Modeling fire problems in ZSoil

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Motivation

- Modeling fire problems for **RC structures** in a simplified manner (so far)
- Detailed analysis of RC structure exposed to the fire → **coupled thermal-hygral-mechanical problem**
- Solution for practicing engineer today → **uncoupled thermal-mechanical analysis**
- **EC2 standard** is used as reference for development
New developments with respect to ZSoil 2016

- Enhanced **thermal module**
- Enhanced **1D model for steel in wide range of temperatures**
- Enhanced **2D/3D plastic damage model to capture effects in high temperatures**
Limitations

- Elements supporting effects of high temperatures in mechanical analysis
  1. **Continuum** elements + **truss** elements as discrete reinforcement
  2. **Shell** elements + smeared reinforcement via **shell fibers**
Convective flux:
\[ \dot{h}_c = \alpha_c (\Theta_g - \Theta_m) \]

Radiative flux:
\[ \dot{h}_r = \Phi \varepsilon_m \varepsilon_f \sigma ((\Theta_r + 273)^4 - (\Theta_m + 273)^4) \]

For elements fully subject to fire: \( \Theta_g = \Theta_r \)

Standard curve:
\[ \Theta_g(t) = 20 + 345 \log_{10}(8t + 1) \text{ (time in [min])} \]
Convection/radiation BC
Thermal module: standard $\Theta_g$ curve

This curve is used as LTF for ambient temperature in convection/radiation elements
Thermal module: parameters $\alpha(\Theta)$, $\lambda(\Theta)$, $c^*(\Theta)$

<table>
<thead>
<tr>
<th>Name</th>
<th>Cont./Struct. type</th>
<th>Material formulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1: No name</td>
<td>Continuum</td>
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<tr>
<td>2: No name</td>
<td>Heat convection</td>
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<td>Heat radiation</td>
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- Elastic
- Unit weights
- Flow
- Non linear
- Heat

Extension to fire problems: Concrete: EN1994-1-2:2005+AC:2
Thermal module: parameters $\alpha(\Theta), \lambda(\Theta), c^*(\Theta)$

Thermal evolution functions
Thermal module: parameters $\alpha(\Theta), \lambda(\Theta), c^*(\Theta)$

Thermal evolution functions
Thermal module: parameter $\alpha(\Theta)$

<table>
<thead>
<tr>
<th>X [°C]</th>
<th>Y [1/°C]</th>
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<tbody>
<tr>
<td>20</td>
<td>9.0276e-006</td>
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<tr>
<td>40</td>
<td>9.1104e-006</td>
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<td>60</td>
<td>9.2484e-006</td>
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<td>9.9935e-006</td>
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<tr>
<td>160</td>
<td>0.00000103524</td>
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<tr>
<td></td>
<td>0.00000107664</td>
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</tbody>
</table>
Thermal module: parameter $\lambda(\Theta)$
Thermal module: parameter $c^*(\Theta)$
Thermal module: fire simulation 2D

Show animation  video
Mechanical analysis: reinforcement steel in high temperatures

- EC2 shows only the monotonic curves at constant temperature
Mechanical analysis: reinforcement steel in high temperatures

- Some generalization must be made for unloading-reloading loops

![Graph showing stress-strain loops at different temperatures](image)
Reinforcement steel in high temperatures: 

$E$ degradation function
Reinforcement steel in high temperatures: $f_y$, $f_{yo}/f_y$ degradation functions
Reinforcement steel in high temperatures:

\( \alpha \) evolution function

Thermal dilatancy coefficient
Plastic damage model: extension to high temperatures

- Modified Lee-Fenves model is extended to range of high temperatures
- Implemented both for continuum and shells
Plastic damage model: material dialog

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<td>5: No name</td>
<td>Truss</td>
<td>Truss/Cable</td>
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<td>6: No name</td>
<td>Continuum</td>
<td>Elastic</td>
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EC2: 1D model in compression

- Initial modulus: $E_o(\theta) = \frac{1.5 \, f_c(\theta)}{\varepsilon_{cu}(\theta)}$
- Current modulus: $E(\theta) = E \frac{E_o(\theta)}{E_o(20)}$
EC2: $\varepsilon_{cu}(\theta)$ function
Plastic damage model: evolution of Poisson ratio

\[ \nu = \begin{cases} 
\nu_{20} & \text{for } \theta \leq 20^\circ C \\
\nu_{20} \left( 0.2 + 0.8 \frac{500 - \theta}{500 - 20} \right) & \text{for } 20^\circ \leq \theta \leq 500^\circ C \\
0.2 \nu_{20} & \text{for } \theta > 500^\circ C 
\end{cases} \]
Plastic damage model: evolution of compressive strength $f_c(\theta)$ (EC2) and fracture energy $G_c$

- $f_c(\theta) = k_c(\theta) f_c$
- $G_c(\theta) = k_c(\theta) G_c$

Assumption: $f_{co}(\theta)/f_c(\theta) = const$ is essential
Plastic damage model: evolution of biaxial compressive strength $f_{cb}(\theta)$

- $f_{cb}/f_c = 1.16$ for $\theta < 350^\circ$
- $f_{cb}/f_c = 1.16 \left(1 + 0.6 \frac{\theta - 350}{750 - 350}\right)$ for $350^\circ < \theta < 750^\circ$
Plastic damage model: evolution of tensile strength $f_t(\theta)$ (EC2) and fracture energy $G_t$

- $f_t(\theta) = k_{ct} f_t$
- $G_t(\theta) = k_{ct} G_t$
- $k_{ct}(\theta) = \begin{cases} 
1.0 & \text{for } \theta \leq 100^\circ C \\
1.0 - \frac{\theta - 100}{500} & \text{for } 100^\circ C \leq \theta \leq 600^\circ C \\
0.0 & \text{for } \theta > 600^\circ C 
\end{cases}$
Creep in tension is usually neglected
Creep in compression $\rightarrow$ under consideration
Example: slab subject to fire

Show animation video
Conclusions

- Intensive benchmarking is needed to validate the model.
- However, most of the degradation functions are taken directly from the EC2.