Application field of 3D FE code MASA to Concrete & RC structures

• Theoretical framework
  – Continuum mechanics & irreversible thermodynamics

• Mechanics
  – 3D static and dynamic analysis of RC structures
    • Rate sensitive microplane model
    • Plasticity & damage mechanics based models
    • Discrete bond model
    • Creep & shrinkage of concrete
    • Contact mechanics
    • Remeshing

• Thermo-hygro-mechanical model
  – Modeling of concrete at high temperature

• Chemo-thermo-hygro-mechanical model
  – Modeling of corrosion of reinforcement (processes before and after depassivation)
Modeling of quasi-brittle materials

- **Modeling level**
  - Macro scale (phenomenological models)
    - global
    - detailed
  - Meso scale
  - Micro scale

- **Modeling approach**
  - Continuous models: smeared cracking + regularization
  - Discrete models
  - Combination

- **Spatial discretization**
  - Finite elements
  - Finite difference
  - Meshless methods
Detailed macro modeling:

- Constitutive law
- Fracture mechanics
- Continuum/Discontinuum
- Cycling
- Time dependent behavior
- Objectivity of analysis
- ...

Concrete

Bond

- Smeared bond
- Discrete bond

Reinforcement

- 1D vs. 3D modeling
- Constitutive relations
- Cyclic behavior
Concrete as a composite material

Section through a concrete cylinder showing grading of the aggregate particles
Typical stress-strain characteristics of aggregate, hardened cement paste (hcp), mortar and concrete under compressive loading
Compressive load

Nominal stress $\sigma_1 - \sigma_3$ versus axial strain $\varepsilon_1$ curves obtained in displacement controlled standard triaxial compression tests

$(\sigma_1 < \sigma_2 = \sigma_3 \leq 0)$
Tensile load

Localization zone - Fracture Process Zone (FPZ)

Size of the FPZ for different aggregate sizes
Modeling of quasi-brittle materials

A Representative Volume Element (RVE) must be small enough to avoid smoothing of high gradients but large enough to represent an average of the microprocesses. “

J. Lemaitre

For experimental and numerical purposes the following orders of magnitude on the meso-level are suggested:

- metals and ceramics: \((0.1 \text{ mm})^3\)
- polymers and most composites: \((1 \text{ mm})^3\)
- wood: \((10 \text{ mm})^3\)
- concrete: \((100 \text{ mm})^3\)
Steel reinforcement: 1D stress-strain relationship

\[ \sigma = \begin{cases} \sigma_y & \text{for } \varepsilon < \varepsilon_y \\ \sigma_f & \text{for } \varepsilon \geq \varepsilon_y \\ \end{cases} \]

Where:
- \( \sigma \) is the stress
- \( \sigma_y \) is the yield stress
- \( \sigma_f \) is the ultimate stress
- \( \varepsilon \) is the strain
- \( \varepsilon_y \) is the yield strain
- \( \varepsilon_f \) is the ultimate strain

The diagram illustrates the stress-strain relationship for different strengths (\( f_y = 300 \text{ MPa}, 400 \text{ MPa}, 520 \text{ MPa} \)).
Steel reinforcement: 3D plasticity based constitutive law
Bond between steel and concrete

- Primary crack
- Deformed bar in tension
- Internal bond cracks
- Internal cracking zone
- Radial forces on concrete
- Uncracked zone
Typical bond-slip relationship

\[ \tau_{\text{max}} = 11.5 \div 15.5 \text{ MPa} \]
\[ \tau_f = 4.2 \div 6.0 \text{ MPa} \]
\[ s_1 = 1.0 \text{ mm} \]
\[ s_2 = 3.0 \text{ mm} \]
\[ s_3 = 10.5 \text{ mm} \]
**Bond-slip relationship**

\[ \tau = \tau_m + \tau_f \]
\[ \tau_f = \tau_{f,v} + \tau_{f,r} \]

\[ \tilde{\tau} = \bar{s} \cdot \left( b + (1-b) \left( \frac{1}{1 + \left| \frac{1}{R} \right|} \right) \right) \]

**Inflenced by:**
- bar geometry (diameter & rib form and height)
- stress-strain state of reinforcement bar
- stress-strain state of concrete
- and taken into account by \( \Omega \):

\[ \tau = \Omega \tau_0 \]
RC beam: Cracks, Analysis vs. Experiment (Rüsch & Rehm, 1963)

FE-Analysis

Experiment

Crack width [mm]
RC beam in tension
Beam-column connection (cyclic loading)
Punching of RC slab
RC Beam-Column Joint before and after Retrofitting

FE simulation – crack patterns
## Crack patterns: analysis vs. experiment

### Table

<table>
<thead>
<tr>
<th>Drift</th>
<th>Exp.</th>
<th>FE</th>
<th>Exp.</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5 %</td>
<td>Bending and shear cracks</td>
<td>Bending and minor shear cracks</td>
<td>Bending cracks in the beam and shear cracks in the joint</td>
</tr>
<tr>
<td>1.0 %</td>
<td>Spalling of concrete cover in the joint panel,</td>
<td>bending cracks do not grow anymore</td>
<td></td>
</tr>
<tr>
<td>3.0 %</td>
<td></td>
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</tr>
</tbody>
</table>

### Diagrams

- **Drift 0.5%**
  - Experimental: Bending and shear cracks
  - FE: Bending and minor shear cracks

- **Drift 1.0%**
  - Experimental: Bending cracks in the beam and shear cracks in the joint
  - FE: Spalling of concrete cover in the joint panel, bending cracks do not grow anymore
FE simulations of as built joints

Beam end displacement [mm]

Beam end load [kN]

Top drift [%]

Joint shear distortion, $\gamma$ [rad]

Model's calibration (JT4-1)

1st Shear crack
FE simulations of retrofitted joints

Beam end displacement [mm]

Beam end load [kN]

Specimen JT1-3

Top drift [%]
Analysis of prestressed concrete railroad tie
Prestressed concrete railroad tie

Detail: steel-concrete connection

Fastening through torque moment
Analysis of prestressed concrete railroad tie
Prestressed concrete railroad tie

Detail: splitting cracks

Post-peak

At peak load