MODELING OF CONCRETE MATERIALS AND STRUCTURES

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Class Meeting #7: Discrete Interface Formulations

Zero-Thickness Interface Models:

Cohesive Damage and Elasto-Plastic Traction-Separation Models

Inherent Length Scale:

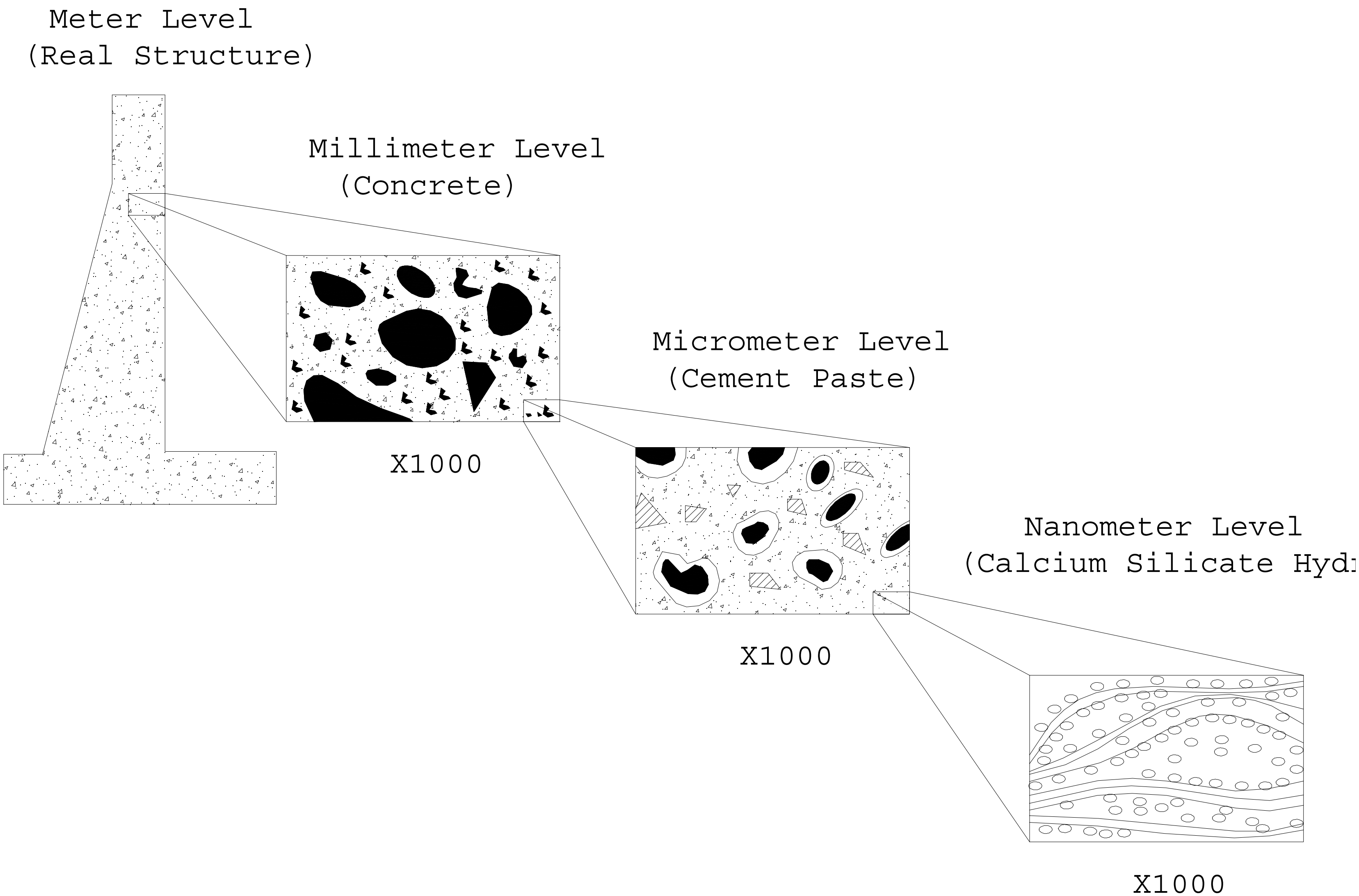
Fracture Energy Basis G_f^I *and* G_f^{II} *of Softening*

Example Problems:

- *Thermal Softening of Axial Strength due Mismatch*
- *High Temperature Bond: Pull-Out Experiment vs FE Model*

MULTI-SCALE ASPECTS OF CONCRETE MATERIALS

Four Scales of Observation, Continuum vs Particle Models-Size Effects?

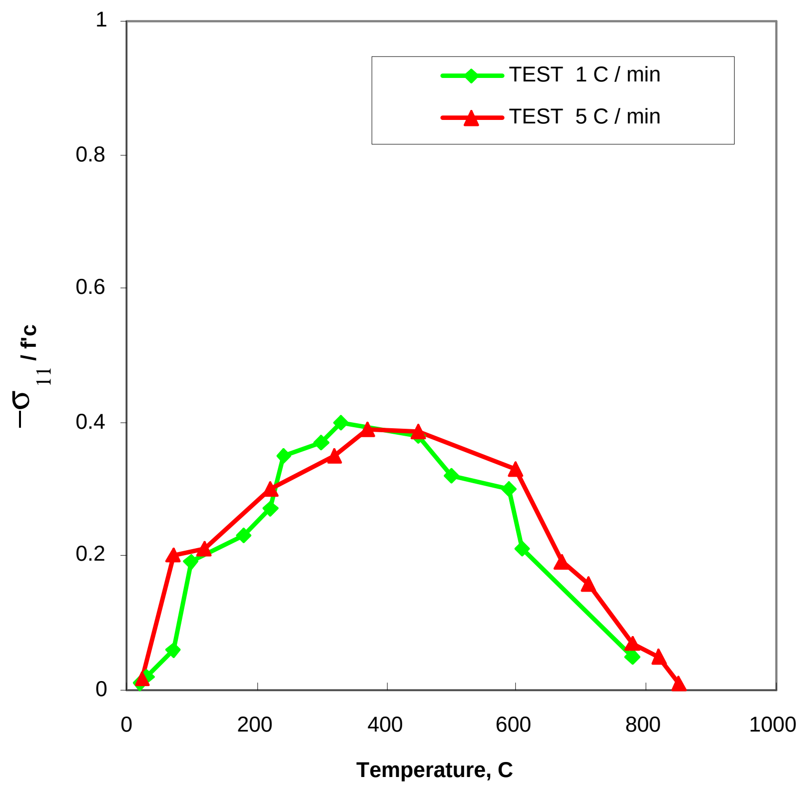


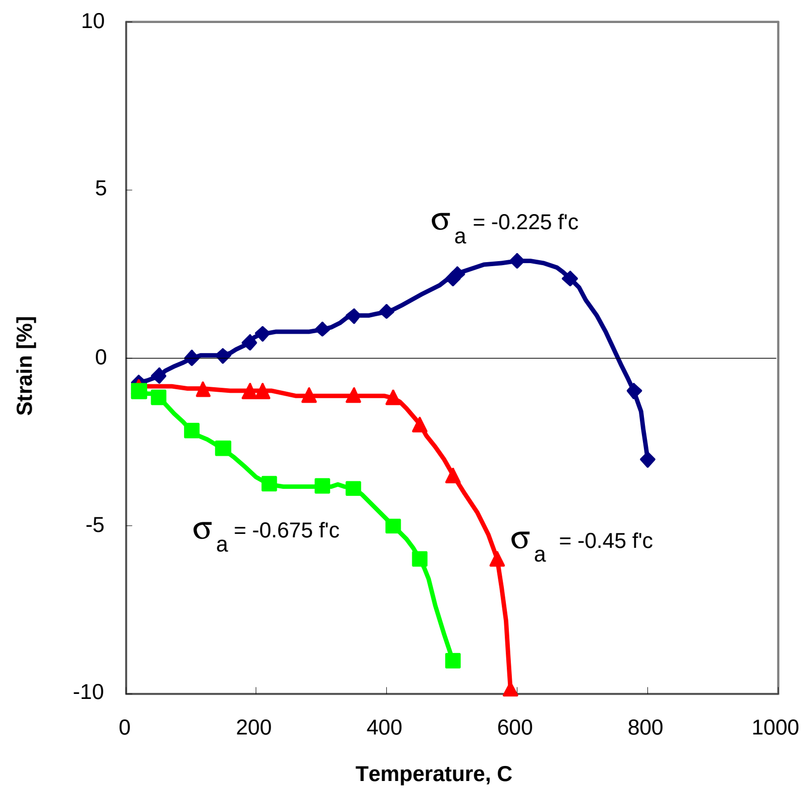
HIGH TEMPERATURE EFFECTS IN CONCRETE MATERIALS

Concrete Spalling: Temperature gradient vs pore pressure effects.

Transient Effects: Load-induced thermal strains-LITS.

Andersen and Thelandersen [1984]: Thermal sweep experiments.

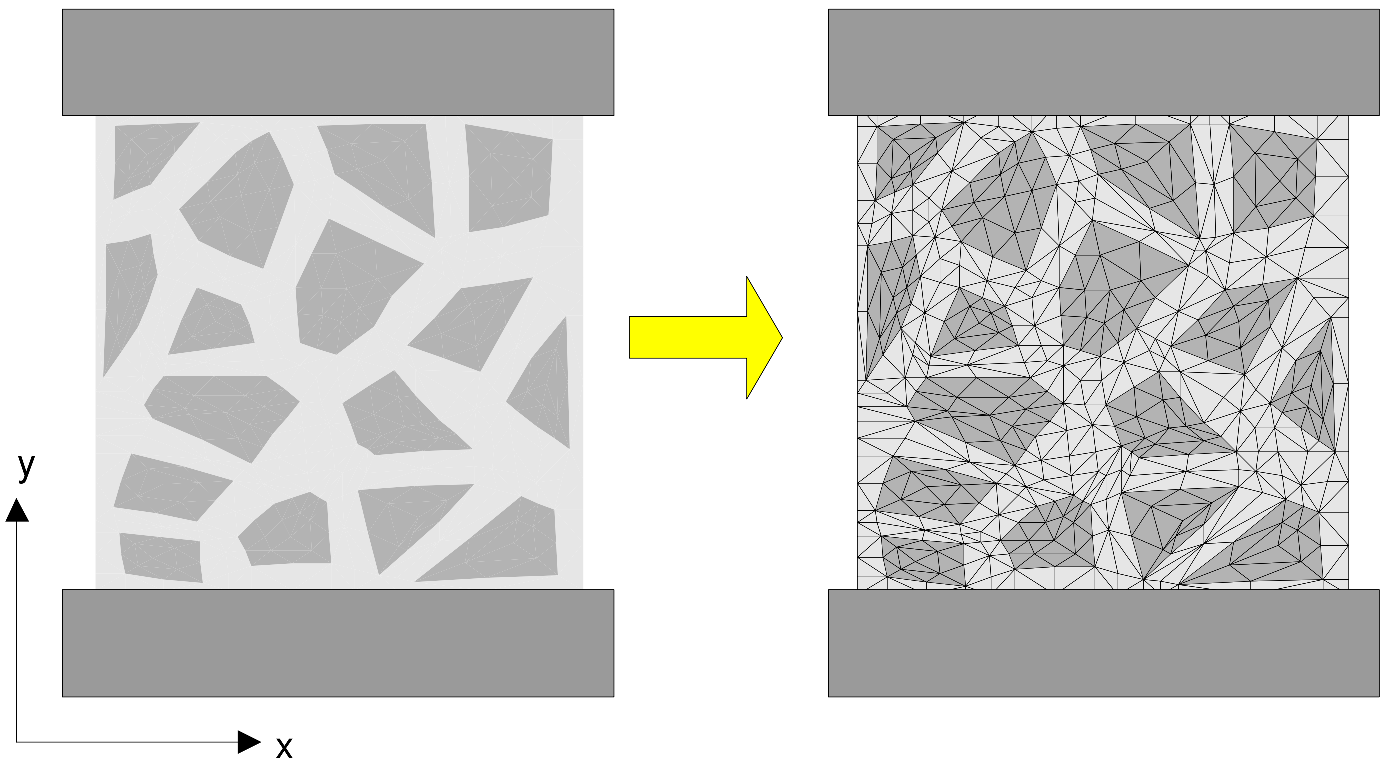




THERMAL MISMATCH OF CONCRETE MATERIALS

Heterogeneity of Mesostructure:

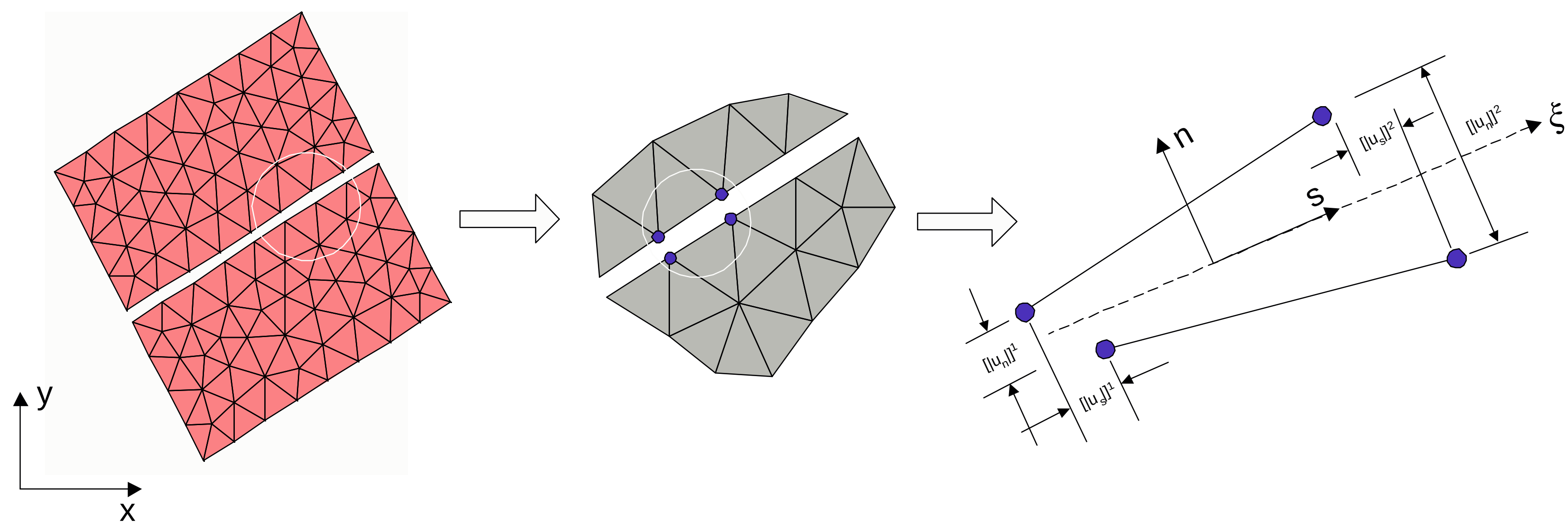
Aggregate vs Cement Paste and Bond of ITZ



ZERO-THICKNESS INTERFACE FORMULATION

Weak ITZ-Cohesive Traction-Separation Relations:
Softening Damage and Plasticity Models

Fracture Energy Basis:
Coupling of Mode I and Mode II Softening Damage/Plasticity Models
(softening of tensile bond vs tangential shear strength).



BIMATERIAL INTERFACE CONDITIONS

Perfect Bond:

$$[|\mathbf{u}_N|] = \mathbf{u}_N^a - \mathbf{u}_N^c = \mathbf{0} \quad \text{and} \quad [|\mathbf{t}_N|] = \mathbf{t}_N^a - \mathbf{t}_N^c = \mathbf{0}$$

Weak Discontinuities: all strain components exhibit jumps across interface except for $\epsilon_{TT}^a = \epsilon_{TT}^c$ restraint.

Note: Jump of tangential normal stress, $\sigma_{TT}^a \neq \sigma_{TT}^c$.

Imperfect Contact:

$$[|\mathbf{u}_N|] = \mathbf{u}_N^a - \mathbf{u}_N^c \neq \mathbf{0} \quad \text{whereas} \quad [|\mathbf{t}_N|] = \mathbf{t}_N^a - \mathbf{t}_N^c = \mathbf{0}$$

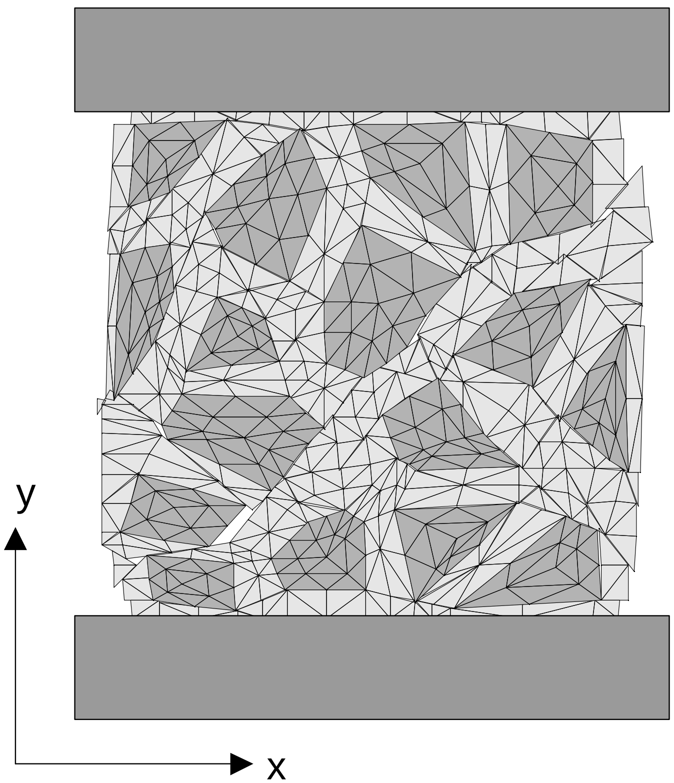
Strong Discontinuities: all displacement components exhibit jumps across interface.

Note: FE Displacement method enforces traction continuity in ‘weak’ sense only, hence $[|\mathbf{t}_N|] \neq 0$.

ZERO-THICKNESS INTERFACE FORMULATION

Deformed FE Mesh after Thermal Sweep:

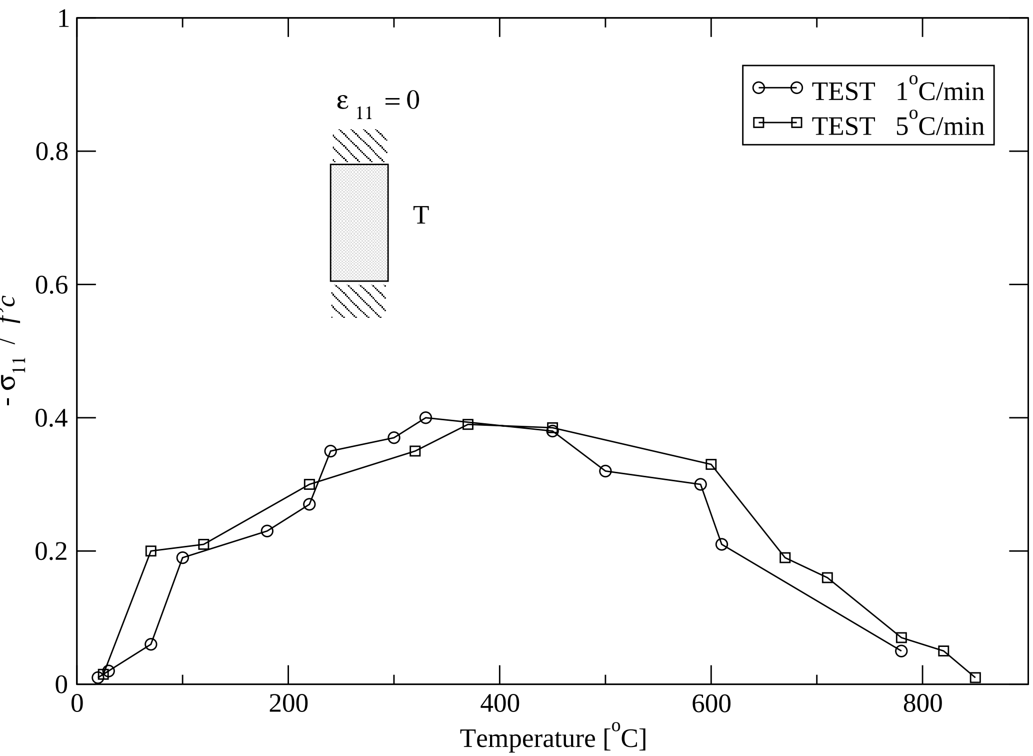
Diagonal separation of RVE due to slip.

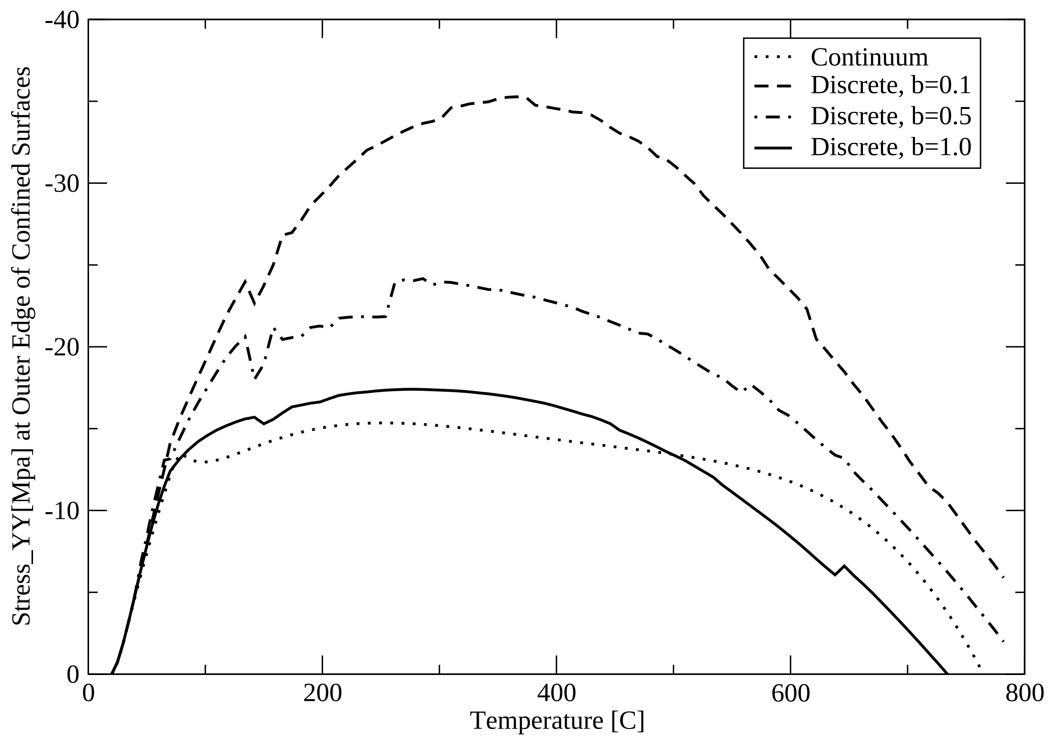


ZERO-THICKNESS INTERFACE FORMULATION

Axial Thermal Stress due to Temperature Sweep:

Experimental observations vs computational results.





HIGH TEMPERATURE BOND

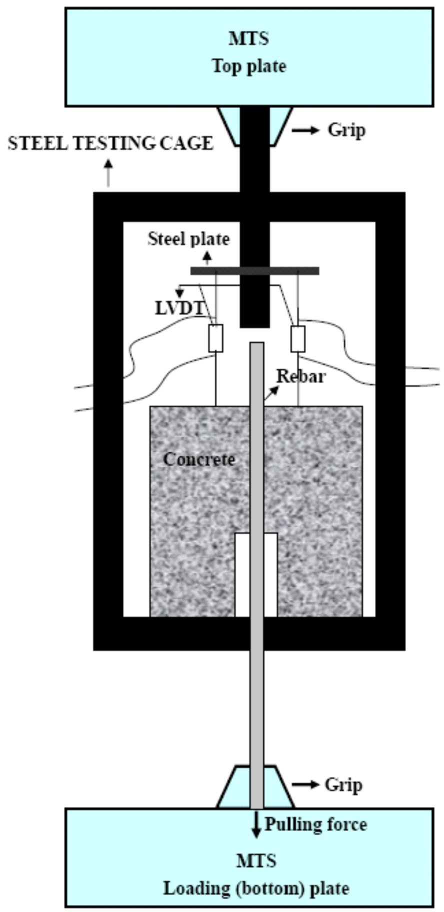
Pull-Out Test Setup: Residual Experiments after Cooling.

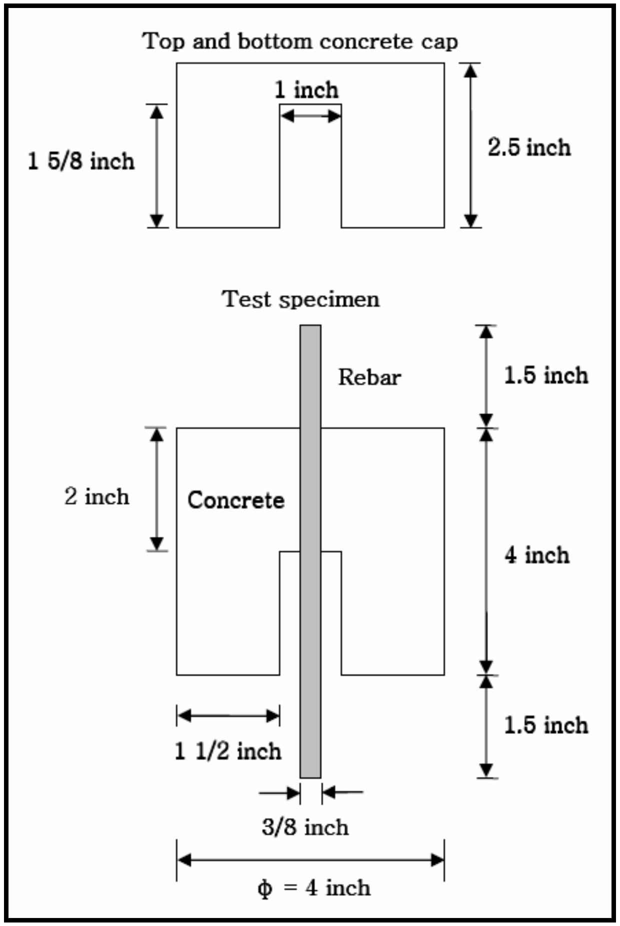
Test Variables:

- Coated-Uncoated Rebars
- Slow-Rapid Heating Rates
- Target Temperatures: $20^oC, 200^oC, 400^oC, 600^oC$
- Natural-Water Cooling

HIGH TEMPERATURE BOND

Pull-Out Test Program: Residual Experiments after Cooling.

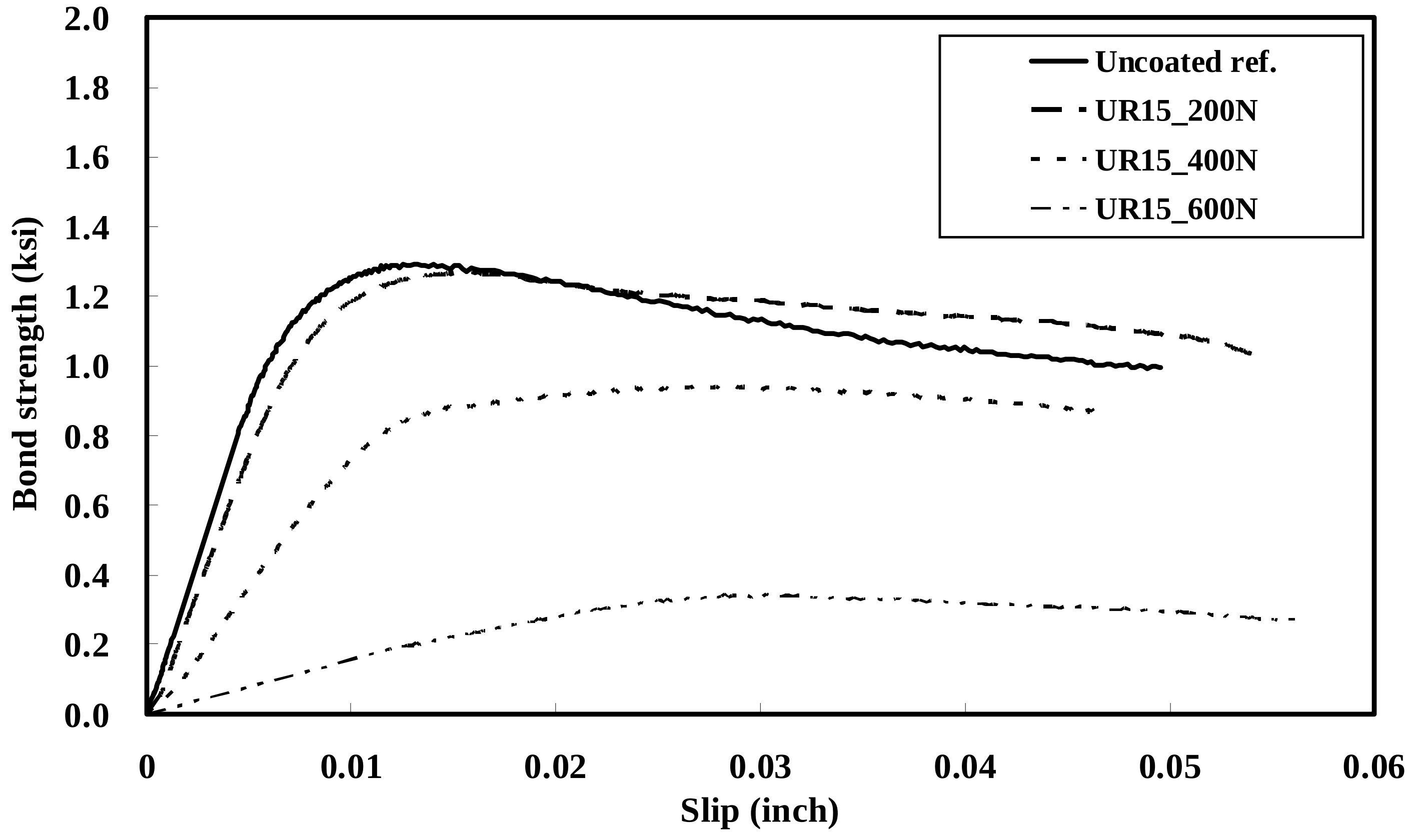




HIGH TEMPERATURE BOND

Pull-Out Test Results:

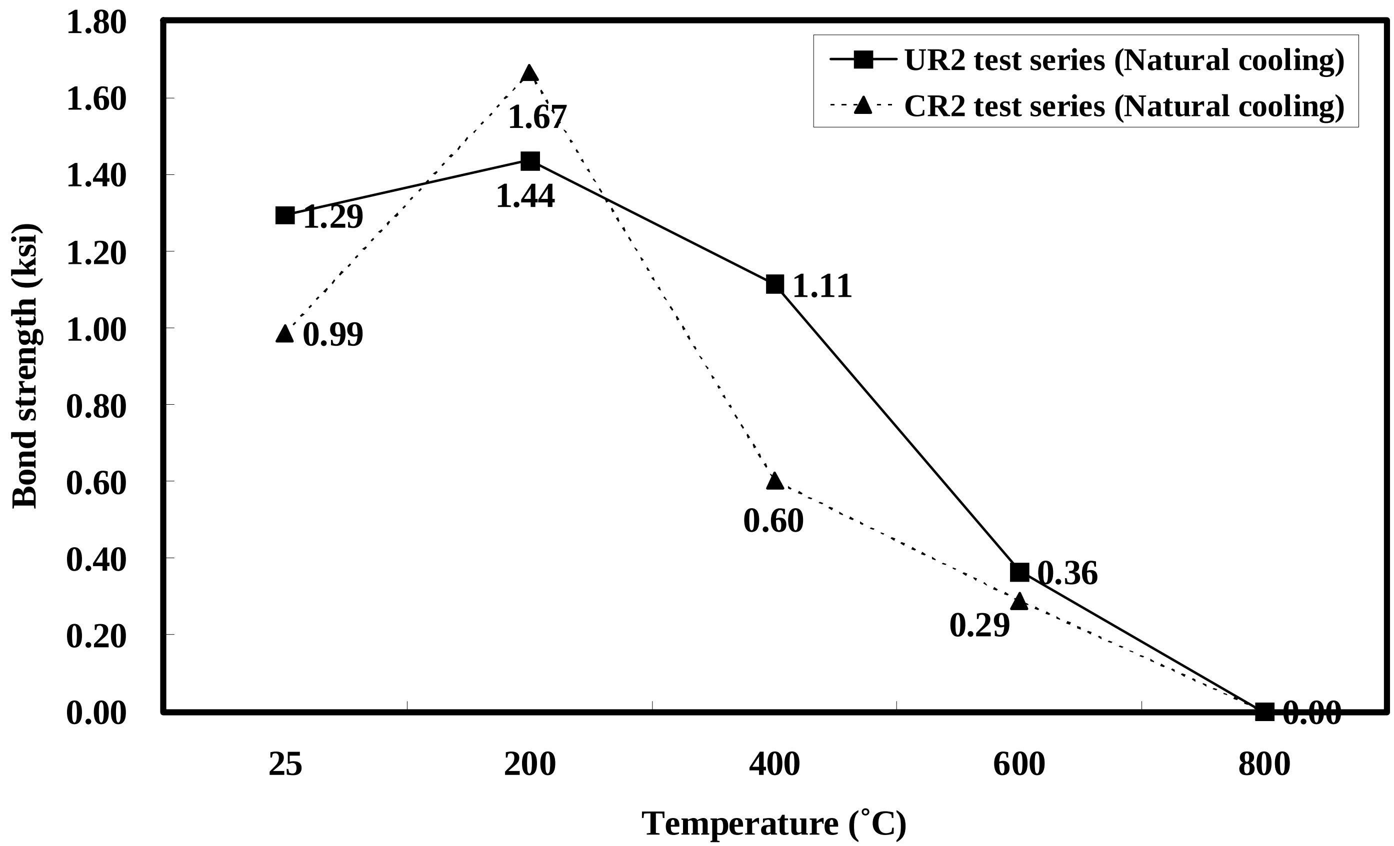
Bond-Slip Relationships for T=20, 200, 400, 600C (rapid heating)



HIGH TEMPERATURE BOND

Pull-Out Test Results:

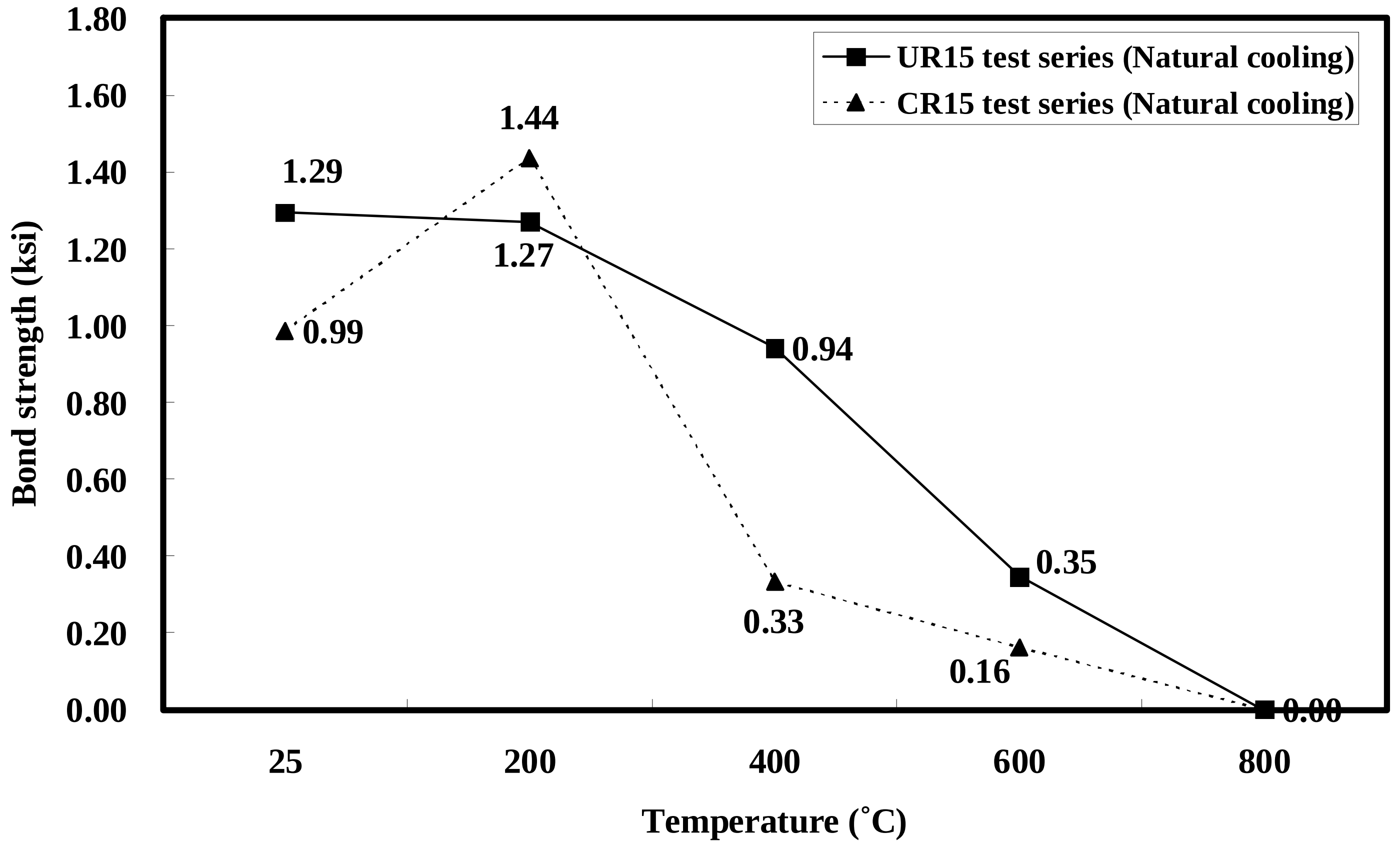
Bond Strength of slow heating tests up to $T = 20^o, 200^o, 400^o, 600^oC$



HIGH TEMPERATURE BOND

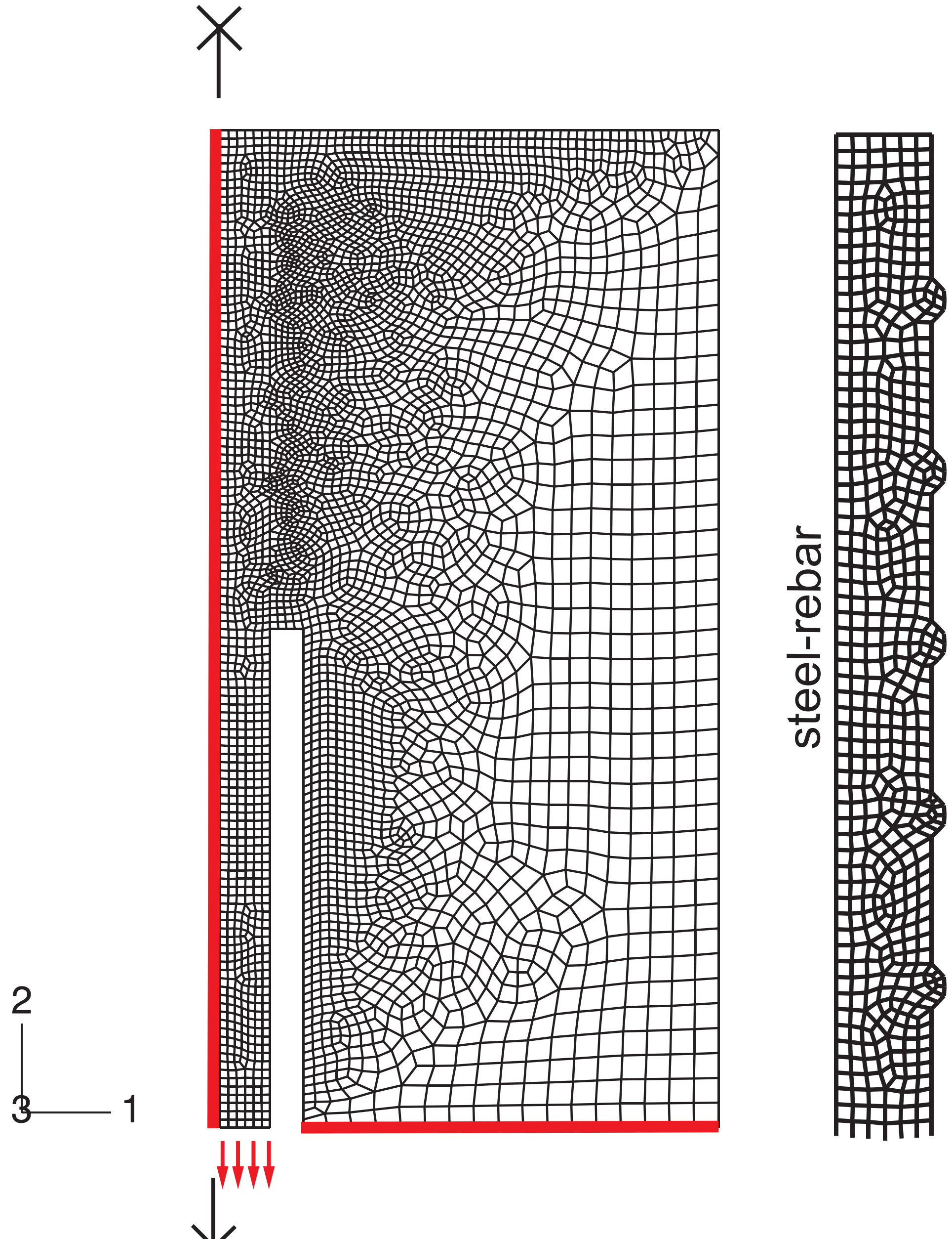
Pull-Out Test Results:

Bond Strength of rapid heating tests up to $T = 20^o, 200^o, 400^o, 600^oC$



PULL-OUT PROBLEM

Finite Element Model of Pull-Out Test Specimen



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Strong Discontinuities: all displacement components exhibit jumps across interface.

Note: FE Displacement method enforces traction continuity in 'weak' sense only, hence $[|\mathbf{t}_N|] \neq 0$.

MISMATCH OF THERMAL EXPANSION

3-D Thermoelastic Response:

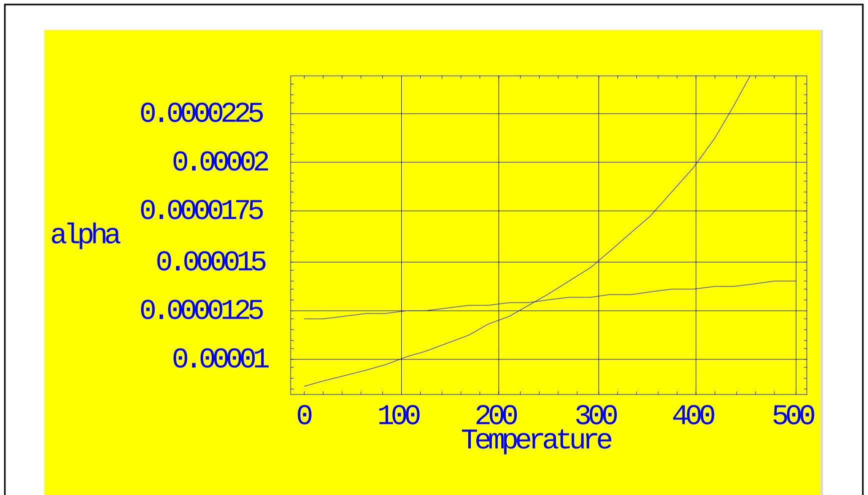
$\Delta\boldsymbol{\epsilon}_{co} = \boldsymbol{E}_{co}^{-1} : \Delta\boldsymbol{\sigma}_{co} + \boldsymbol{\alpha}_{co}\Delta T$ and $\Delta\boldsymbol{\epsilon}_{st} = \boldsymbol{E}_{st}^{-1} : \Delta\boldsymbol{\sigma}_{st} + \boldsymbol{\alpha}_{st}\Delta T$

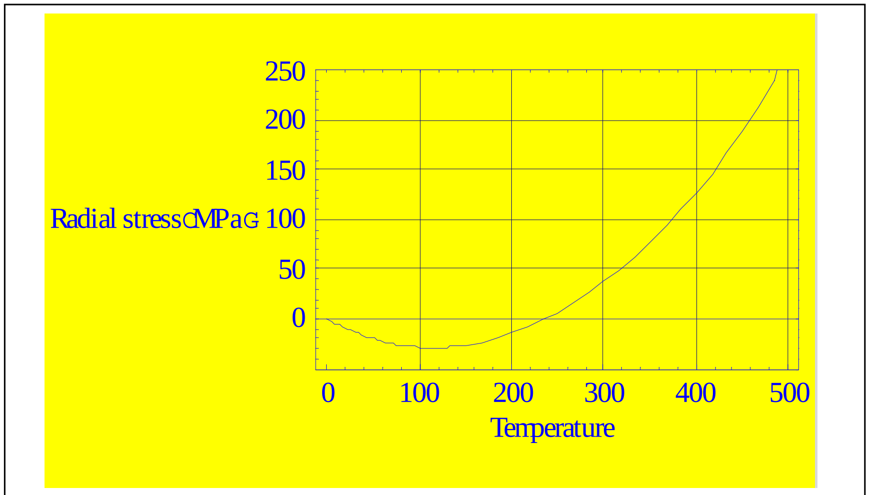
Interface Bond Kinematics: $\Delta\epsilon_z^{st} = \Delta\epsilon_z^{co}$

Interface Bond Traction: $\Delta\sigma_r^{st} = \Delta\sigma_r^{co}$

Radial Contact Stress:

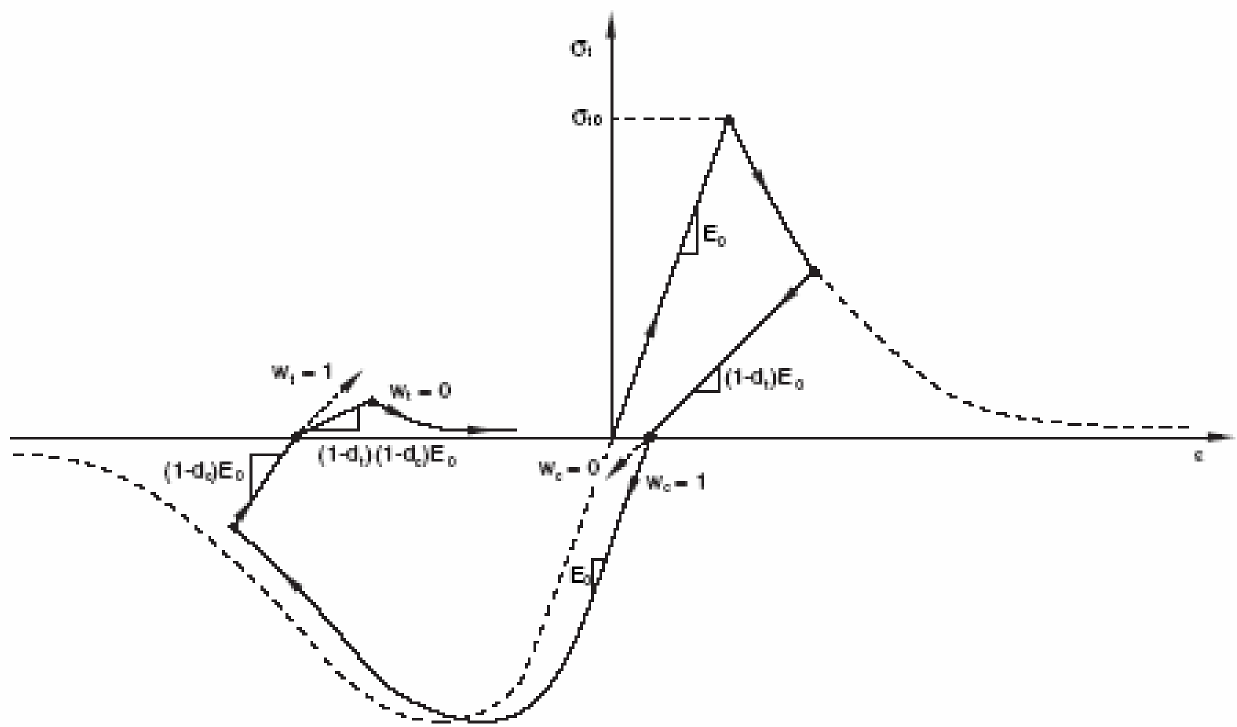
$$\sigma_r = \frac{E_{co}E_{st}}{E_{st}\nu_{con} - E_{co}\nu_{st}}[\alpha_{co} - \alpha_{st}]\Delta T + HO$$





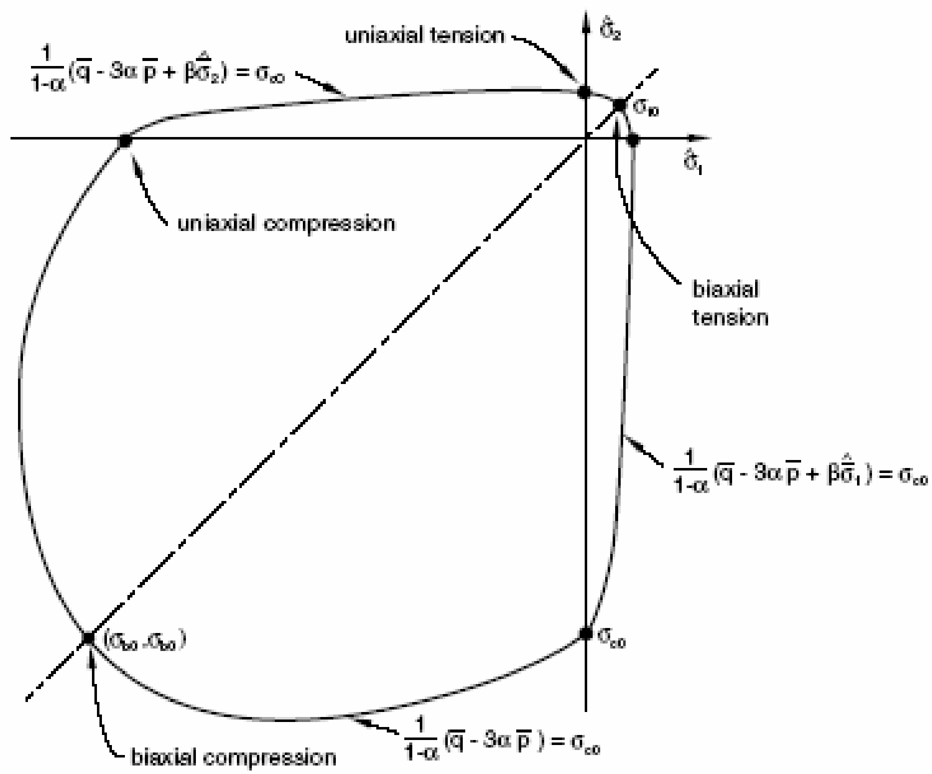
TRIAXIAL CONCRETE MODEL

Damage-Plasticity Model in ABAQUS: Lee & Fenves [1998]



PLANE STRESS FAILURE ENVELOPE

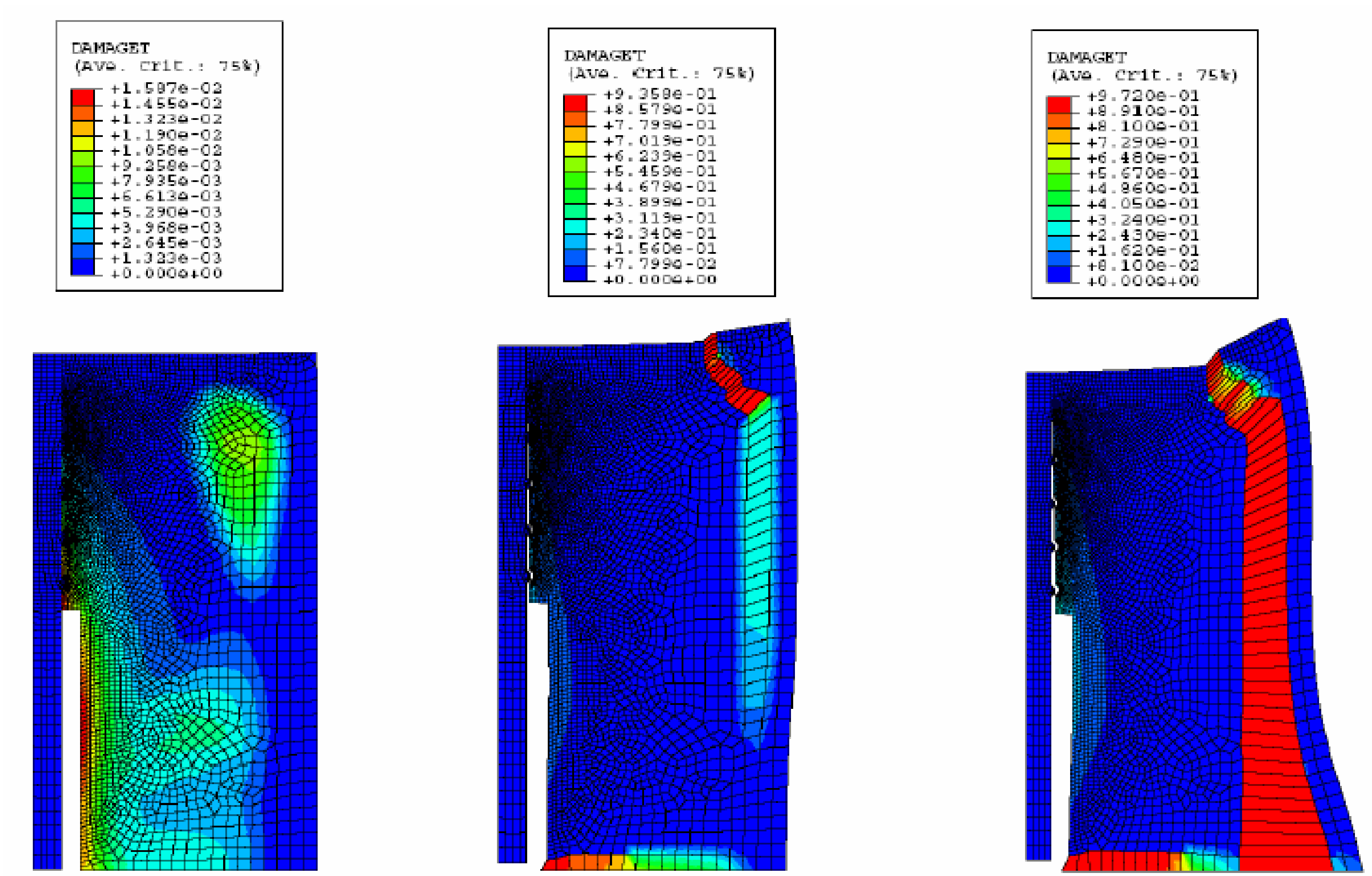
Damage-Plasticity Model: Lee & Fenves [1998]



PULL-OUT PROBLEM

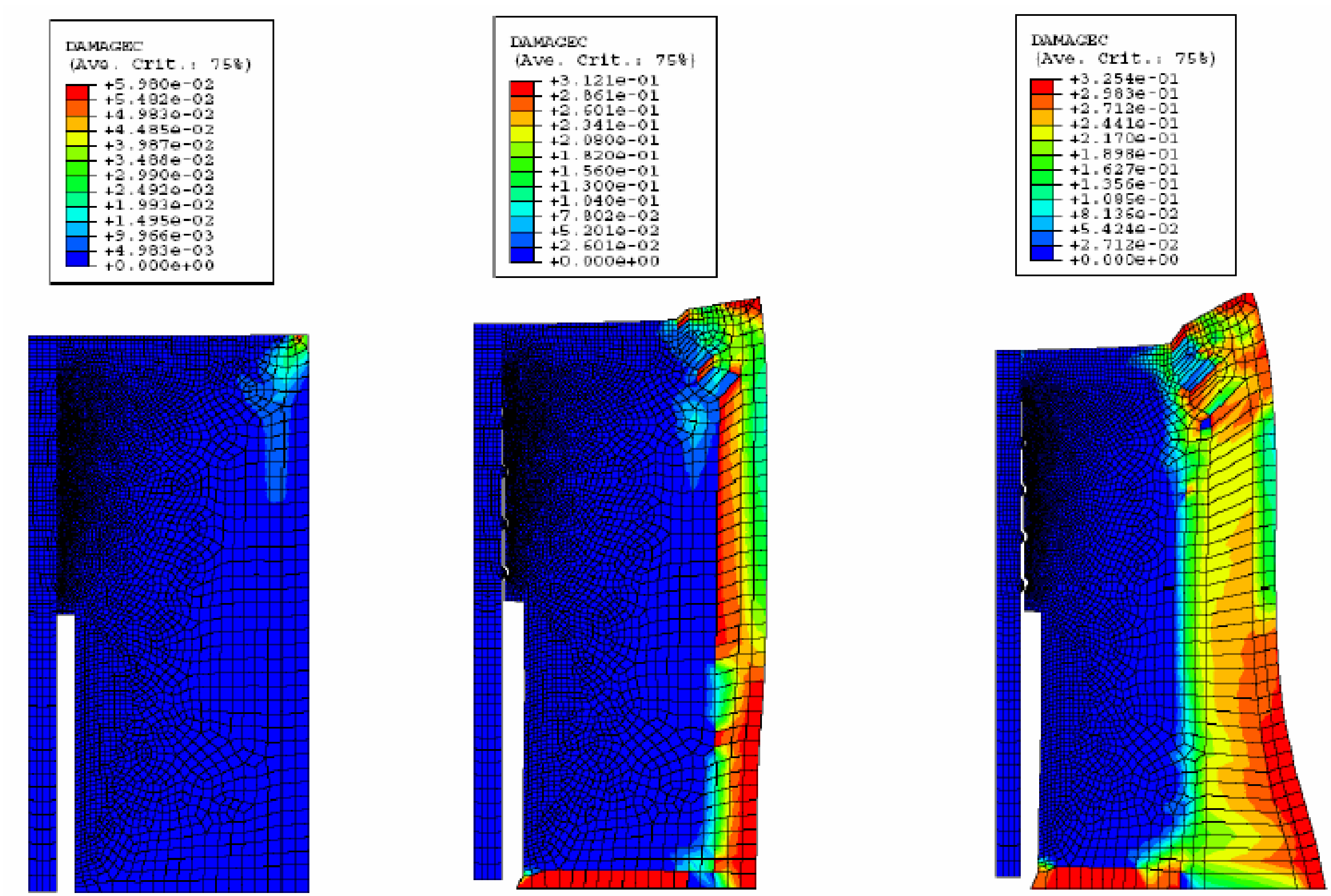
Evolution of Tensile Damage at Different Outside Temperatures

T = 100, 300, 580°C



PULL-OUT PROBLEM

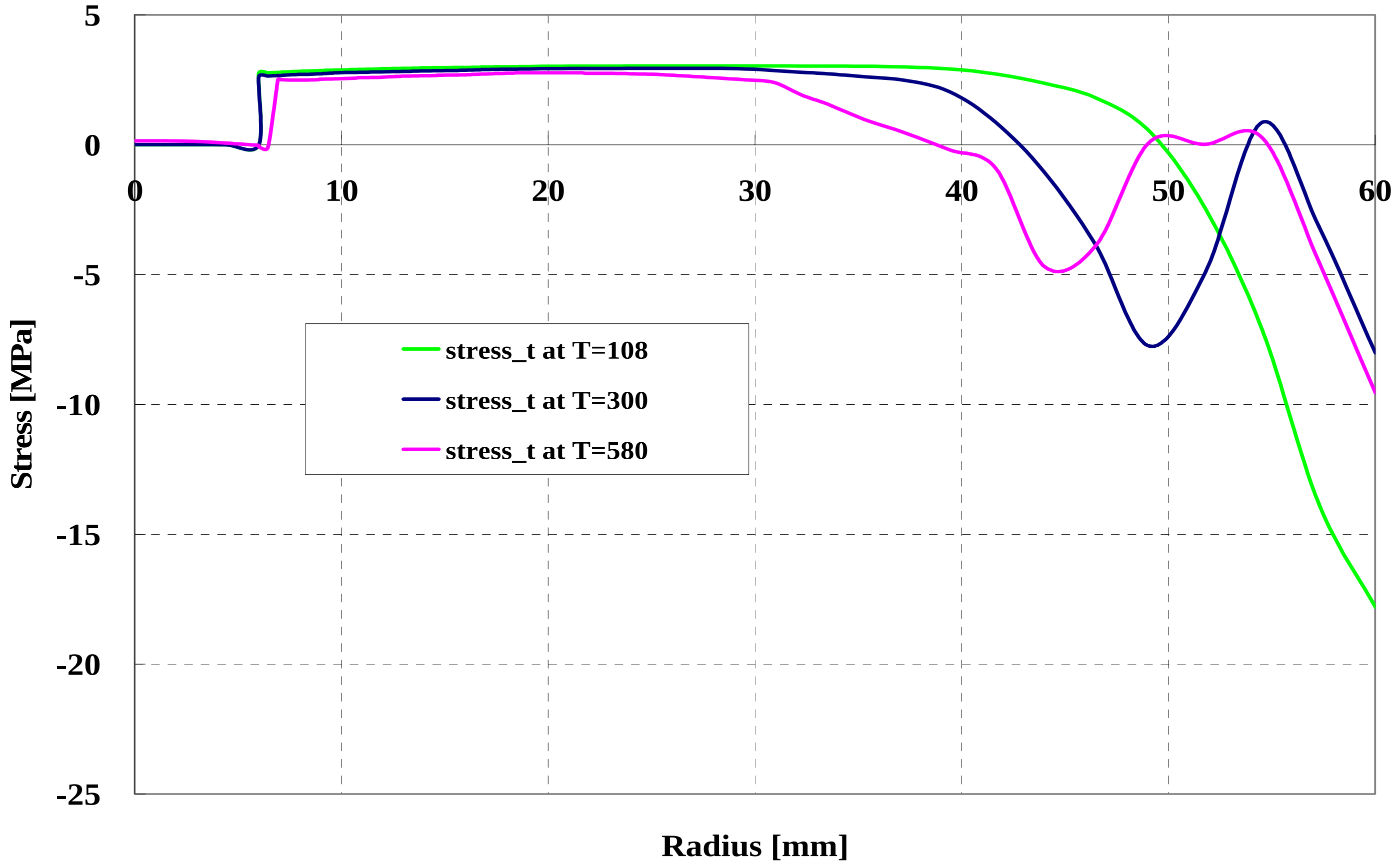
Evolution of Compression Damage at Different Outside Temperatures
T = 100, 300, 580°C



PULL-OUT PROBLEM

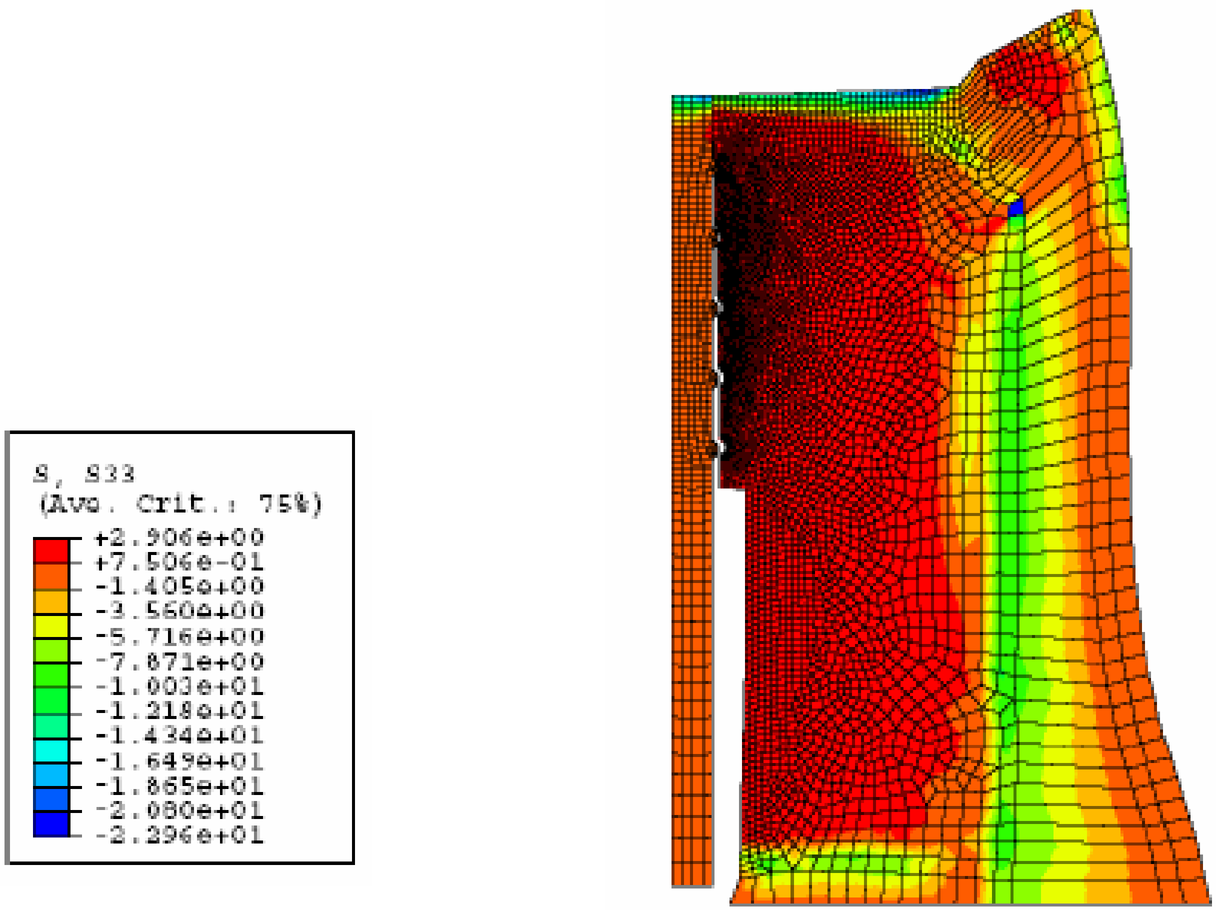
Circumferential Stress Distribution at Outside Temperatures

$$T = 100,\ 300,\ 580^{o}C$$

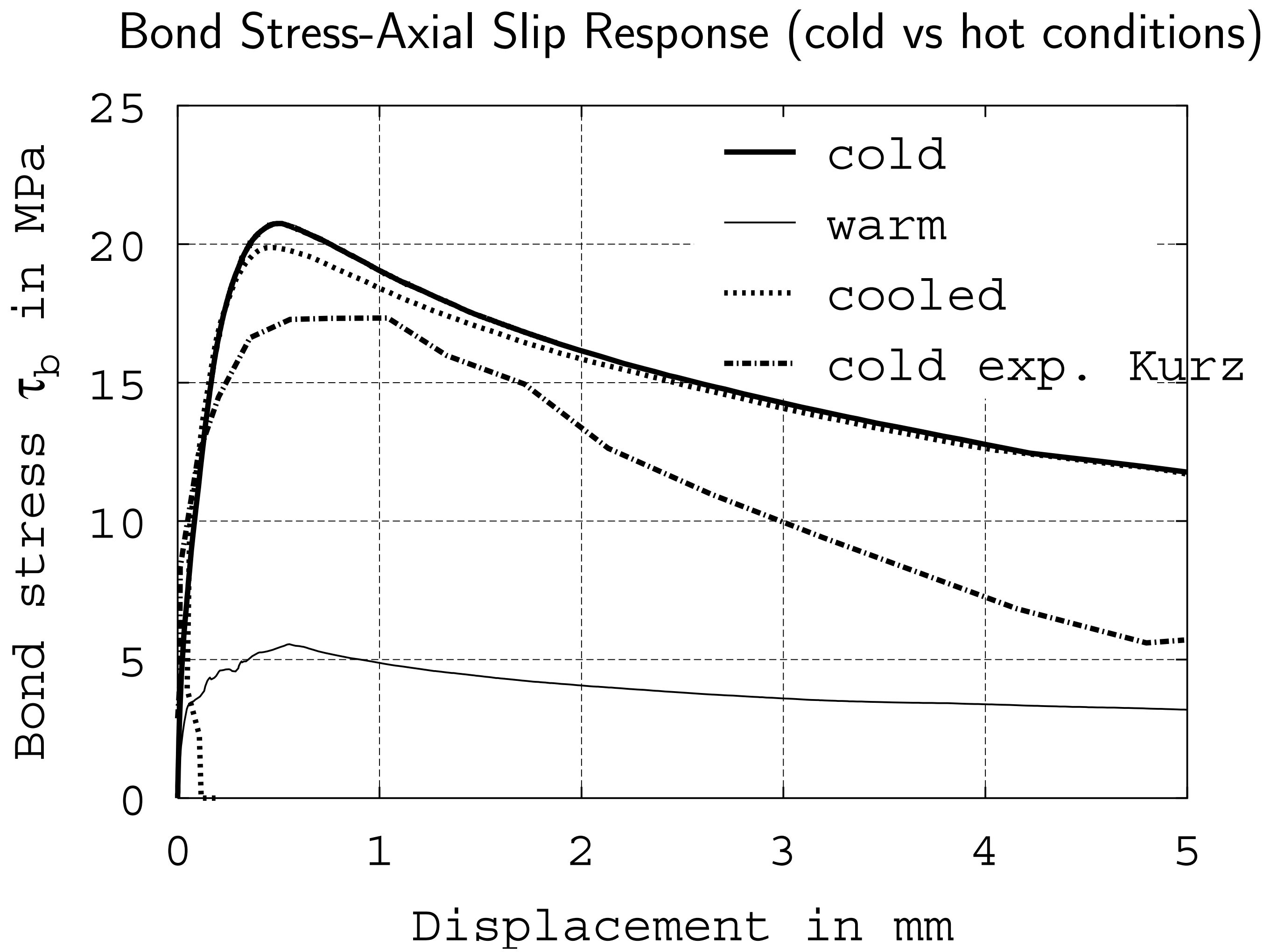


PULL-OUT PROBLEM

Circumferential Stress Contours at Outside Temperature $T = 580^oC$

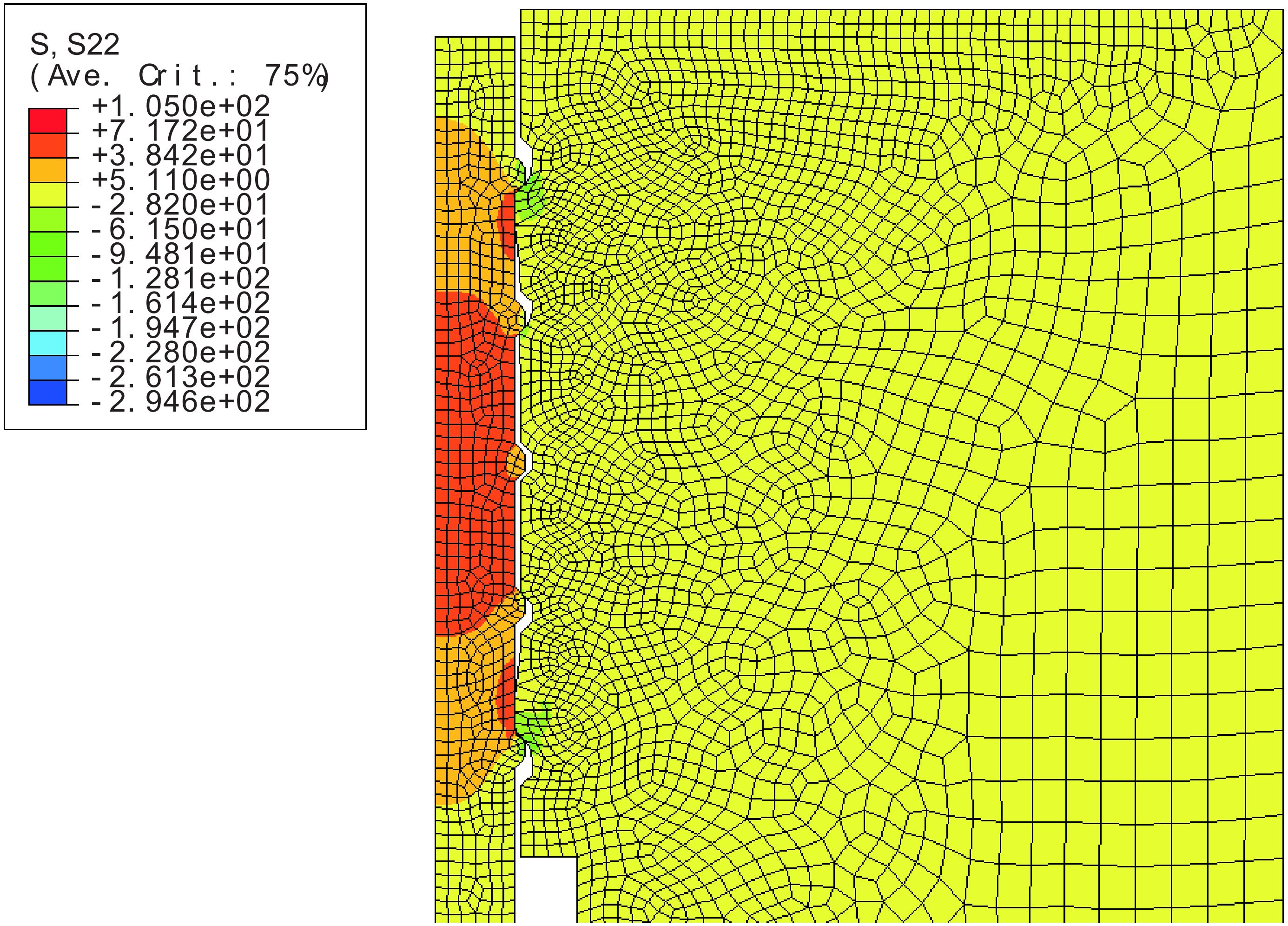


PULL-OUT PROBLEM



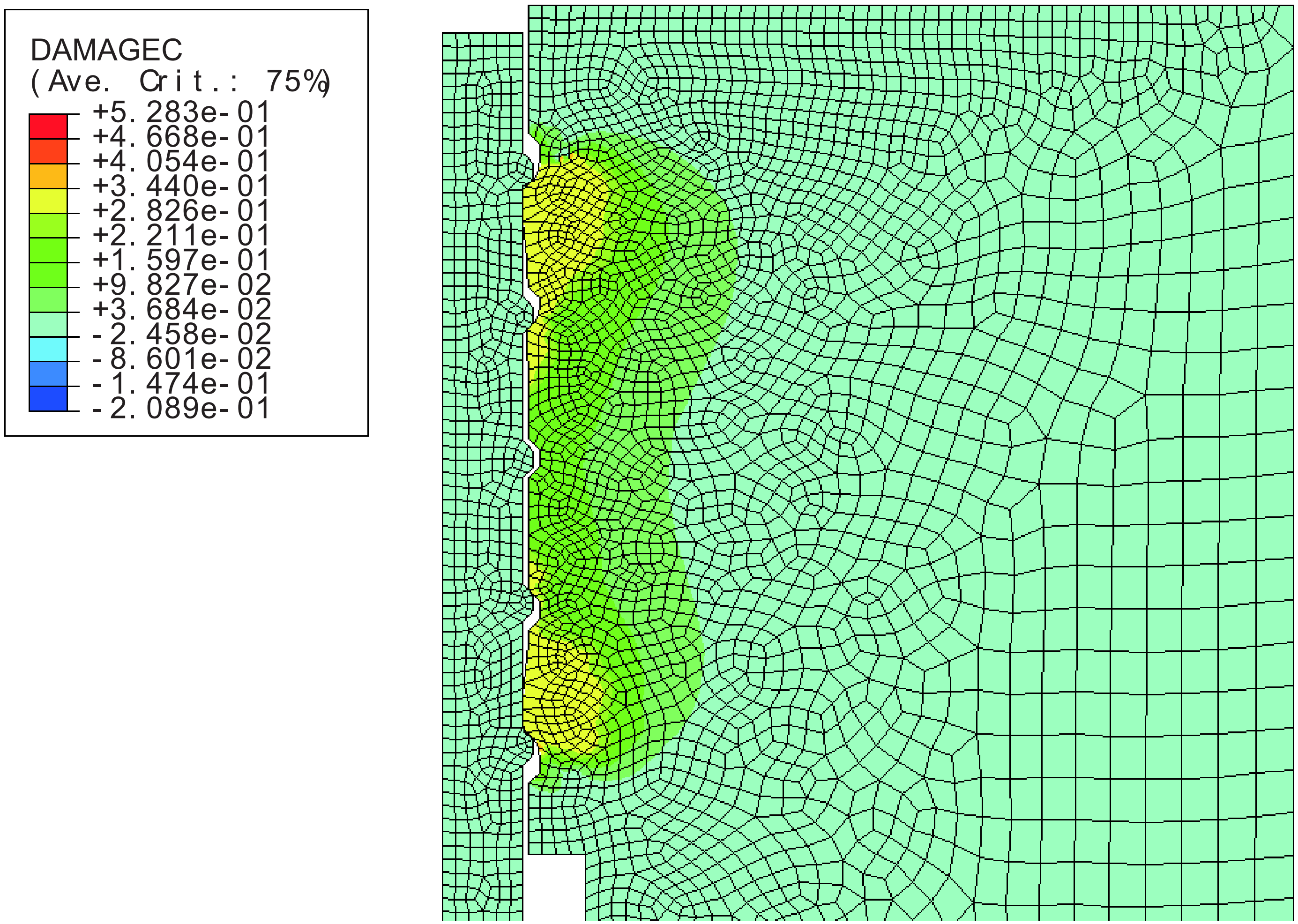
PULL-OUT PROBLEM

Axial Stress Contours after Heating to T $= 580^oC$



PULL-OUT PROBLEM

Compression Damage after Heating to T = 580^oC



CONCLUDING REMARKS

Thermal Mismatch of Steel and Concrete:

Full Bond vs Cohesive Interface Formulation - Loss of Confinement.

Mesoscale Analysis of Concrete RVE:

Interaction of tensile cracking and shear debonding along weak zero-thickness interface layers-ITZ.

High Temperature Pull-Out:

Residual experiments and axisymmetric FE simulation of steel-concrete contact separation.