Fatigue behaviour in bending of HSFRC

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Topic fatigue in bending of HSFRC

- Outline
- Static behaviour
  - Three and four point bending
  - Uniaxial tensile test
  - Model
- Fatigue experimental behaviour
- Fatigue development model
Tested concrete mixtures

• **BSI**: steel fibres 2.5% straight 20mm 0.3mm thick  
  • $E_c=50$GPa $f_c=200$ MPa

• **HSFRC**: steel fibres 1.6% straight 13mm 0.16mm thick  
  • $E_c=40-45$GPa $f_c=120$ MPa

• **Hybrid HSFRC**: steel fibres  
  0.5% straight 13mm 0.2mm  
  1% hooked-end 60mm and 0.75mm thick  
  • $E_c=40-45$GPa $f_c=120$ Mpa
<table>
<thead>
<tr>
<th>Method</th>
<th>Dimensions</th>
<th>Mixtures</th>
<th>Aim</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compression</td>
<td>100 mm long cubes</td>
<td>All mixtures</td>
<td>Compressive strength 28d; quality control of concrete</td>
</tr>
<tr>
<td></td>
<td>Prisms 100/100/400mm</td>
<td>HSFRC only</td>
<td>E-Modulus; Compressive strength; (\sigma-\varepsilon) diagram in compression</td>
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<tr>
<td>Tension</td>
<td>100 mm long cubes</td>
<td>All mixtures</td>
<td>Splitting tensile strength; quality control of concrete</td>
</tr>
<tr>
<td></td>
<td>dogbone specimens 140/100/70</td>
<td>HSFRC only</td>
<td>Uniaxial tensile strength; (\sigma-\varepsilon) diagram in tension</td>
</tr>
<tr>
<td>Bending</td>
<td>150/150/600mm; 25mm notch</td>
<td>HSFRC only</td>
<td>Static flexural tensile strength (preliminary testing series)</td>
</tr>
<tr>
<td></td>
<td>125/125/1000mm</td>
<td>All mixtures</td>
<td>Static and fatigue tests. Load-deflection diagram; multiple cracking evaluation; fatigue behaviour (S-N curve)</td>
</tr>
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<td></td>
<td>125/125/1000mm; 20mm notch</td>
<td>HSFRC only</td>
<td>Static and fatigue tests. Load-crack opening relation; strains compressive zone.</td>
</tr>
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</table>

Combined durability / fatigue experiments
Notched and un-notched tensile tests

• Measuring lengths 35 mm (post-peak behaviour) and 110 mm
Uniaxial tensile strength HSFRC

Only the curve from the un-notched specimen will be used as input for model
Notched specimen give stable descending branch (stress-crack width relation)
Multilayer Model flexural response

- Beam divided into 2 halves, springs and a number of layers.
- Strain in each spring represents deformation in each layer.
- Length spring equal to influence length = 0.5 beam depth.
Multilayer Model flexural response

• Strain in each spring represents deformation in each layer and gives associated stress based on uni-axial stress-displacement relation.
• External load \( P=4*\frac{M}{L} \) calculated from internal stresses if horizontal equilibrium is met.
• Incremental procedure applied (increase strains at bottom) to find load-displacement curve
Apply model on four point bending tests

Average of 6 specimen
Material input MLModel HSFRC

- Idealized tensile input curve
- Equivalent strain ($l=35$ mm)
  - 1) linear elastic part
  - 2) linear hardening branch
  - 3) stress-crack width relation linear from peak value down to zero at $w_c = l_f / 4$

- Idealized compressive stress strain relation
Results MLModel notched and un-notched beams

\[(H=\text{constant})\]
Effect position crack from midspan
4 point bending

![Graph showing deflection over relative stress for different crack positions.]

- x = 150 mm
- x = 100 mm
- x = 50 mm
- x = 0 mm

Deflection [mm] vs. Relative stress [-]
Fatigue tests

- Frequency 10 Hz
- Upper load levels 50%-90% of the static strength
- Load controlled
- Tests most on un-notched beams 4 point bending
- Ratio lower to upper load level $R = 0.2$ (constant)
Fatigue test results

Mixtures:
Triangle: BSI (<50%)
Circles: HSFRC (<70%)
Squares: hybrid HSFRC (<60%)

BSI has the best fatigue performance at high load levels >50kN
Comparison fatigue test results fiber concrete with plain concrete

- HSFRC
- hybrid HSFRC
- BSI/CERACEM
- plain concrete
- FRC 1% fibres

The graph shows the comparison of fatigue test results for fiber reinforced concrete (FRC) with 1% fibers, hybrid high-strength fiber reinforced concrete (HSFRC), and plain concrete. The graph plots the logarithmic number of cycles (log N) on the x-axis against the remaining load capacity (S) on the y-axis.
Average deflection beams tested at 75% upper load level

BSI has a much higher stiffness (50 GPa to 40 GPa) upper load level is different
Unique relation between slope of deflection increase and n cycles to failure (all mixtures)

The same relation holds true for the crack opening increase and is in accordance with plain concrete.
Initial deflection related to fatigue life

Relation holds true for two mixtures
These beams had initial deflections which were much smaller than the beams that did fail
Concluding remarks

• Only HSFRC showed improved fatigue performance compared to plain concrete; no failure for upper load levels lower than 70%

• A fatigue limit seems to exist for both HSFRC mixtures

• A unique relation existed for all mixtures between slope of deflection and number of cycles to failure
Implementation fatigue HSFRC into MLModel

- Linear strength decrease (Kessler-Kramer)
  \[ f_{ct,N} = f_{ct,0} - 0.2 \log N \]

- Bilinear strength decrease
  \[ f_{ct,N} = f_{ct,0} \quad \text{if} \ \log N < 1 \]
  \[ f_{ct,N} = f_{ct,0} - 0.27 \log N \]
Implementation fatigue HSFRC into MLModel

- Linear degradation
  - LE strength drop at $N=10^7$
  - 8.5 Mpa to 7.1 Mpa
  - hardening strength
  - 9.0 Mpa to 7.6 Mpa

- Bilinear degradation
  - LE strength drop at $N=10^7$
  - 8.5 Mpa to 6.6 Mpa
  - hardening strength
  - 9.0 Mpa to 7.1 Mpa
Results MLModel for HSFRC

- Model underestimates the crack openings
- bi-linear strength degradation more suitable
Adding gradual stiffness decrease into MLModel

\[ E_N = E_0 - a \log N \]

- \( a = 2 \text{ GPa} \)
- Reduction to 65% at \( N = 10^7 \)

- Test on run-out specimens
- Stiffness decrease HSFRC 38% and hybrid HSFRC 31%
Gradual stiffness decrease

- Tensile strength limits constant
- First variant
  \[ \text{fct, } N = 0.425 \log N \]

- Tensile strain limits constant
  Second variant
Gradual stiffness decrease and tensile strength or strain limits constant

<table>
<thead>
<tr>
<th>Load level</th>
<th>90%</th>
<th>80%</th>
<th>70%</th>
<th>60%</th>
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</thead>
<tbody>
<tr>
<td>Experiments notched</td>
<td>N</td>
<td>1583780</td>
<td>4806455</td>
<td>7684815</td>
</tr>
<tr>
<td></td>
<td>logN</td>
<td>6.20</td>
<td>6.68</td>
<td>6.89</td>
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<tr>
<td>Experiments un-notched</td>
<td>N</td>
<td>11464</td>
<td>2577654</td>
<td>10000000</td>
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<tr>
<td></td>
<td>logN</td>
<td>4.06</td>
<td>6.41</td>
<td>7.00</td>
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<tr>
<td>Model stiffness decrease</td>
<td>N</td>
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<tr>
<td>(first variant)</td>
<td>logN</td>
<td>7.00</td>
<td>7.00</td>
<td>7.00</td>
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<tr>
<td>Model stiffness decrease</td>
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<tr>
<td>(second variant)</td>
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<td>2.11</td>
<td>4.20</td>
<td>6.28</td>
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</table>

HSFRC
Second variant too severe tensile strength decrease
Gradual stiffness decrease and tensile strain limits constant

Tendency is present but too severe as a result of the decrease in tensile strength
Proposed fatigue model HSFRC

- Combine two variants
- LE strength decrease and strain increase

- Tensile strength decrease with 0.27 log N and
- Tensile strain increase to match actual stiffness and strength value. For N=10^6 this means:
  - LE strength 6.6 MPa (-22%) hardening strength 7.1 MPa
  - Stiffness 26 GPa Compressive strength (-22%)
## Results MLModel HSFRC

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<td>Proposed model</td>
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<td>w [mm]</td>
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<td>0.605</td>
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<tr>
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<td>δ [mm]</td>
<td>1.922</td>
<td>2.016</td>
<td>1.156</td>
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Model predicts number of cycles to failure
No difference predicted between notched and un-notched beam
Results MLModel for notched beam

Agreement between calculated and measured values of one beam
Results MLModel notched beam

80%

70%
Conclusions

• The model is capable to generate the deformation evaluation curve of fatigue experiments
• The fatigue lives are in better agreement with results on un-notched beams and no failure is predicted up to 10 million cycles at upper stress ratio 0.7
• Failure occurs always due to insufficient tensile load capacity, as also observed in experiments
• Proposed fatigue model can easily be implemented into other material models and serve for larger structural elements
• The model can be applied to other concrete mixtures as well