Workshop on
FIBER REINFORCED CONCRETE (FRC):
MATERIALS, APPLICATIONS AND DESIGN ASPECTS

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Sustainable Construction Materials and Structural Systems Research Group,
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JOINTLY WITH

Structural Design Research Group,
University of Brescia (Italy)

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University of Brescia, Italy
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KEY SPEAKERS

Prof. Giovanni Plizzari,
University of Brescia, Italy

Prof. Salah Altoubat,
University of Sharjah, UAE

Prof. Mohamed Maalej,
University of Sharjah, UAE

Dr. Moussa Leblouba,
University of Sharjah, UAE
Fiber Reinforced Concrete

Design concepts

Prof. Salah Altoubat
Department of Civil & Environmental Engineering
SCMASS Research Group
College of Engineering
University of Sharjah
Outline

1. Introduction
2. Design concepts
3. Design for flexure
4. Design for flexure – hybrid reinforcement
5. Design Examples
6. Slab on Ground Design
7. Design Example
8. Design for shear
1. Introduction

- Fibers influence the mechanical properties of concrete in all failure modes (compression, tension, shear,...);
- The most important variables governing the properties of FRC include: fiber bond efficiency (controlled by pullout test) and dosage rate;
- When a concrete matrix is subjected to tension, stresses are transferred by interfacial shear. When the matrix cracks, the stress gets transferred to the fibers, progressively;
- This process results in: increase in the load carrying capacity, the energy dissipation, and the ductility at serviceability and at ultimate limit design states for FRC.
What do structural fibers add to concrete

**Material level**

1. Toughness
2. Ductility
3. Residual strength

**Structural level**

1. Yield capacity, post-cracking capacity
2. Rotational capacity
3. Yield strength

- FRC: Substantially enhance the post-cracking response of the composite (toughness).
- **Post-cracking response**: is evaluated through toughness testing
  - Toughness: area under the load deformation curve

*Toughness and ductility are key properties that fibers impart to concrete structure*
Where does FRC as structural material stand?

**Material characterization**

1) Test Standards
   - ASTM C 1609
   - JCI-SF 4
   - ASTM 1399
   - ASTM 1550
   - EN 14651
2) Specification

Well established

**Structural Performance**

1) Demonstrated by experiment
2) Structural tests and models

Recognized at research level

**Structural design**

Progressing in North America

Recognized in Europe

Progressing
Requirements

- When fibers are intended to contribute to the structural performance of an element or structure, the FRC needs to be designed accordingly and the fibers contribution to the load-bearing capacity needs to be properly assessed and justified.

Fibers intersect cracks when they initiate. This allows for a uniform distribution of the stresses that develop and slow down crack propagation.
ACI 544: Fiber Reinforced Concrete

ACI 544-9R, and ACI 544.2R-17: Report on the Measurement of Fresh State Properties, Mechanical Properties, and Fiber Dispersion of Fiber-Reinforced Concrete

ACI 544.8R-16 Report on Indirect Method to Obtain Stress-Strain Response of Fiber-Reinforced Concrete

ACI 544-4R: Design Guide for Fiber Reinforced Concrete

544.6R-15 Report on Design and Construction of Steel Fiber-Reinforced Concrete Elevated Slabs

544.7R-16 Report on Design and Construction of Fiber-Reinforced Precast Concrete Tunnel Segments

ACI 544.5R-10 and New Document on Testing, Creep, Shrinkage, Service life, Crack Width Prediction
1. Introduction

- Since the fibers are randomly distributed with small spacing (compared to typical steel bars), the tensile stresses in FRC are borne by the fibers are early stages;
- In design, the type, size, geometry, and dosage rates for fibers is dependent on the application, loading level, and exposure conditions;
- Fibers change the post-crack response of concrete from brittle to ductile under all types of loads.
2. Design concepts

- The material properties (such as the residual strength determined by standard tests—ASTM C1609) are inserted into equations to determine the performance of an FRC element and its load-carrying capacity.

- Tensile strength of plain concrete is insignificant, hence, not taken into account in the design of conventional RC sections.

- **Effective tensile strength of FRC sections is used in the design process.**

- Direct tensile test on FRC is difficult, instead, the residual tensile strength is derived from the measured flexural strength by means of conversion factors.
KEY PROPERTY: Stress-strain diagram

Fiber Reinforced Concrete

Plain Concrete

$F_{ct,eq,3}$ Equivalent strength at deflection of 3 mm (L/150)

$F_{ct,eq,1.5}$ Equivalent strength at deflection of 1.5 mm (L/300)
Post-cracking behavior

- The cracked section of fiber-reinforced concrete (FRC) does carry tensile load while plain concrete becomes ineffective after cracking as indicated in the stress-strain diagram.
2. Design concepts

• In the post-crack state, the residual flexural strength of FRC is typically between 2.5 and 3 times its residual tensile strength, hence, the tensile resistance is calculated from the flexural resistance using a factor between 0.4 and 0.33.

• For design purposes, the tensile residual strength of FRC may be taken as 0.37 times the flexural strength obtained from a standard beam test.

• Two levels of design can be considered: design for serviceability limit state (SLS) at small deflections (cracks in the range of 0.4-1.0 mm and design for ultimate limit state (ULS) with larger deflections (larger crack widths: 2.0-3.0 mm).
2. Design concepts

When ASTM C1609/1609M-12 is used to characterize FRC, parameters such as $f_{600}^D, f_{150}^D, R_{D,150}^T$ (or $f_{e,3}$) may be used for design.

- $f_{600}^D$: Residual strength at a deflection of L/600 (psi or MPa)
- $f_{150}^D$: Residual strength at a deflection of L/150 (psi or MPa)
- $T_{150}^D$: Toughness or area under the curve up to a deflection of L/150
- $R_{D,150}^T$: Equivalent flexural strength ratio at a deflection of L/150 (%)
- $f_{e,3}$: Equivalent flexural strength at a deflection of L/150 (psi or MPa)

\[ f_{e,3} = f_p \times R_{D,150}^T \]

- $f_p$: Peak strength (psi or MPa)
To determine the first-peak, peak and residual strengths, the respective load value is substituted in the modulus of rupture formula:

$$ f = \frac{PL}{bd^2} $$

Where:
- $f$ = the strength, MPa (psi),
- $P$ = the load, N (lbf),
- $L$ = the span length, mm (in.),
- $b$ = the average width of the specimen, mm (in.), at the fracture, and
- $d$ = the average depth of the specimen mm (in.), at the fracture.

Values of loads at specified deflection points are used for measuring residual strength of FRC.
Equivalent flexural strength, $f_{e,3}$

ASTM C1609-06
JSCE, JCI-SF4
NBN B15-238

$$f_{e,3} (\text{MPa}) = \frac{L (\text{mm}) \cdot T_{150,3,0} (\text{Nmm})}{L (\text{mm})} \cdot \frac{W (\text{mm})}{150} \cdot D (\text{mm})^2$$

For Span, $L = 450$ mm

$$f_{e,3} = \frac{450 \cdot T_{150,3,0}}{3 \cdot W \cdot D^2} = \frac{150 \cdot T_{150,3,0}}{W \cdot D^2}$$

**Equivalent Flexural Strength:** Have the same toughness, $T_{150,3,0}$, obtained from experiment to a deflection of $L/150$ (same area under load-deflection curve)

$$R_{e,3} (%) = \frac{f_{e,3}}{f_p} \cdot 100$$
3. Design for flexure (Fiber Reinforced Section)

\[ M_{n-FRC} = f_{150}^D \frac{bh^2}{6} \]

Schematics of stress block for a cracked RC and FRC flexural member

\[
M_{n-FRC} = (f_t)(0.9h)(0.5h)b \\
= (0.37f_{e3})(0.9h)(0.5h)b \\
= 0.166f_{e3}bh^2 \\
\rightarrow M_{n-FRC} \approx (f_{e3})\frac{bh^2}{6}
\]

Note:
\[
\begin{align*}
f_{t-FRC} &= 0.37f_{e3} \\
1 & f_{e3} = f_p \times R^D_{T,150}
\end{align*}
\]
3. Design for flexure

\[ M_{n_{-RC}} = A_s f_y \left( d - \frac{a}{2} \right) \]

\[ M_{n_{-FRC}} = f_{150}^b \frac{bh^2}{6} \]

Schematics of stress block for a cracked RC and FRC flexural member
4. Design for flexure – hybrid reinforcement

FRC section

\[ M_{n-FRC} = f_{e,3} \frac{bh^2}{6} \]

Normal Stresses (Actual)

Normal Stresses (Simplified)

FRC section with hybrid reinforcement

\[ M_{n-FRC^*} = f_{e,3} \frac{bh^2}{6} + A_s f_y (d - 0.03h) \]

Normal Stresses/Forces (Actual)

Normal Stresses/Forces (Simplified)

Schematics of stress block for a cracked FRC (with and without hybrid reinforcement)
Ultimate resistance

• Assumptions
  • Plane section remains plane
  • Stress in tension and compression are derived from stress-strain diagram
  • For FRC with additional rebars, the strain in tension is limited to 10% at the level of rebars
  • The maximum crack width is limited to 1.5 mm (RILEM TC162)
Post-cracking behavior

• The cracked section of fiber-reinforced concrete (FRC) does carry tensile load while plain concrete becomes ineffective after cracking as indicated in the stress-strain diagram.

Conventional RC     FRC
Stresses in fiber reinforced concrete at ultimate loading

Fiber Reinforced Concrete + bar reinforcement

Fiber Reinforced Concrete

RILEM TC162
8. Example

Assume an 8” (200 mm) precast panel reinforced with #4@16” placed in mid-section to provide post-crack moment capacity. Find the value of $f_{150}^D$ for FRC to provide the same level of post-crack flexural strength as rebar. Assume 5,000 psi concrete and grade 60 steel and a moment capacity factor of 0.9 for steel.

$$\varphi M_{n-RC} = \varphi A_s F_y (d - \frac{a}{2}) = 0.9 \times 0.147 \times 60,000 \times \left(\frac{8}{2} - \frac{0.17}{2}\right) = 31,120 \text{ lb} - \text{in}$$

$$a = \frac{A_s F_y}{0.85 f'_c b} = \frac{0.147 \times 60,000}{0.85 \times 5,000 \times 12} = 0.17 \text{ in}$$

$$\varphi M_{n-FRC} = \varphi M_{n-RC} = 31,120 \text{ lb} - \text{in} = \varphi f_{150}^D \frac{b h^2}{6}$$

$$f_{150}^D = \frac{6 M_{n-FRC}}{\varphi b h^2} = \frac{6 \times 31,120}{0.9 \times 12 \times 8^2} = 270 \text{ psi (1.86 MPa)}$$

Specify Fiber Dosage Accordingly
Example 2: Determine the moment capacity of the concrete slab that is reinforced with fibers (0.5% of Fiber below)

\[ M_n = 0.37 f_{e3} (0.9h)(0.5h)b \]

\[ f_{t,frc} = 0.37 f_{e3} \]

ASTM 1609 Results for the fibers used is shown in the next slide
Example: Determine the moment capacity

\[ M_n = 0.37 f_{e3} (0.9h)(0.5h) b \]

\[ T_{150}^D = 45900N - mm = 45.9 J \]

\[ f_{e3} = \frac{150T_{150}^D}{bd^2} = 2.04 MPa \]

\[ M_n = 0.166 f_{e3}bh^2 = 7.62 kN\text{-}m \]
Example: Determine the Tension capacity

\[ M_n = 0.37 f_{e3} (0.9h)(0.5h) b \]

\[ T_{150}^D = 45900N \text{ } mm = 45.9 \text{ } J \]

\[ f_{e3} = \frac{150T_{150}^D}{bd^2} = 2.04 \text{MPa} \]

\[ T_n = 0.37 f_{e3} bh = 113.2 \text{kN} \]
Example: ACI 318 cracking control

\[ w = 0.076 \beta Z \]

Gergely-Lutz

\[ Z = f_s \sqrt[3]{d_c A} \]

ACI requires that the term Z does not exceed 175 for interior exposure and 145 for exterior exposure (based on 0.4 mm and 0.3 mm crack width)

\[ f_s = \frac{M}{A_s jd} \]

Stress in the steel

\[ f_s = \frac{M}{A_s jd} - \frac{0.37 F_{ct,eq,3} A_{ct}}{A_s} \]

(For RC)

(For RC with fibers)

Conventional RC

FRC
Example: ACI 318 cracking control

\[ w = (1.1 \times 10^{-5}) \beta Z \]

Gergely-Lutz (mm)

\[ Z = f_s \frac{3}{d_e A} \]

\[ F'_c = 30 \text{MPa} \]

\[ 50 \text{KN} \]

\[ f_s = \frac{M}{A_s jd} = 244 \text{MPa} \]

\[ w = 3 \text{mm} \quad \text{(For RC)} \]

\[ w = 0.2 \text{mm} \quad \text{with 3.5 kg of synthetic fibers} \]
The steel ratio is

\[ A_{s,sh,temp} = 0.0017bh \sim W4 @ 4x4 \]

\[ F'_c = 25 \text{MPa} \]
\[ F_y = 400 \text{MPa} \]
\[ Z = 20000 \text{N/m} \]

\[ Z = f_s^3 \sqrt{d_c A} \]

\[ d_c = 75 \text{mm} \]

\[ A = \frac{1000 \times 120}{10} = 12000 \text{mm}^2 \]

\[ f_s = 207 \text{MPa} \]

Crack Width

\[ \beta = \frac{h_2}{h_1} \approx 2.6 \]

\[ w = (1.1 \times 10^{-5}) \beta Z \]

\[ w = 0.57 \text{mm} \]
Required STRUX 90/40 to Obtain Same Z-Value

\[ F_{ct} \approx 0.3F_{ct,eq,3} hb \]

\[ f_{s,eq} = 207\, MPa \]

\[ f_{s,eq} = \frac{F_{ct}}{A_s} \approx \frac{0.3F_{ct,eq,3} hb}{A_s} \]

\[ F_{ct,eq,3} = 1.16\, MPa \]

Specify Dosage of fibers accordingly
Failure and moment capacity of SOG

Horst Falkner, Braunschweig, 1995
FRC versus PC slabs

• Bending moment distribution after cracking is different
  • Plain concrete exhibit a regular hinge
  • Fiber concrete exhibit plastic hinge (yield capacity)
• Final design of PC slab is governed by slab stiffness and interaction with sub-base
• Final design of FRC slab is governed by the interaction between positive and negative moment as a function of slab stiffness and sub-base
FRC versus PC slabs

- Collapse load of FRC slab is a function of the sum of the negative and positive moment

\[ M_{ult} = \sum (M^+ + M^-) \]

- Resist Moment by fiber (Plastic Hinge)

- Collapse load of PC slab is a function of the cracking moment

\[ M_{ult} = M^- = M_{cracking} \]
Flexural capacity

\[ F_d = F_{ct} \]  
\[ M_{ult} = \frac{F_{ct}bh^2}{6} \]  

Plain concrete

\[ F_d = F_{ct} \times (1 + \frac{R_{e,3}}{100}) \]  
\[ M_{ult} = \left[ 1 + \frac{R_{e,3}}{100} \right] \times \left[ \frac{F_{ct}bh^2}{6} \right] \]  

Fiber reinforced concrete

\[ R_{e,3} = \frac{F_{e,3}}{F_{ct}} \]  

Ductility factor, toughness dependent
For $a/l \geq 0.2$: (where $a$ is the equivalent radius of the load patch, and $l$ is the relative stiffness), the ultimate load carrying capacity of the slab will be obtained from the following equations:

For Center Load:

$$P_u = 4\pi(M_p + M_n)\left(1 - \frac{a}{3l}\right)$$

For Edge Load:

$$P_u = [\pi(M_p + M_n) + 4M_n] \left(1 - \frac{2a}{3l}\right)$$

For Corner Load:

$$P_u = 4M_n \left(1 - \frac{a}{l}\right)$$

$L$ is the radius of relative stiffness

$$l = \left(\frac{E_c h^3}{12(1 - \nu^2)k}\right)^{0.25}$$
Given Parameters

Ground Supported Slab
Thickness of Slab = 125 mm
Concrete class S40
Elastic modulus of Concrete = 35000 MPa
Modulus of Subgrade Reaction 68 MPa/m
Joint spacing variable (6 m)

P = 100 kN
Area = 0.025 m²
a = equivalent radius = 89.2 mm
radius of relative stiffness = 538 mm

Use Factored Load = \( P_u = 1.5 \times 100 = 150 \) kN

For center point load \( R_{e,3} \) will be equal to 25.6 %

\[ M_{ult} = M_n + M_p = 0.075P_u \]

\[ 2.27M_n + M_p = 0.283P_u \]

\[ M_p = \frac{f_{cm}}{\gamma_c} R_{e,3} \left( \frac{h^2}{6} \right) \]

\[ M_n = \frac{f_{cm}}{\gamma_c} \left( \frac{h^2}{6} \right) \]

\[ f_{cm} = f_{cdm}(1.6 - h/1000) \]

\[ 5.16 \text{ MPa} \]

\[ \text{fiber content} \]

\[ R_{e,3} = 0.256 \times 5.16 = 1.32 \text{ MPa} \]
7. Slabs on ground

- Slabs on ground are designed according to ACI 360R specifications.
- Steel fibers are typically used at a dosage rate between 10 and 36 kg/m³ as the sole reinforcement.
- Synthetic fibers are used at a dosage rate between 1.8 and 4.5 kg/m³ as the sole reinforcement.
- The residual strength of FRC is used for design and specifying FRC slabs.
5. Design for shear

- As per ACI 318, if used in lieu of stirrups in flexural members, steel fibers must have an aspect ratio between 50 and 100 and provide a minimum of $R_{D,150}^T$ of 75% when tested according to ASTM C1609 (ACI 318 sec 5.6.6).

- Altoubat et al. (2015) have shown that synthetic macrofibers can also provide the required shear resistance in flexural members when used at a proper dosage rate.

- For members with conventional longitudinal reinforcement but without shear reinforcement, the shear capacity for FRC is given by (Model Code 2010 sec 7.7.3.2):

$$V_{Rd,F} = \left\{ \frac{0.18}{\gamma_c} k \left[ 100 \rho_l \left( 1 + 7.5 \frac{f_{Ftu}}{f_{ctk}} \right) f_{ck} \right]^{\frac{1}{3}} + 0.15 \sigma_{cp} \right\} \times b_w \ d$$

- For members with conventional longitudinal reinforcement and shear reinforcement, the contribution of fibers can be added to the equation: $V_{Rd} = V_{Rd,F} + V_{Rd,s}$
Macro Synthetic Fiber Improve Shear Strength of RC Beams

Shear Strength of Beams reinforced with synthetic macro fibers,” Eighth RILEM Conference on fiber reinforced Concrete BEFIB2012, Portugal, 2012
**fib-MC2010 Formulations**

\[ V_{Rd} = V_{Rd,F} + V_{Rd,s} \]

- Fibers contributions embedded in concrete
- Fiber contribution depends on residual tensile strength
- Formulas based on characteristic properties

\[ V_{Rd,F} = \left[ \frac{0.18}{\gamma_c} \cdot k \cdot 100 \rho_l \left( 1 + 7.5 \frac{f_{Ftuk}}{f_{ck}} \right) \cdot f_{ck} \right]^{\frac{1}{3}} + 0.15\sigma_{cp} b_w d \]

\[ f_{Ftu}(w_u) = f_{Fts} - \frac{w_u}{2.5} (f_{Fts} - 0.5.f_{R3} + 0.2.f_{R1}) \geq 0 \]

\[ f_{Ftuk} = 0.51 f_{Ftu} \]

\[ f_{Fts} = 0.45 f_{R,1} \]

Based on linear post-cracking behavior constitutive model

\[ f_{R,j} = \frac{3F_j L}{2bh_{sp}^2} \]
Residual Flexural Tensile Strength Parameters (EN 14651)

<table>
<thead>
<tr>
<th>$j$</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
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</thead>
<tbody>
<tr>
<td>CMOD$_j$</td>
<td>0.5</td>
<td>1.5</td>
<td>2.5</td>
<td>3.5</td>
</tr>
<tr>
<td>$F_{R,j}$ (MPa) for $V_f =0.5%$</td>
<td>1.94</td>
<td>1.80</td>
<td>1.63</td>
<td>1.43</td>
</tr>
<tr>
<td>$F_{R,j}$ (MPa) for $V_f =0.75%$</td>
<td>2.36</td>
<td>2.28</td>
<td>2.06</td>
<td>1.80</td>
</tr>
<tr>
<td>$F_{R,j}$ (MPa) for $V_f =1.0%$</td>
<td>2.66</td>
<td>2.62</td>
<td>2.37</td>
<td>2.06</td>
</tr>
</tbody>
</table>
Analysis: Prediction versus Experimental

• fib-MC2010 and RILEM can be both safely used to predict shear strength of SNFRC
• The fib-MC2010 predict shear strength of long beams with reasonable accuracy but is more conservative for short beams
Thank you!

SCMASS
Prof. Salah Altoubat
Coordinator
saltoubat@sharjah.ac.ae