Royal HaskoningDHV
Enhancing Society Together

PSE Protected Storage Engineers

Design of prestressed concrete structures subject to severe thermal loading

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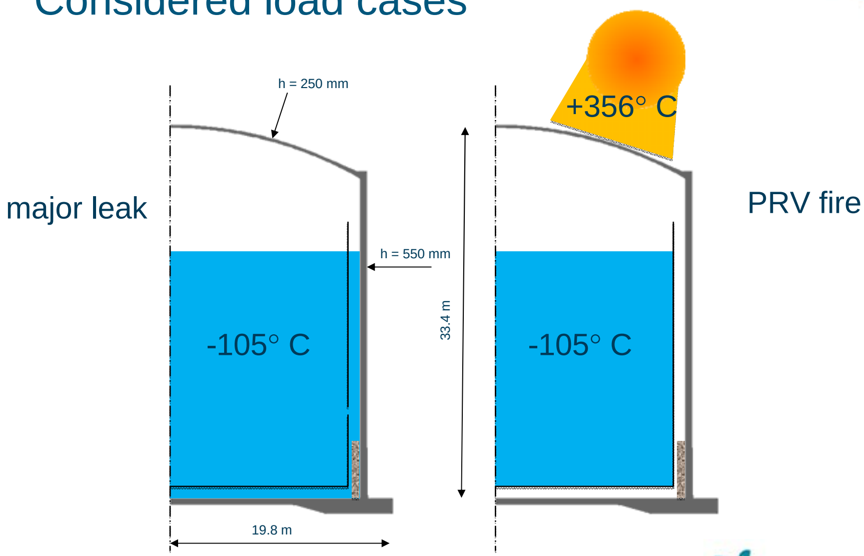
Presentation outline

- Introduction
- Considered load cases
- Modelling
- Computation strategies for combined mechanical and thermal loading

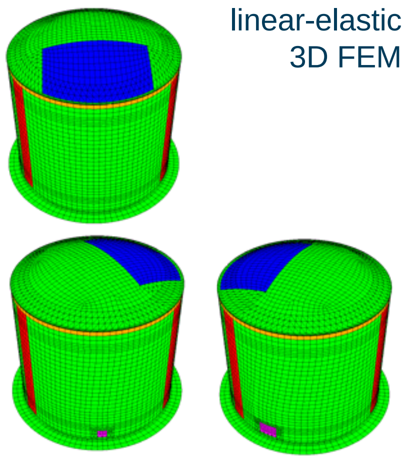
  Non-linear elastic concrete cross-section analysis
  Superposition of thermal restraint

- Comparison of results
- Conclusion
- Discussion

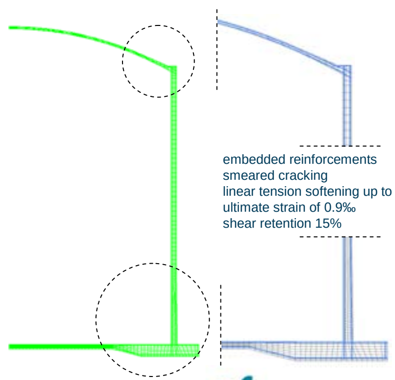
Considered load cases



Modelling



non-linear elastic
axi-symmetrical FEM



Computation strategies for combined mechanical and thermal loading

	Linear-elastic 3D FEM		Non-linear elastic axi-symmetrical FEM
1	mechanical loading	thermal loading	mechanical en thermal loads sequential
1a	M,N,V section forces	M,N,V section forces	
1b	non-linear elastic cross-section analysis	linear equations	
1c	mechanical strains	thermal restraint	
2	superposed strains (linear)		concrete (crack) and rebar strains
3	concrete and rebar stresses		⟺ concrete and rebar stresses

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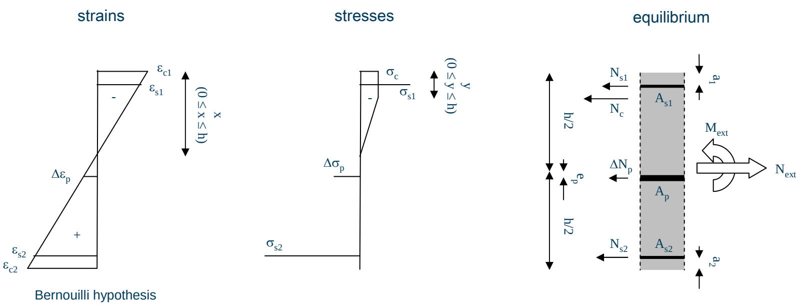
dedicated user subroutine in DIANA

Non-linear elastic concrete cross-section analysis



$$\begin{Bmatrix}\varepsilon_{c1}\\ \varepsilon_{c2}\end{Bmatrix} \Longrightarrow \begin{Bmatrix}N_{ext}\\ M_{ext}\end{Bmatrix}$$

find roots of coupled, at least 3rd order polynomials

Non-linear elastic concrete cross-section analysis

define

$$\mathbf{u}_j = \begin{Bmatrix}\varepsilon_{c1,j}\\ \varepsilon_{c2,j}\end{Bmatrix} \quad , \quad \mathbf{r}_j = \begin{Bmatrix} N_{c,j} + N_{s1,j} + N_{s2,j} + \Delta N_{p,j} - N_i \\ M_{c,j} + M_{s1,j} + M_{s2,j} + \Delta M_{p,j} - M_i \end{Bmatrix}$$

iterate

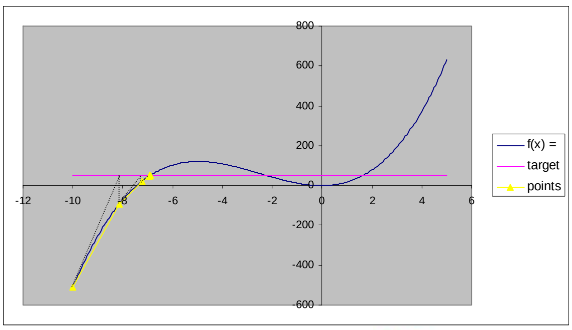
$$\mathbf{S}_j = \left(\frac{d\mathbf{r}}{d\mathbf{u}}\right)_j = \begin{bmatrix} \left(\frac{\partial r_1}{\partial u_1}\right)_j & \left(\frac{\partial r_1}{\partial u_2}\right)_j \\ \left(\frac{\partial r_2}{\partial u_1}\right)_j & \left(\frac{\partial r_2}{\partial u_2}\right)_j \end{bmatrix}$$

$$d\mathbf{u}_j = -\mathbf{S}_j^{-1}\mathbf{r}_j$$

$$\mathbf{u}_{j+1} = \mathbf{u}_j + d\mathbf{u}_j$$

until

$$\frac{|\mathbf{r}|_j}{|\mathbf{r}|_0} < Tol$$



Superposition of thermal restraint

total strain as influenced by boundary conditions ↔ amount of restraint

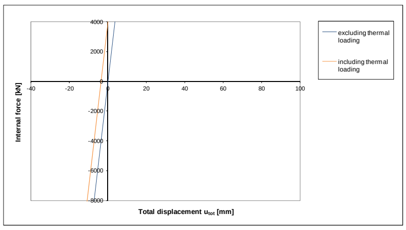
strain causing stress

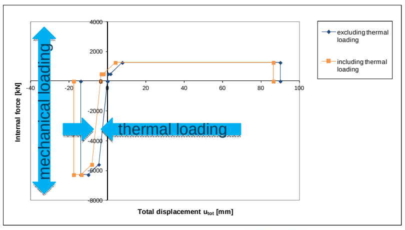
thermal loading in terms of strain

$$\varepsilon_{tot} = \varepsilon_S + \varepsilon_T$$

superimpose on strains due to mechanical loading

cross-sections	
linear-elastic	non-linear elastic
e.g.	e.g.
$(k_1 + k_2)u_{tot} = F_{mech} + k_2 u_{T,2}$	$f_1(u_{tot}) + g_2(u_{tot}) = F_{mech}$





Computation strategies for combined mechanical and thermal loading revisited

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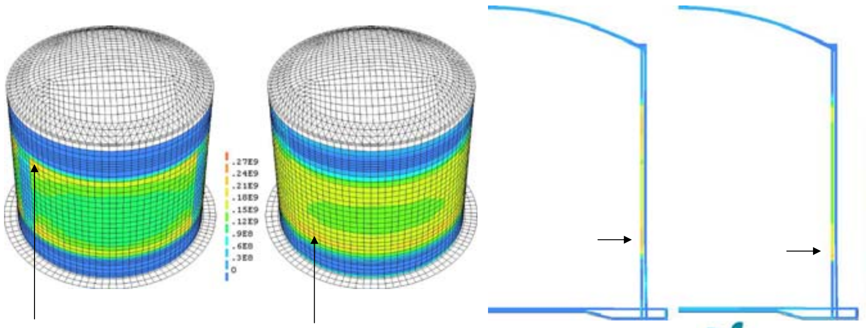
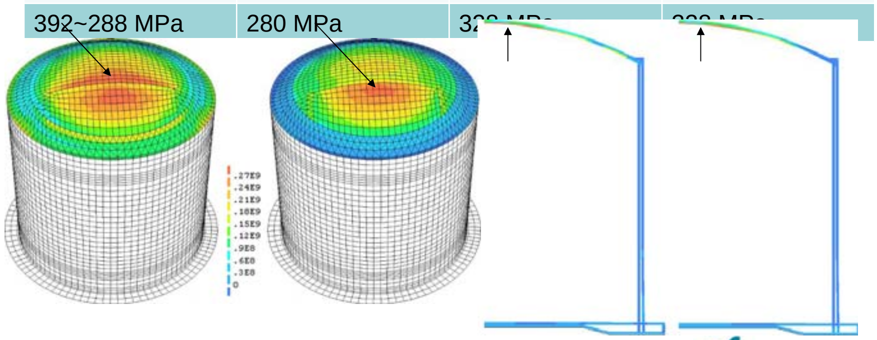
Comparison of results

Major leak rebar stresses			
linear-elastic 3D FEM		non-linear elastic axi-symm. FEM	
circumferential inner rebar	vertical inner rebar	vertical rebar	circumferential rebar
243~166 MPa	213 MPa	257 MPa	215 MPa



Comparison of results

PRV fire rebar stresses			
linear-elastic 3D FEM		non-linear elastic axi-symm. FEM	
radial/parallel inner rebar	circumferential/ transv. inner rebar	radial rebar	circumferential rebar
392~288 MPa	280 MPa	32[illegible]	[illegible]



Conclusion

- geometric discontinuities only considered in linear-elastic 3D FEM analysis
- overall fair correspondence between results of linear-elastic 3D FEM with superposition of thermal restraint and non-linear elastic axi-symmetrical FEM
- economy of thermal restraint superposition method

Discussion