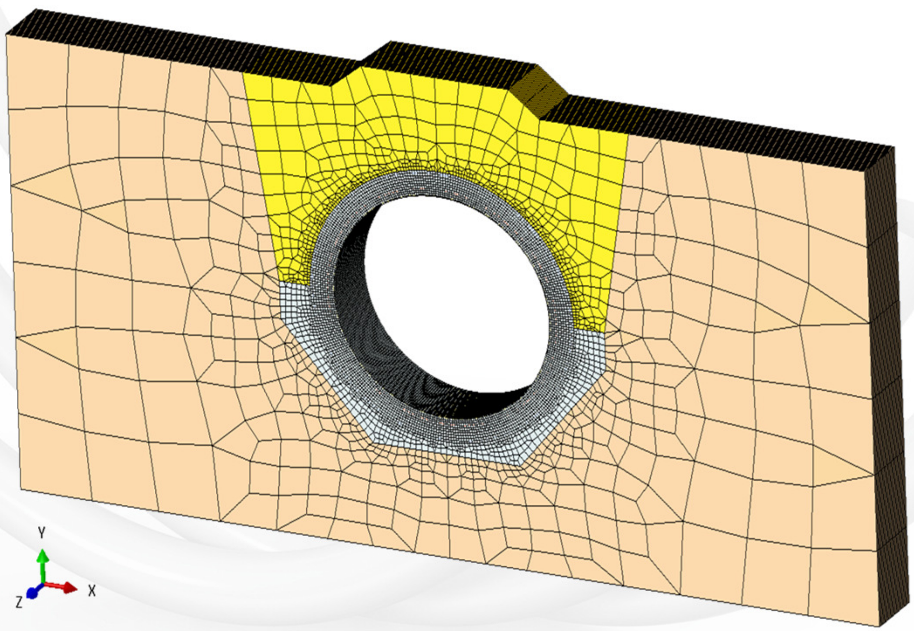
Serviceability limit states verification

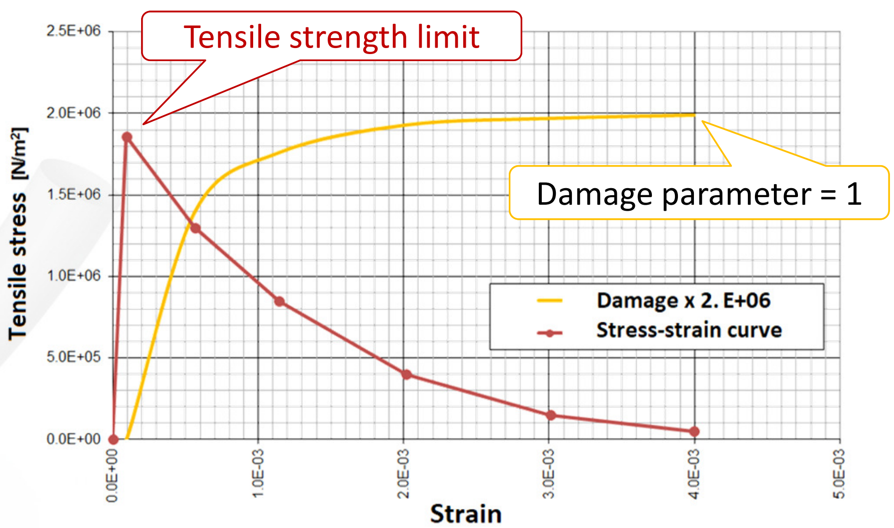
In the sections where thickness changes, the cracking limit state is not verified

- **The presence of the reinforcements was thus considered to assess the strength of the structure**

3D finite element model of a cross section 1 m thick

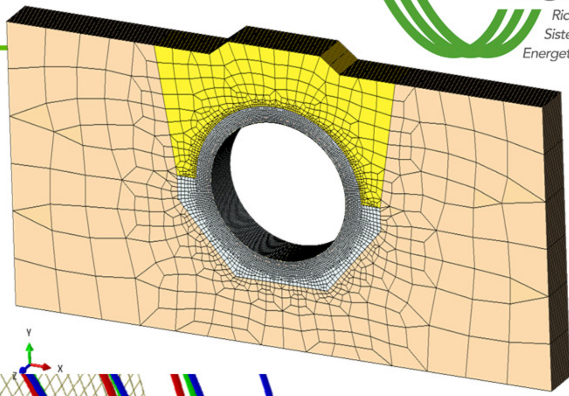
- **Concrete behavior** modelled with the **damage plasticity constitutive law** (parameters set up based on laboratory data)

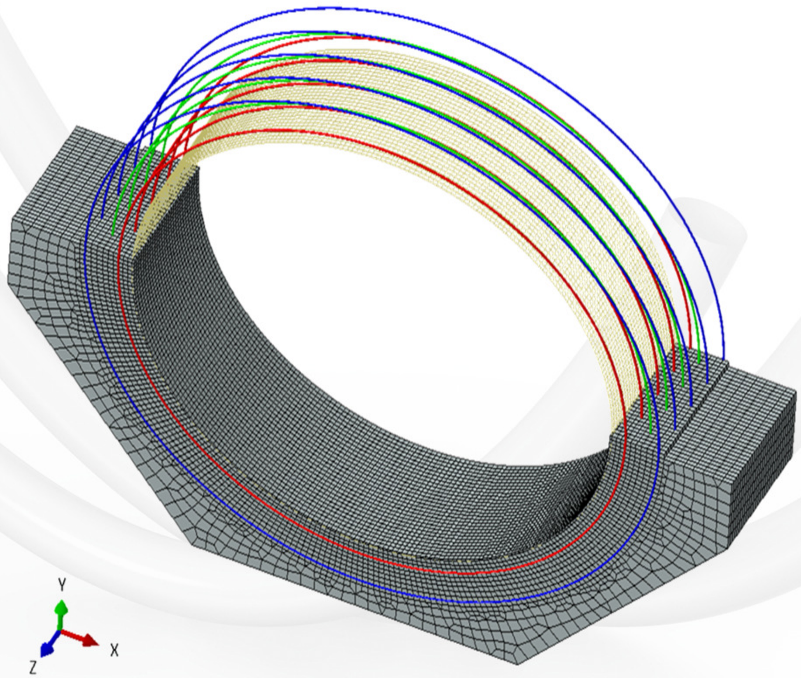


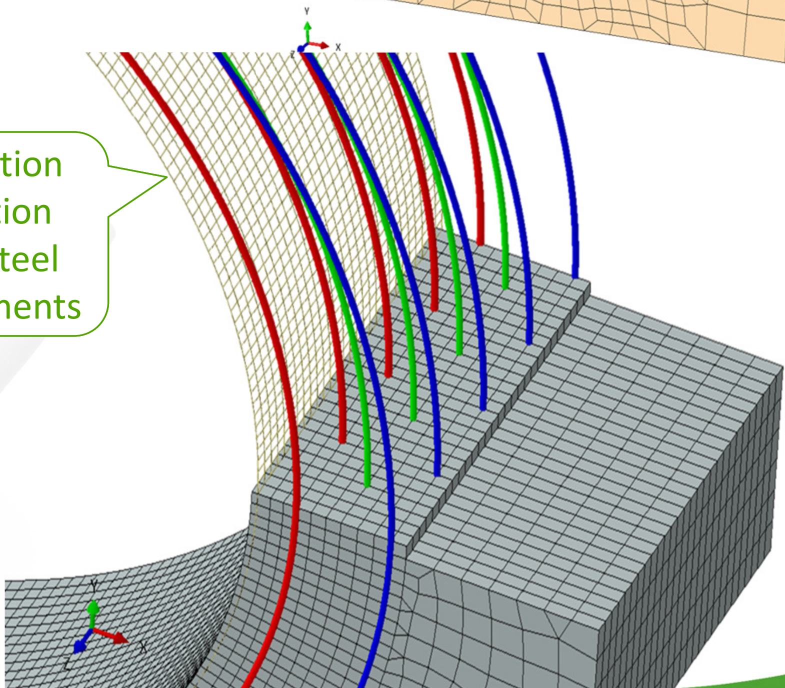


Safety assessment of a weakly reinforced concrete buried penstocks (3/4)

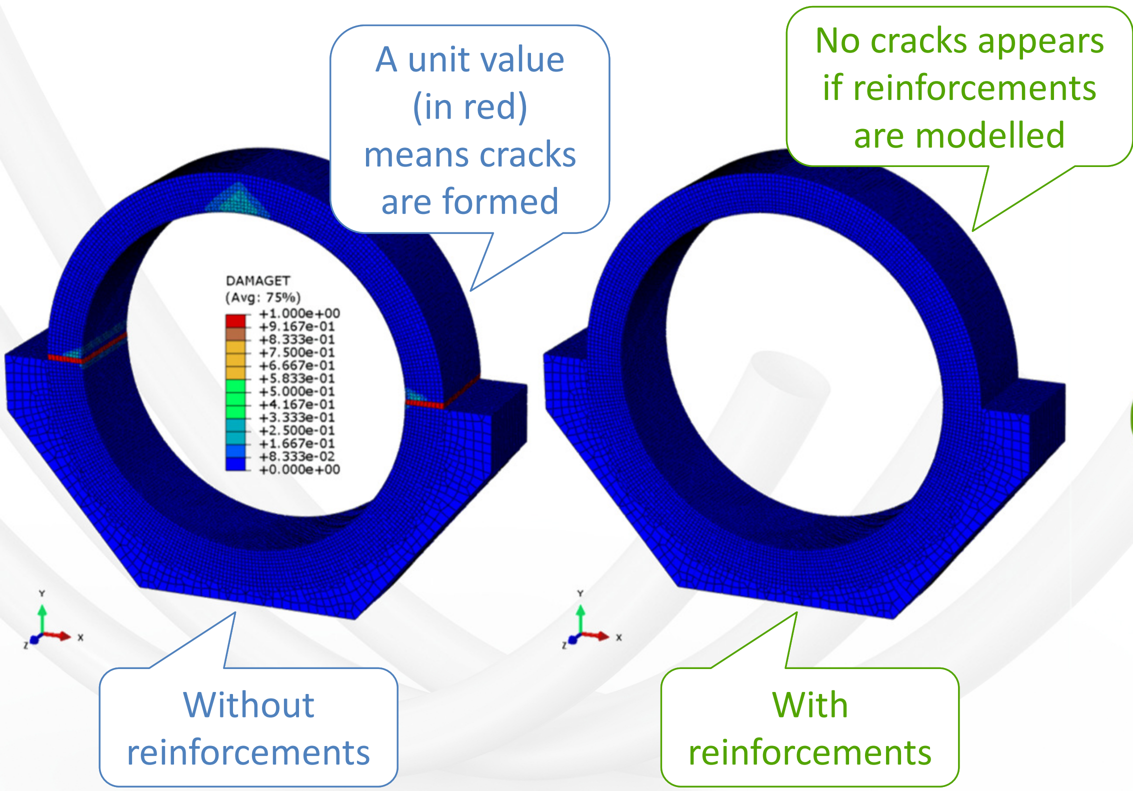
- **Reinforcements** modelled using **truss finite element** with the real cross-section area
- A linear elastic constitutive law was adopted

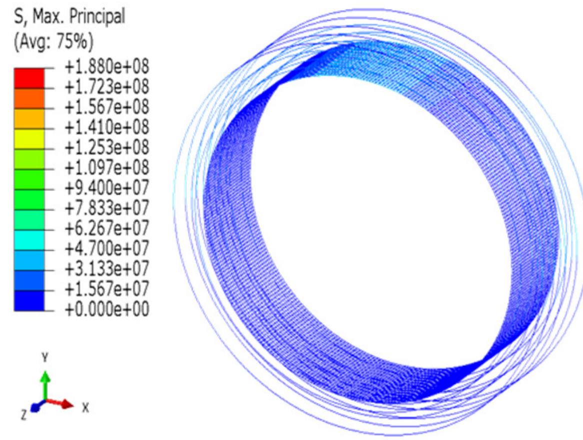






Damage parameter





Maximum principal stresses in rebars

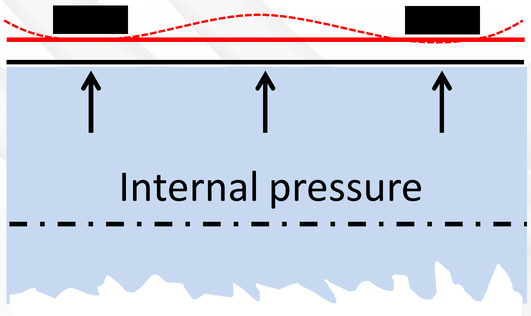
Serviceability limit states verification

- In concrete the cracking limit state is verified (no cracks are formed)
- In steel rebars the maximum principal stresses also comply with the ultimate limit states verification (working rate less than 60% for the worst loading condition)

Some manufacturing processes must be considered to comply with the limit states verification

Verification of stiffened penstock built according to the autofrettage process (1/4)

The autofrettage process

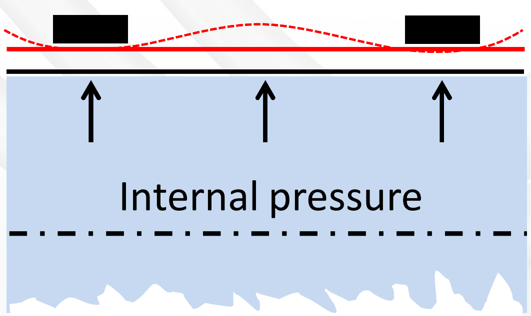


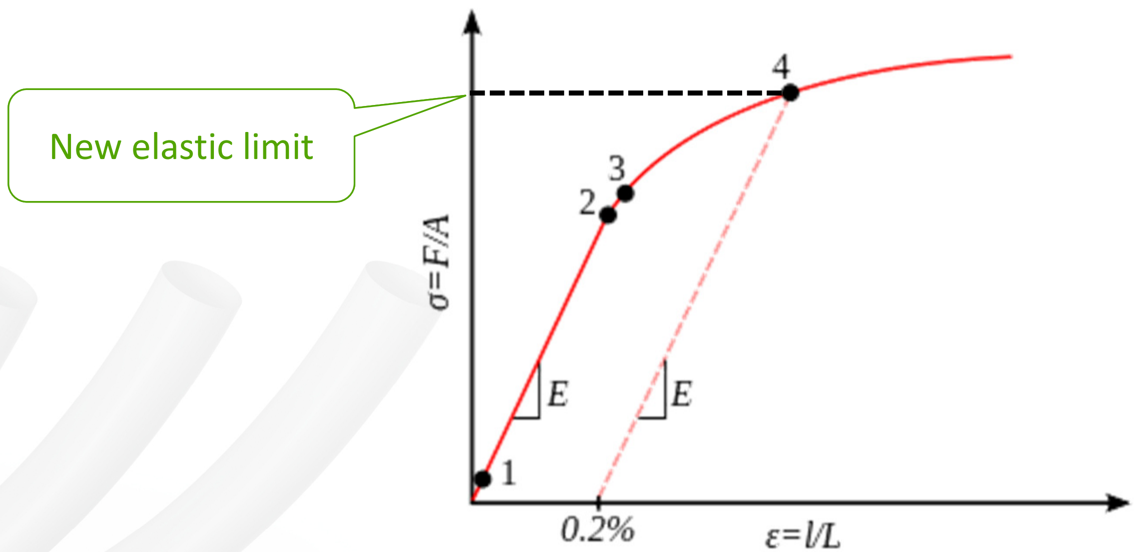
Construction phases

- ✓ The thick wall of the steel penstock is built with an external diameter slightly smaller than the internal diameter of the ring stiffeners
- ✓ In factory, the ring stiffeners are inserted on the steel layer and a large internal pressure is applied
- ✓ The steel layer starts yielding plastically when it comes into contact with the external ring stiffeners (contact pressure)
- ✓ During the whole process the external ring stiffeners are not stretched in tension beyond their elastic limit
- ✓ Once the internal pressure is removed, the inner steel layer is no longer able to return to its original shape, remaining permanently stretched
- ✓ The external rings have still an elastic material behavior, but the inner layer prevent them to come back to their original shape
- ✓ The final effects is that the inner steel layer is put under compression by the external rings that remain in tension (autofrettage pressure)

The goal of autofrettage is to increase the pressure carrying capacity of the final system

The autofrettage process



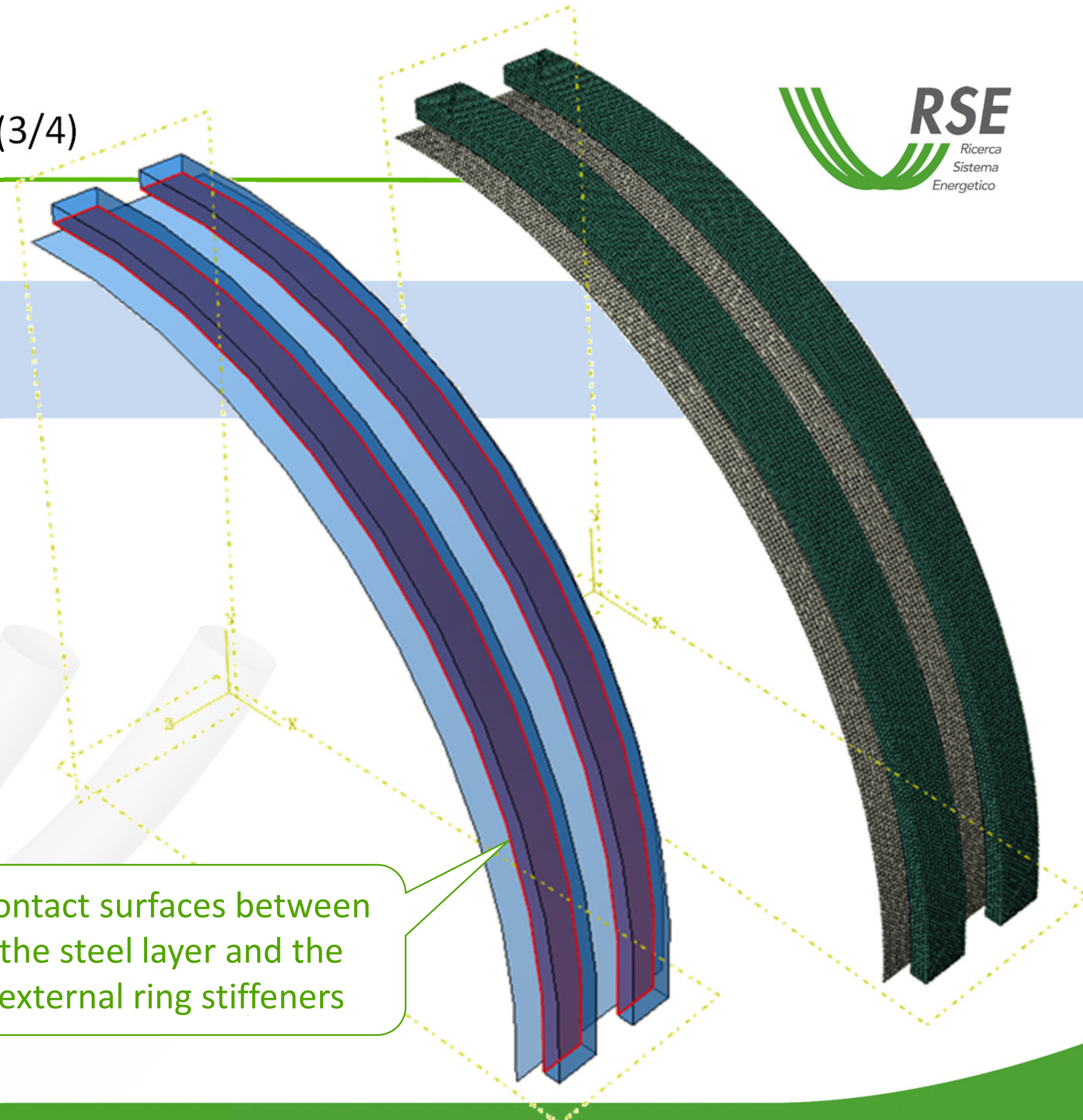


The new elastic limit of the stiffened penstock must be considered in the limit state assessment

Numerical modelling of the autofrettage process (3/4)

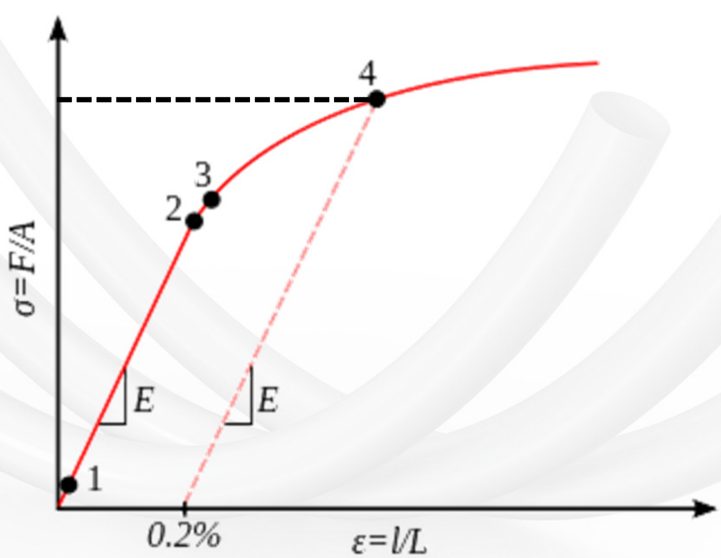
3D models of two ring stiffeners taking into account the symmetry of the problem

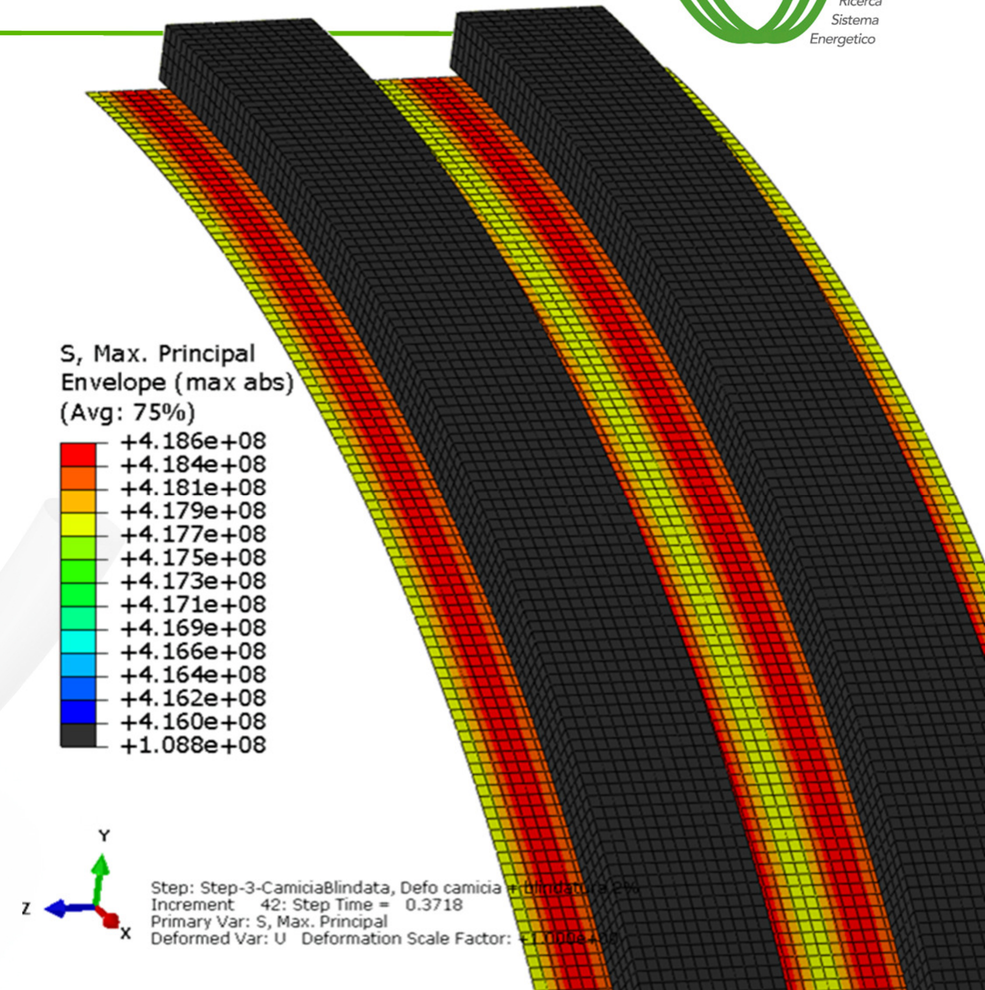
- **Shell elements** (in grey) used to model the steel layer and **brick element** (in dark green) for the ring stiffeners
- During the analysis, the stiffeners are inserted into the model when the steel layer attains the contact pressure value
- The Coulomb friction law assumed to model the interaction between the steel layer and the external rings (outlined with a red line)



Numerical modelling of the autofrettage process (4/4)

The 3D model allows the evaluation of the **new elastic limit** of the steel thick wall of the stiffened penstock and of its **initial stress-strain pattern**





Penstocks, pressure shafts
& pressure tunnels
workshop

4th November 2022

Numerical modelling of existing penstocks: from simple to advanced methods

Antonella Frigerio

This has been the first open workshop organized by the EWG "Penstocks & Pressure Shafts"!

Any technical or organizational proposals for future events are welcome

Send an email to Antonella Frigerio to suggest **topics for discussion, propose your talk** in future events or **participate in the EWG technical activity**

antonella.frigerio@rse-web.it

European ICOLD Club

Penstocks, pressure shafts & pressure tunnels *workshop*