Cracking due to restrained shrinkage of massive concrete structures

Results of the CEOS.fr experiments

Jean-Michel Torrenti – IFSTTAR

On behalf of the CEOS.fr project
Building in Komaba campus!
Context of the project
• A 4 years national research project
• Involving 50 partners (building owners, construction firms, eng. offices, cement companies, research centers)

• Scientific Topics
  – Cracking under monotonic loading
  – Early-age concrete, thermo-hydro-mechanical effects
  – Cyclic loading

• Scientific know-how
  – Modeling (material, structure)
  – Experimental approach and monitoring
  – Engineering practices
Restrained shrinkage – CEOS experiments

• Cf. Buffo-Lacarrière et al., EJECE, 2015
  http://dx.doi.org/10.1080/19648189.2015.1072587
• And see https://cheops.necs.fr/ all the results available!
REINFORCEMENT OF THE 3 TESTED BEAMS

<table>
<thead>
<tr>
<th></th>
<th>RG8</th>
<th>RG9</th>
<th>RG10</th>
</tr>
</thead>
<tbody>
<tr>
<td>% of longitudinal</td>
<td>2%</td>
<td>0.56%</td>
<td>2%</td>
</tr>
<tr>
<td>reinforcement</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>cover</td>
<td>30 mm (50 mm for</td>
<td>30 mm (50 mm for</td>
<td>50 mm (70 mm for</td>
</tr>
<tr>
<td></td>
<td>longitudinal rebar)</td>
<td>longitudinal rebar)</td>
<td>longitudinal rebar)</td>
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</table>
INSTRUMENTATION

- Vibrating wires
- Temperature sensors
- Internal long-base optical-fiber
- Displacement sensors
- Strain gauges
TEMPERATURE EVOLUTION – RG8 TEST

T (°C)

formwork and isolation removed

Text

Time from casting (h)
STRAINS FROM OPTICAL FIBERS – RG8 TEST
Total force in longitudinal reinforcements versus time (RG8 specimen)
**Stresses in the reinforcement—RG8 test**

- Before cracking, the reinforcement is under compression (to balance autogenous shrinkage of concrete).

- After cracking, near the crack, the reinforcement is under tension. Far from the crack, it is still under compression.
Just before cracking, the mean tensile stress in concrete = 1.9 MPa
To compare with a tensile strength of 4.1 MPa!
Several possible causes:
• The effect of dead weight;
• The existence of a temperature gradient;
• A probabilistic scale effect [Rossi, 94] [Sellier, 14];
• A coupling between creep and damage [Briffaut, 11], [Torrenti, 11];
• The effect of temperature history on the strength;
• The possible influence of the great quantity of sensors in the central section.
The non-homogeneous stress profile because of the dead weight that induced a stress of +5MPa in the low steel corresponding to +0.7MPa in the low concrete part.
Evolution of temperature difference between core and upper face (green curve) and between core and lower face (red curve) in RG8 test
### Probabilistic Scale Effect

Strength

\[ f_{ctm}^{Veq} = f_{ctm}^{Vref} \left( \frac{V_{ref}}{V_{eq}} \right)^{1/k} \]

\[ f_{ctm}^{Veq} = 4 \times (310^{-3}/0.5)^{1/11} = 2.5 \text{ MPa}. \]
COUPLING BETWEEN CREEP AND DAMAGE

[Rusch, 1960]
Effect of temperature on the strength

[Daloia, 97]
Guidelines for the Control of Cracking - THM

- Minimal reinforcement of thick concrete elements (Chap 6)
  - Early age
  - Long term behaviour (drying)

- Combining effects of imposed deformations and external loadings (Chap 9)
  - Structures with water or air tightness requirements
  - Structures with sustainability requirements
GUIDELINES FOR THE CONTROL OF CRACKING - THM

- Minimal reinforcement of thick elements (Chap 6)
  - Early age
  - Around 3 days after concreting

<table>
<thead>
<tr>
<th>Concrete area in tension $A_c$</th>
<th>Stress profile</th>
<th>Minimum reinforcement and value of $h_t$</th>
</tr>
</thead>
<tbody>
<tr>
<td>When limited surface cracking of the concrete results from the temperature difference between the core and the surface, the area of the concrete in tension is given by $A_c = 0,20 \cdot h \cdot 1,0 , \text{m}^2$ with a tensile stress distribution profile in the form of a double triangle</td>
<td>Heating or formwork removal</td>
<td>$A_{s_{\text{min}}} = \frac{0,5 \cdot 0,2h \cdot 1 \cdot f_{ctm,\text{scale}}}{f_{yk}}$</td>
</tr>
</tbody>
</table>

$f_{ctm,\text{scale}}$ is calculated for a layer thickness of $h_t$ at maximum stress of $h_t = 0,2 \, h / 3$
### Guidelines for the Control of Cracking - THM

- **Minimal reinforcement of thick elements (Chap 6)**
  - Early age
  - Around 10 to 30 days after concreting

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<td>When the cracking results from the overall cooling of the element or is due to drying while under restraint, the area of the concrete in tension is given by $A_c = 0.5 \times 1.0 \text{ m}^2$ with a quasi-uniform tensile stress distribution profile</td>
<td>Cooling while under end restraint, but no edge restraint</td>
<td>$A_{s_{\text{min}}} = \frac{k \cdot 0.5h \cdot 1 \cdot f_{\text{ctm, scale}}}{f_{yk}}$</td>
</tr>
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</table>

$f_{\text{ctm, scale}}$ is calculated for a layer thickness of $h_t$ at maximum stress of: $h_t = 0.6 \times \text{h}$
• Minimal reinforcement of thick elements (Chap 6)
  – Daily temperature cycle (long term)

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<td>When the cracking is due to daily temperature cycle, the thickness $h_t$ is equal to 0,30 m and the area of the concrete in tension is given by $A_c = 0,30 \cdot h \cdot 1,0 \text{ m}^2$ with a tensile stress distribution profile in the form of a triangle</td>
<td>[Diagram of daily temperature cycle] $0,30 \text{ m}$</td>
<td>$A_{s\text{min}} = \frac{0,50 \cdot 0,30 \cdot 1 \cdot f_{ctm,\text{scale}}}{f_{yk}}$</td>
</tr>
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$f_{ctm,\text{scale}}$ is calculated for a layer thickness of $h_t$ at maximum stress of $h_t = 0,3/3 = 0,1 \text{ m}$
• Minimal reinforcement of thick elements (Chap 6)
  – Scale effect
COMBINING EFFECTS OF IMPOSED DEFORMATIONS AND EXTERNAL LOADINGS

• Proposal for the next Eurocode – annex D Guidance to restrict early age cracking (actually discussed)

• Three design states should be verified:
  – At temperature-equilibrium between the recently cast concrete and the restraining structure
  – At commissioning of the structure
  – During the design service life

• If particular demands are related to tightness, durability or appearance, cumulative impact of early age effects, load effects and later imposed deformations must be considered in the crack control verification.
• Otherwise, the crack control corresponding to these states can be verified separately.
Thank you for your attention
ご清聴ありがとうございます。