Dynamic Fracture of Ultra-High Performance Fibre-Reinforced Concrete

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Outline

• Introduction to CARDIFRC
• Incubation time dynamic fracture criterion
• Experimental set-up
• Dynamic compression test
• Dynamic split cylinder test
• Dynamic single-edged notched beam test
• Results
• Conclusions
Development of CARDIFRC

- High performance fibre reinforced cement-based composites (HPFRCCs) made possible by advances in processing technology, exclusion of coarse aggregate to eliminate internal stress concentration sites and use of silica fume and surfactants to reduce water demand and to densify the matrix thereby improving the fibre-matrix interfacial bond.

- The first HPFRCCs were developed in Denmark (DENSIT) and France (RPC). They exhibit very high compressive strength (up to 200 MPa), tensile/flexural strength $f_t$ (up to 30MPa), high energy absorption capacity, i.e. toughness $G_F$ (up to 40,000 J/m$^2$) and remarkable durability characteristics.

- Competition between $f_t$ and $G_F$ - toughness decreases with increasing strength.
Development of CARDIFRC

\[ l_{ch} = \frac{E G_F}{f_t^2} \]

\[ E = E_m \left[ \frac{1 + \Theta + V \Theta (n - 1)}{1 + \Theta - V (n - 1)} \right] \]

\[ f_t = \frac{K_{Ic,m}}{\sqrt{\pi a_o}} (1 - V_f) + \frac{h}{4} L V_f \alpha K_{Ic,m} \sqrt{\frac{E_f}{dE_b}} \]

\[ G_F = \frac{h}{24} L^2 V_f \alpha K_{Ic,m} \sqrt{\frac{E_f}{dE_b}} \]
Maximise \[ l_{ch} = \frac{EG}{f_t^2} \]

by choosing the vector of mix and fibre variables

\[ \begin{bmatrix} f \end{bmatrix}, g, L, d, V_f, w/b, sp/w \]

and any prescribed bounds (inequality constraints) on these variables, e.g.:

\[ 0.15 \leq w/b \leq 0.25 \quad 0.01 \leq V_f \leq 0.08 \]
Mix proportions for optimised CARDIFRC mix Type I and mix Type II (per m³)

<table>
<thead>
<tr>
<th>Constituents (kg)</th>
<th>Mix I</th>
<th>Mix II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
<td>855</td>
<td>744</td>
</tr>
<tr>
<td>Microsilica</td>
<td>214</td>
<td>178</td>
</tr>
<tr>
<td>Quartz sand:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9-300μm</td>
<td>470</td>
<td>166</td>
</tr>
<tr>
<td>250-600μm</td>
<td>470</td>
<td>-</td>
</tr>
<tr>
<td>212-1000μm</td>
<td>-</td>
<td>335</td>
</tr>
<tr>
<td>1-2mm</td>
<td>-</td>
<td>672</td>
</tr>
<tr>
<td>Water</td>
<td>188</td>
<td>149</td>
</tr>
<tr>
<td>Superplasticiser</td>
<td>28</td>
<td>55</td>
</tr>
<tr>
<td>Fibres: - 6mm</td>
<td>390</td>
<td>351</td>
</tr>
<tr>
<td>- 13mm</td>
<td>78</td>
<td>117</td>
</tr>
<tr>
<td>Water/cement</td>
<td>0.22</td>
<td>0.20</td>
</tr>
<tr>
<td>Water/binder</td>
<td>0.18</td>
<td>0.16</td>
</tr>
<tr>
<td>Superplasticiser/water</td>
<td>0.15</td>
<td>0.37</td>
</tr>
</tbody>
</table>
Figure 1: CT captured images and contour plots showing the X-ray absorption densities for the beam cross-section (100mm x 100mm). (a) CT image for slice 2, (b) contour plot for slice 2, (c) CT image for slice 18, (d) Contour plot for slice 18, and (e) plan view of the beam showing the location of each of the slices scanned (10mm section spacing) and the direction of scanning.
Measured pre- and post-peak response of CARDIFRC

Micro- and macro-cracking observed using CCD camera.
Typical mechanical properties of CARDIFRC Mix I

<table>
<thead>
<tr>
<th>Number of Thermal Cycles</th>
<th>Compressive Strength (MPa)</th>
<th>Split Cylinder Strength (MPa)</th>
<th>Modulus of Rupture (MPa)</th>
<th>Elastic Modulus (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>200.0</td>
<td>32.2</td>
<td>37.0</td>
<td>48.0</td>
</tr>
<tr>
<td>30</td>
<td>224.3</td>
<td>30.7</td>
<td>33.5</td>
<td>49.0</td>
</tr>
<tr>
<td>90</td>
<td>225.0</td>
<td>31.0</td>
<td>33.7</td>
<td>49.0</td>
</tr>
<tr>
<td>120</td>
<td>206.5</td>
<td>28.4</td>
<td>40.8</td>
<td>48.3</td>
</tr>
<tr>
<td>180</td>
<td>205.0</td>
<td>28.3</td>
<td>38.4</td>
<td>48.2</td>
</tr>
</tbody>
</table>
Incubation Time Dynamic Fracture Criterion

\[ F(t) = \text{Intensity of local force field leading to fracture}, \]

\[ F_c = \text{Quasi-static strength} \]

\[ \tau = \text{Incubation time of the dynamic process} \]

\[ \alpha = \text{Sensitivity to local force field} \]

\[
\frac{1}{\tau} \int_{t - \tau}^{t} \left( \frac{F}{F_c} \right)^\alpha \, dt' \leq 1
\]
Possible Interpretation of Incubation Time

• Assume that a tensile specimen breaks at a stress $P$ at $t = 0$: $F(t) = PH(t)$

• In a quasi-brittle material fracture is accompanied by an unloading wave which travels through the specimen and can be registered. The history of stress at the fracture site can be written as $\sigma(t) = P - Pf(t)$ where $f(t)$ increases from 0 to 1 in the interval $T$. The function $f(t)$ describes the micro-kinetics of the fracture process from no damage $f(0) = 0$ to complete damage $f(T) = 1$. If we now set $F(t) = PH(t)$ in the incubation time criterion, then we have $T = \tau$ at $P = F_c$
\[ \sigma_n(t) = \frac{EA}{A_s} \varepsilon^T(t) \]
\[ \varepsilon_n(t) = -\frac{2c}{L_0} \int_0^t \varepsilon^R(t) \cdot dt \]
\[ \varepsilon_n(t) = -\frac{2c}{L_0} \cdot \varepsilon^R(t) \]

Схема испытания на сжатие

Схема испытания на раскалывание

\[ \sigma_i(t) = \frac{2EA\varepsilon^T(t)}{\pi LD} \]
Parameters of Test Set-up

- Compact gas guns 10 or 20 mm dia;
- Accelerating projectiles 50 – 500 mm long;
- Impact velocities 10 – 100 m/sec;
- Corresponding strain rates 500 – 5000 /sec;
- Loading and reacting bars made of high strength steel with yield strength 1800 MPa;
- Dimensions of loading bar: diameter 10 or 20 mm, length 1 m
Dynamic Compression Test

- Diameter of loading bar 20 mm
- Dimensions of specimen: Dia 15 mm, thickness 10 mm
Simplified incubation time criterion:

\[ \frac{1}{\tau} \int_{t-\tau}^{t} \sigma(t') \, dt' \leq \sigma_{c}^{\text{compr}} \]

- Until the moment of fracture the rise in stress is nearly linear

\[ \sigma(t) = \dot{\sigma} \cdot t \cdot H(t) = E \cdot \dot{\varepsilon} \cdot t \cdot H(t) \]

- Substitution into the fracture criterion gives

\[ t_{*} = \frac{\tau}{2} + \sigma_{\text{compr}} / (E \cdot \dot{\varepsilon}); \quad t_{*} \geq \tau \]

\[ t_{*} = \sqrt{2 \sigma_{\text{compr}} \cdot \tau / (E \cdot \dot{\varepsilon}); \quad t_{*} < \tau} \]

- Whence

\[ \sigma_{*} = \sigma(t_{*}) = \sigma_{\text{compr}} + \dot{\sigma} \cdot \tau / 2 = \sigma_{\text{compr}} + E \cdot \dot{\varepsilon} \cdot \tau / 2; \quad t_{*} \geq \tau \]

\[ \sigma_{*} = \sqrt{2 E \cdot \dot{\varepsilon} \cdot \sigma_{\text{compr}} \cdot \tau}; \quad t_{*} < \tau \]
For $E = 46 \text{ GPa}$ \quad $\sigma_{c}^{\text{compr}} = 160 \text{ MPa}$ \quad $\tau = 2 \text{ ms}$
Dynamic Brazil Test

- Dimensions of disk: Dia 15 mm, thickness 10 mm
- Diameter of loading bar: 20 mm
- Dimensions of disk: Dia 60 mm, thickness 30 mm
- Diameter of loading bar: 60 mm
Simplified incubation time criterion:

\[
\frac{1}{\tau} \int_{t-\tau}^{t} \sigma(t') \, dt' \leq \sigma_{c}^{\text{tensile}}
\]

- For \( \sigma_{c}^{\text{tensile}} = 23 \text{ MPa} \) \( \tau = 15 \text{ ms} \)

- For Granite \( \sigma_{c}^{\text{tensile}} = 19 \text{ MPa} \) \( \tau = 70 \text{ ms} \)
Three-point bend test. Results not yet analysed