# Mechanisms of Hooked Steel Fiber Reinforced Concrete

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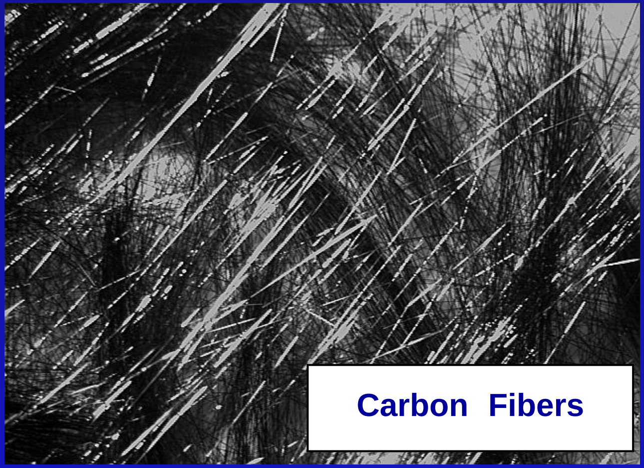
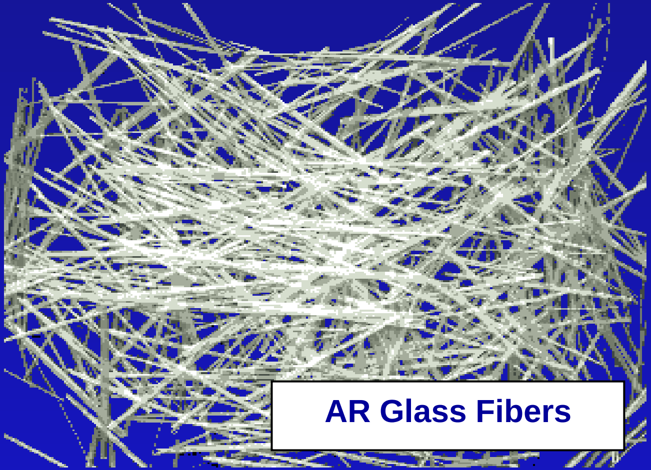
# Fiber Types

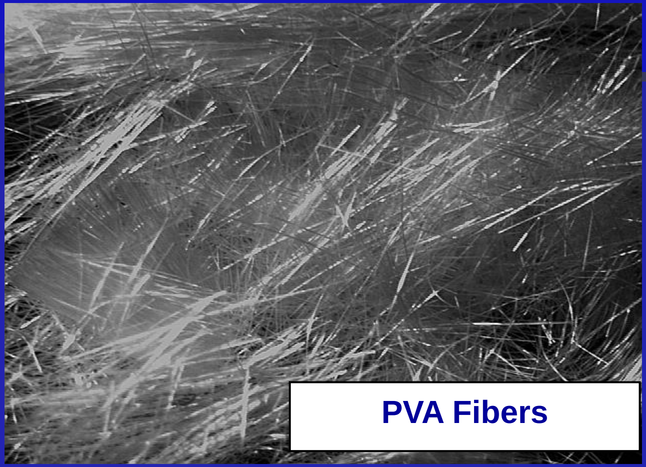
- Natural - asbestos, wood, sisal, kenaf
- Synthetic - steel, glass (E-glass, AR glass), Polypropylene, PVA, Spectra, Nylon

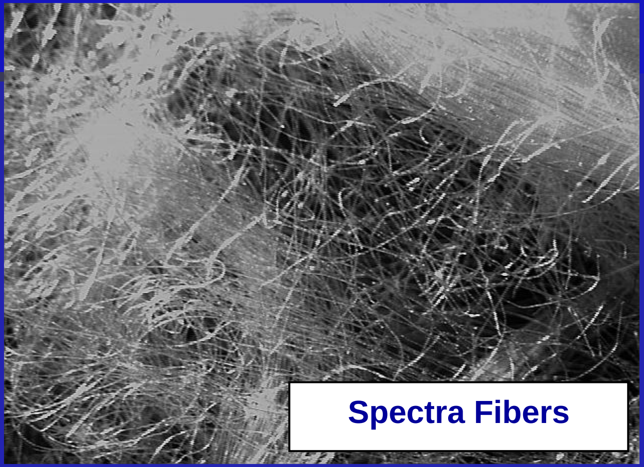
| Fiber Name | Diameter (mm) | Length (mm) | Specific Gravity | Elastic Modulus (GPa) | Tensile Strength (MPa) |
|---|---|---|---|---|---|
| Carbon | 0.009 - 0.01 | 6.35 | 1.90 | 241 | 2825 |
| PVA | 0.040 | 6.0 | 1.31 | 139 | 1010 |
| Spectra | 0.038 | 12.7 | 0.97 | 117 | 2585 |

# Some Synthetic Fibers

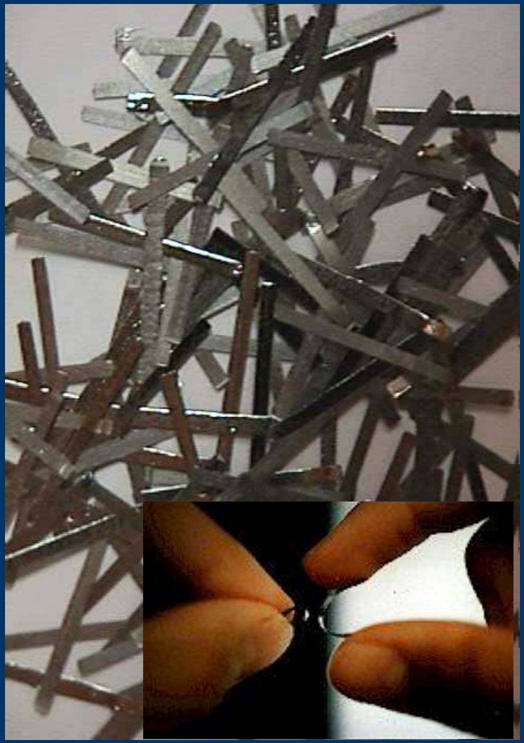


# Some Commercial Steel Fibers

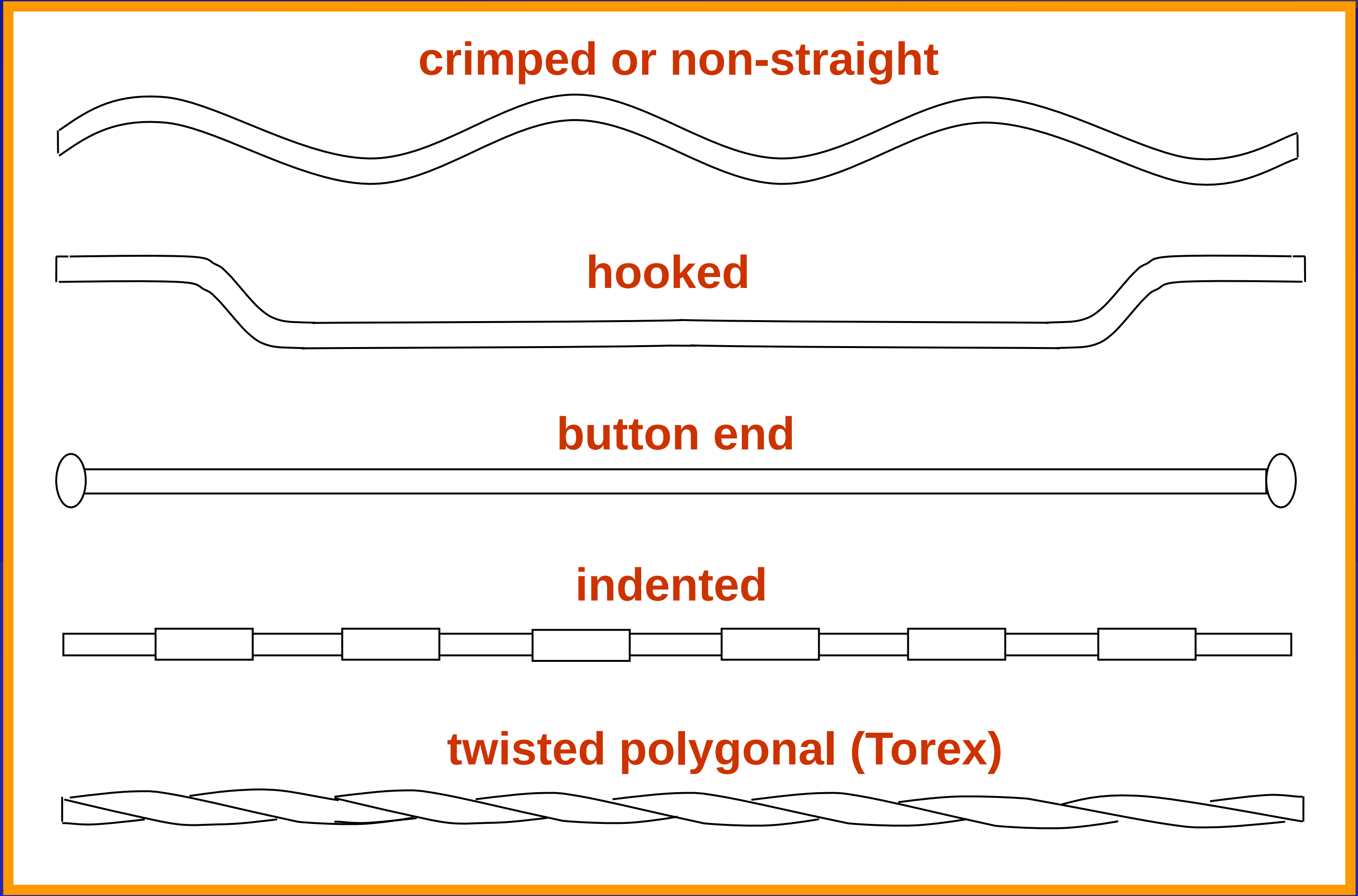


Fibraflex Fibers
0.024 x 1 x 15 mm.

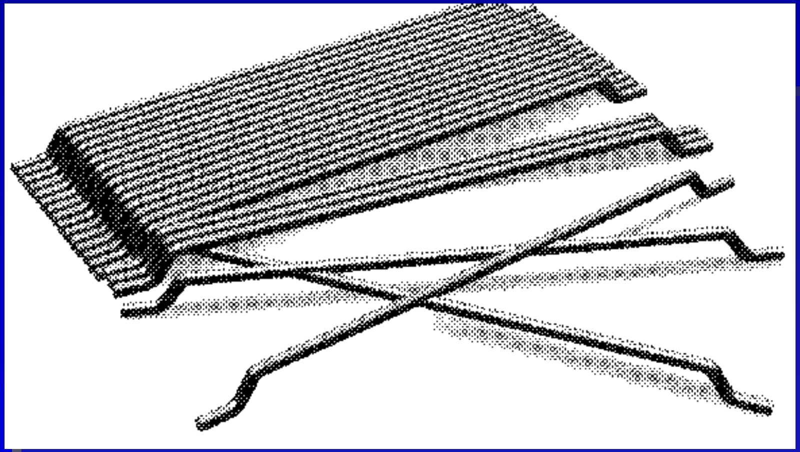
Hooked Steel Fibers
(Dramix)
d = 0.5 mm., L = 30 mm.

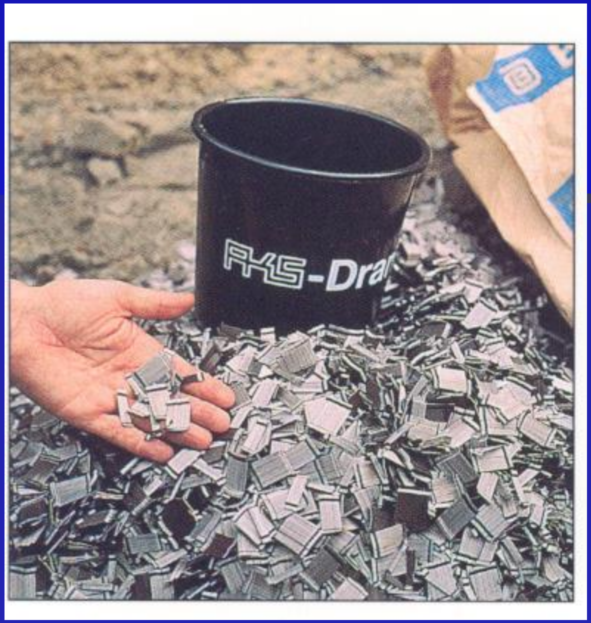
Straight Steel Fibers
(Fibercon)
0.25 x 0.75 x 25 mm

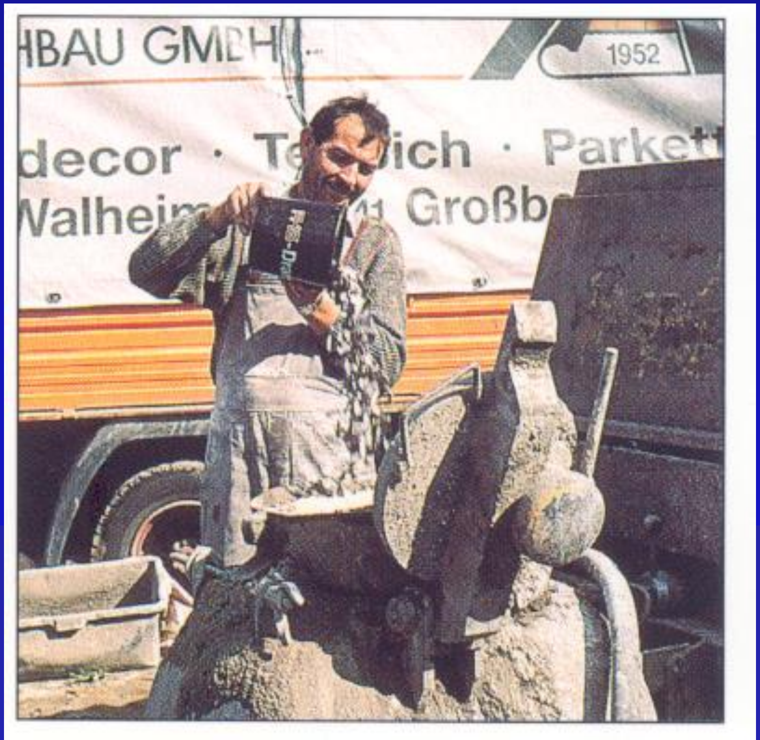
# Deformed Steel Fibers
# To Enhance Mechanical Bond



# Dramix Hooked Steel Fibers







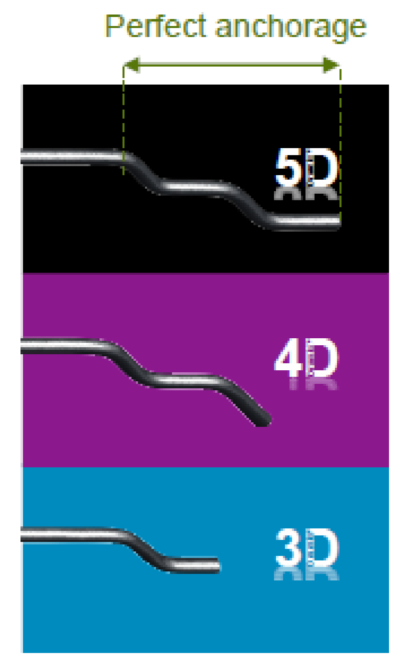

Adding Fibers into the Mixer

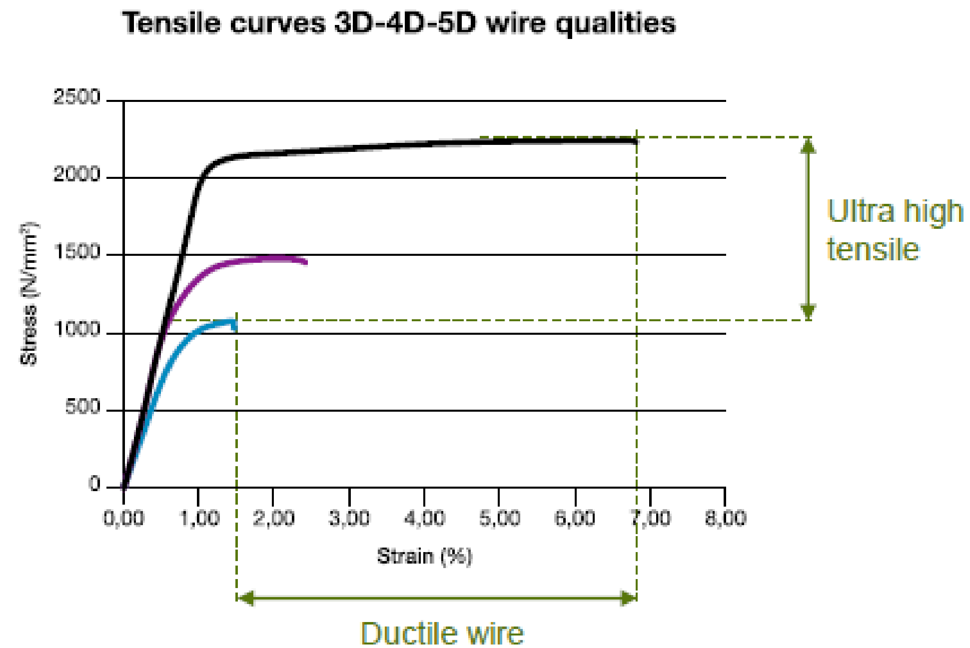
# New Product of Hooked Steel Fibers in 2012

Perfect anchorage

+ Ultra high tensile

+ Ductile wire



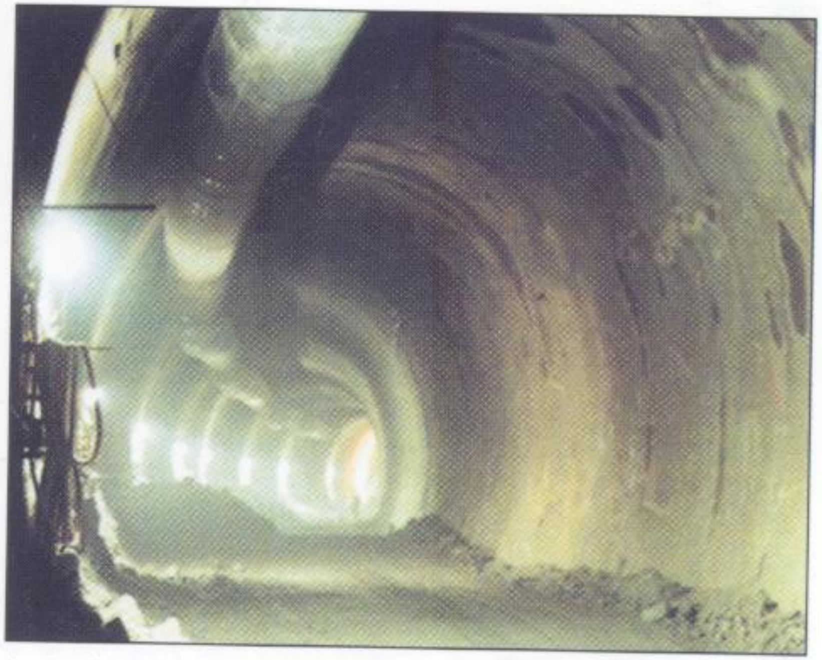
# Some Applications on FRC

# Application: Floor / Pavement

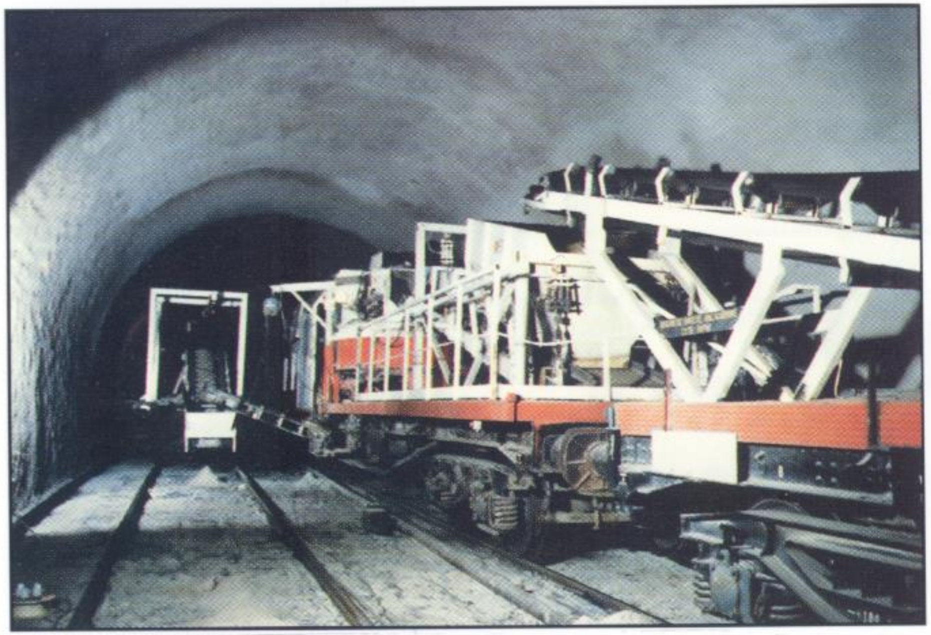
Coldstore (Holland)

*Precast panels + Dramix® Duo 100*

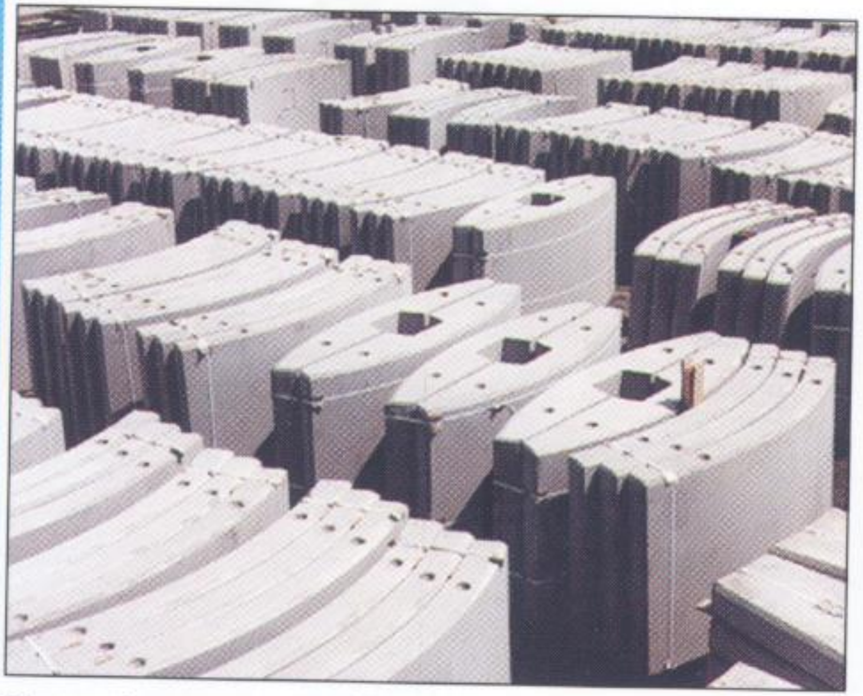
# Application: Tunneling & Mining



Interior lining of a tunnel (Germany)

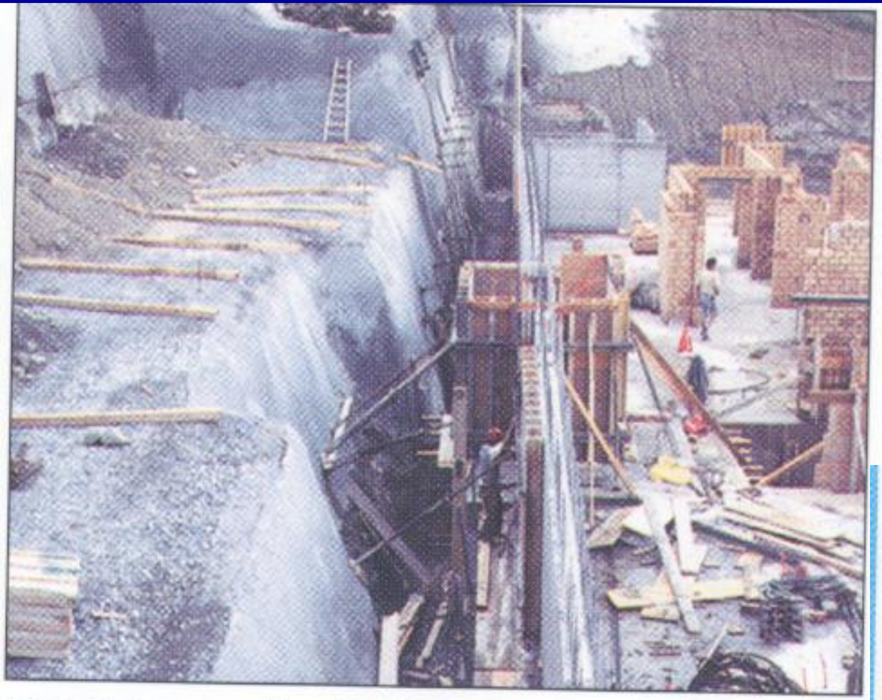


Railway tunnel - Laifour (France).

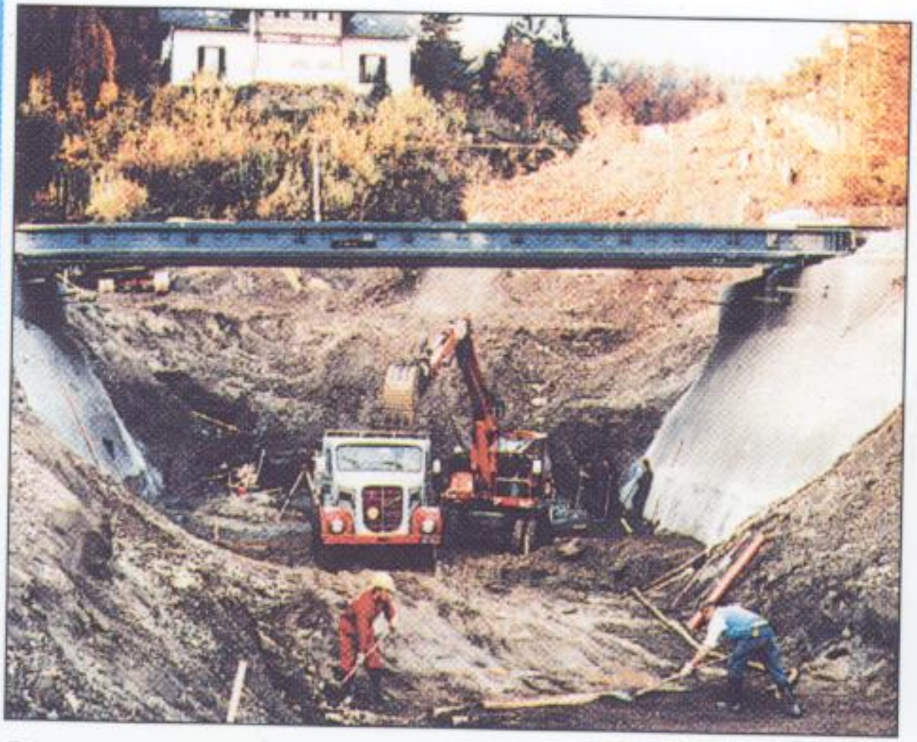


Tunnel segments (England)

Rail tunnel (England)



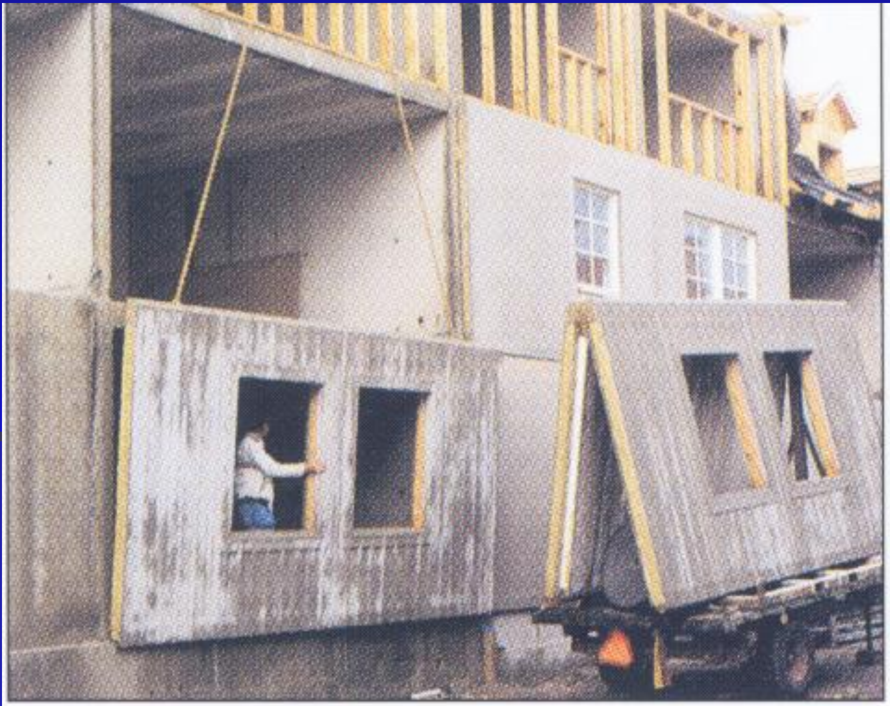
Retaining walls (Switzerland)



Slope stabilization (Austria)

# Application:  Precast Concrete

Water purification  (Austria)



Facade panels  (Sweden)

# SFRC Pipe : With different machinery


Fibre type: RC-80/60-BN
System : Vihy supermatic
Country: Spain


Fibre type: RC-65/40-CN
System : Croci
Country: Italie

# SFRC Drainage element


Fibre type: RC-80/60-CP
Concrete : SCC 70/65
Country: Belgium



Fibre type: OL 6/16
Concrete : C 60/70
Country: Turkey

# SFRC Substations Cabins

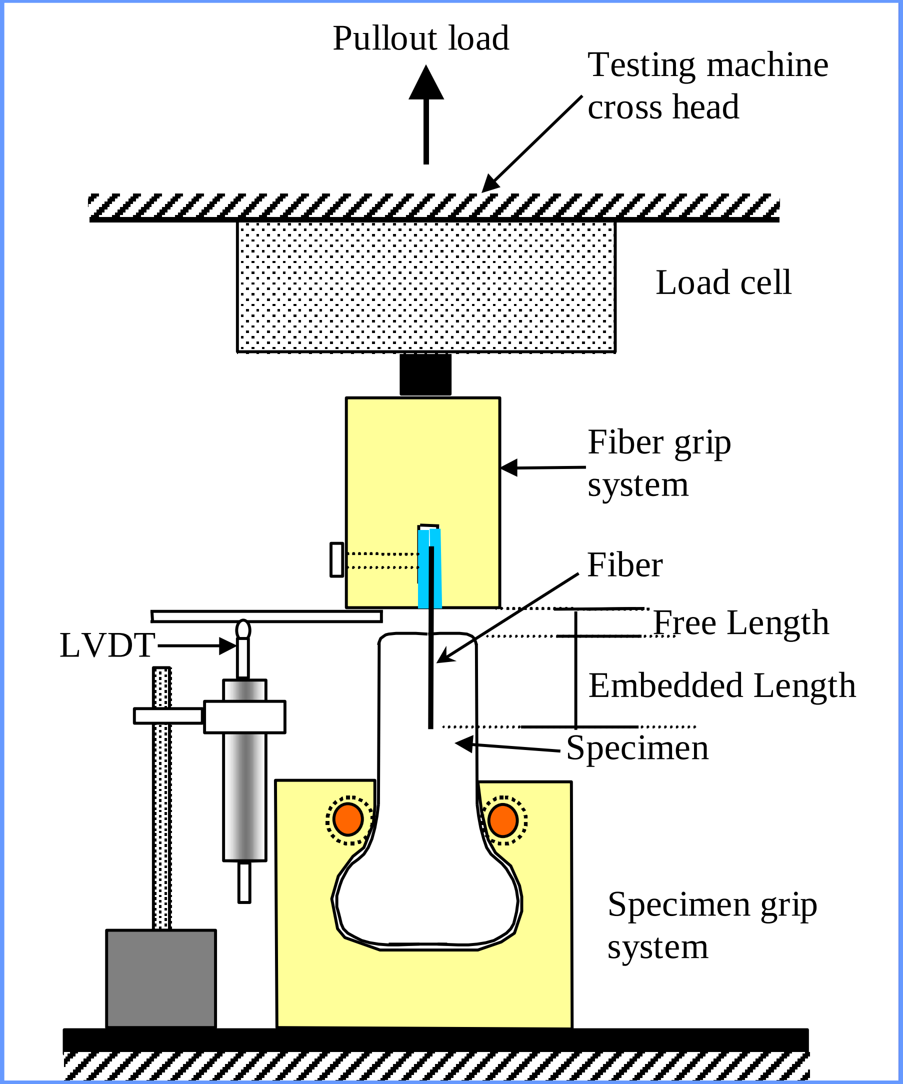

Fibre type: RC-80/60-CN
Concrete: C35/45
Country: Sweden


Fibre type: RC-80/60-CN
Concrete: C 35/45
Country: France

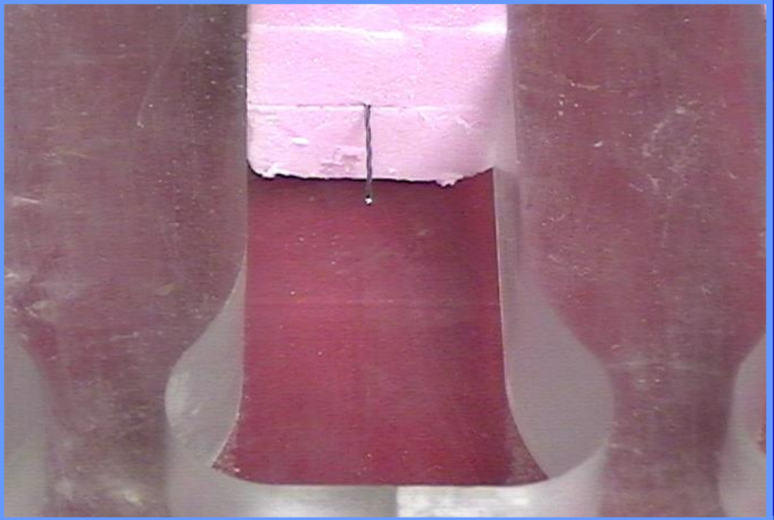
# Bond Mechanisms Between Fiber and Matrix

# Single Fiber Pullout Tests

## Pullout Setup




## Mold and Pullout Specimens



# Components of Bond

(1) Physical and/or Chemical Adhesion

(2) Frictional Resistance

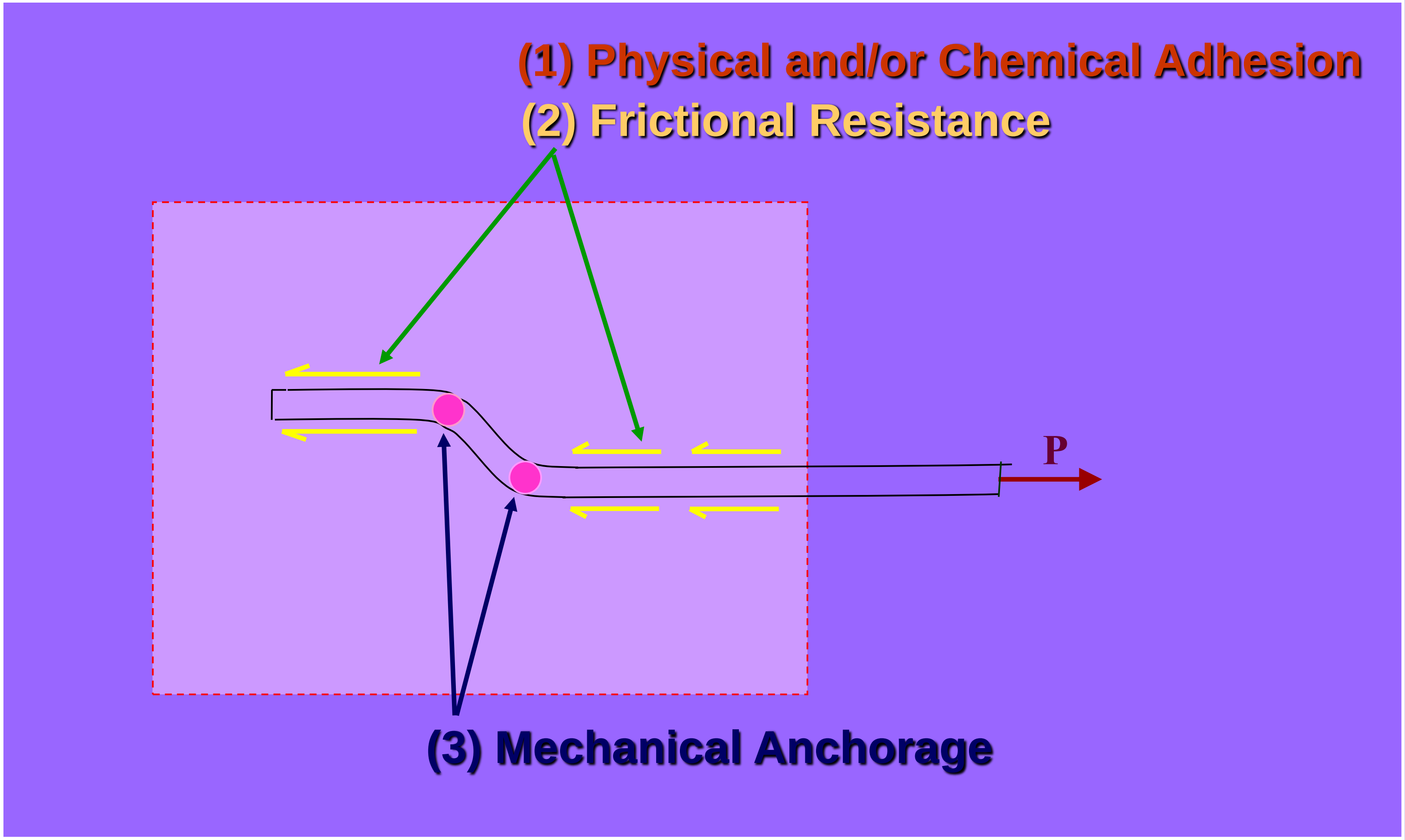
(3) Mechanical Anchorage

Due to particular geometry or deformation of the fibers such as in Torex, twisted wire strand or hooked fibers

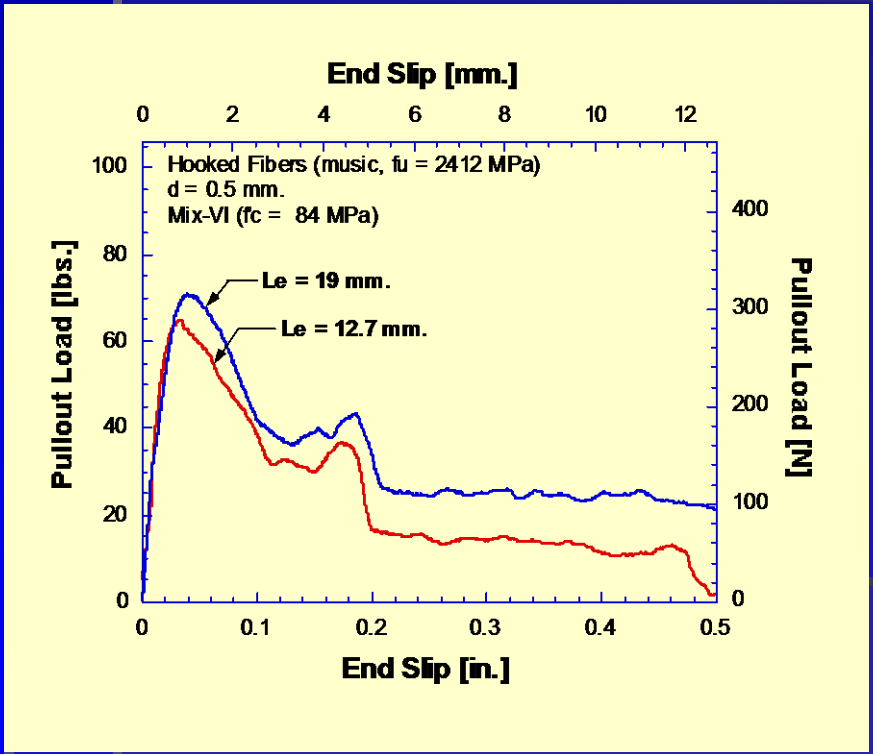
(4) Fiber-to-Fiber Interlock or Entanglement

Existing at very high fiber contents such as in the case of SIFCON

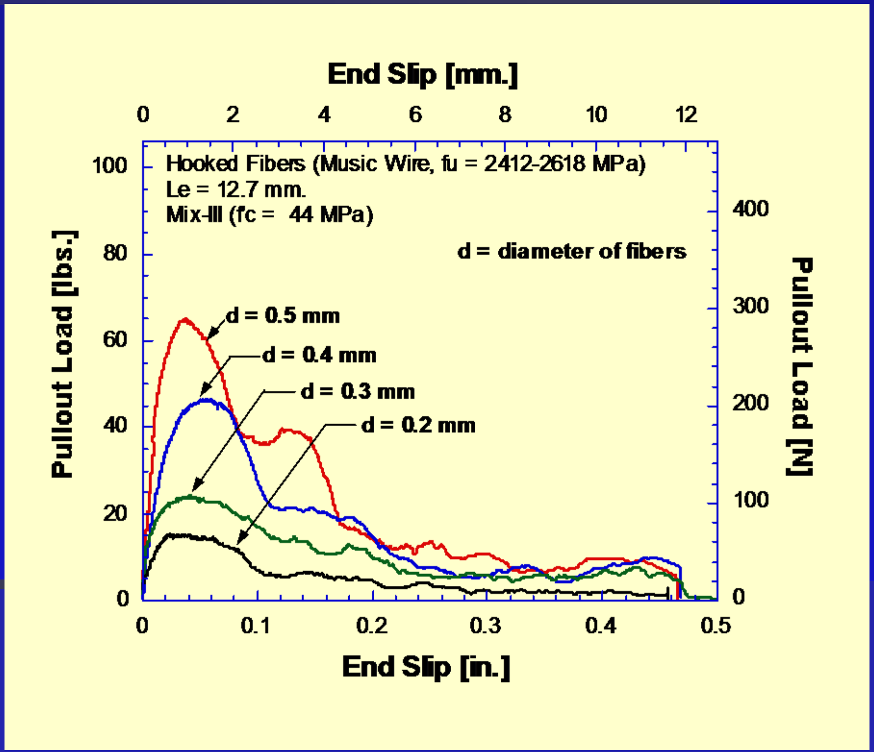
# Components of Bond
## (During Single Pull-out Of Hooked Fiber)



# Results from Pullout Tests of Hooked Steel Fibers

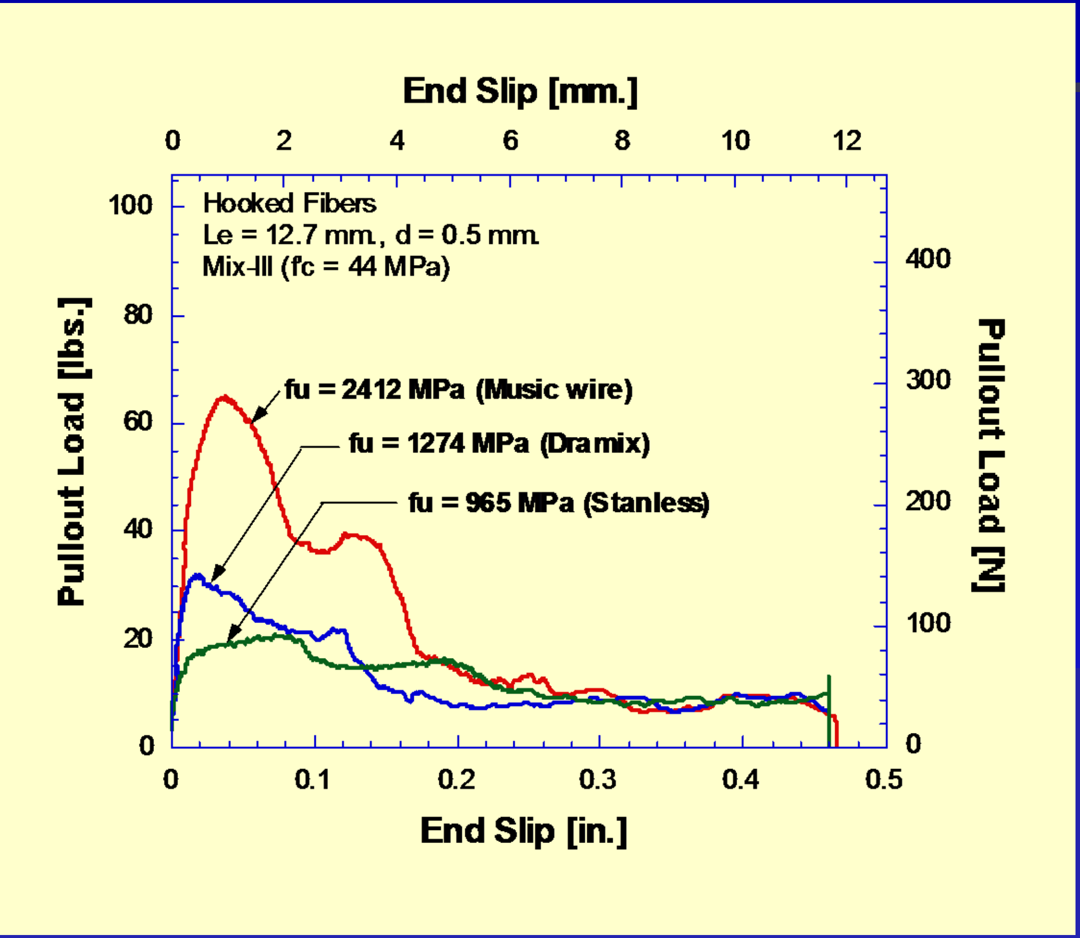



Influence of Fiber Embedded Lengths




Influence of Fiber Sizes

# Results from Pullout Tests of Hooked Steel Fibers (cont.)




Influence of Tensile Strength of Fibers

# Summary of Tested Results from Pullout Tests of Hooked Steel Fibers

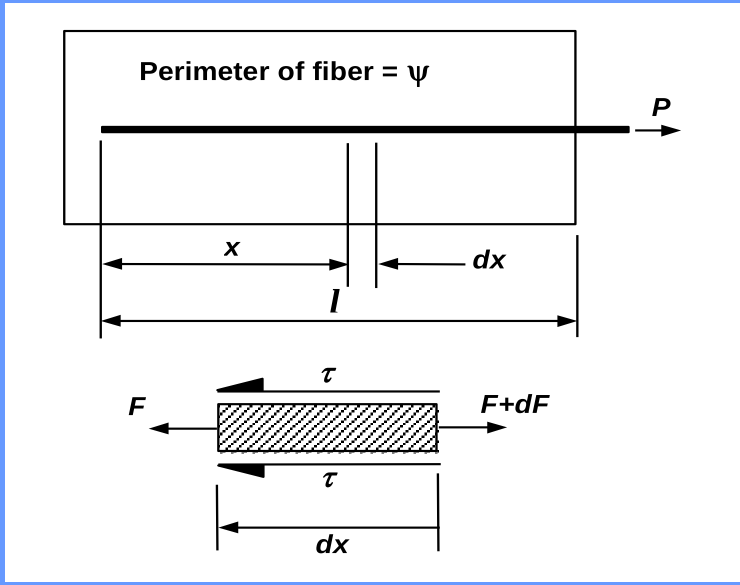
| Series ID | Diameter [mm.] | $f_u$ [MPa] | $L_e$ [mm.] | Matrix | Average P1 | | Average P2 | |
|---|---|---|---|---|---|---|---|---|
| | | | | | Load [N] | % of $f_u$ [%] | Load [N] | % of $f_u$ [%] |
| 1 | 0.2 | 2618[a] | 12.7 | Mix-III | 61.4 | 72 | 33 | 39 |
| 2 | 0.3 | 2618[a] | 12.7 | Mix-III | 106.7 | 56 | 62.3 | 33 |
| 3 | 0.4 | 2618[a] | 12.7 | Mix-III | 213.5 | 64 | 112.5 | 34 |
| 4 | 0.5 | 716[b] | 12.7 | Mix-III | 91.6 | 63 | 65.8 | 46 |
| 5 | | 1274[c] | 12.7 | Mix-III | 135.6 | 56 | 106.7 | 43 |
| 6 | | 1274[c] | | Mix-VI | Fiber fails in tension | | | |
| 7 | | 1274[c] | 25.4 | Mix-III | 148.1 | 61 | 122.3 | 50 |
| 8 | | 2412[a] | 12.7 | Mix-III | 272.2 | 56 | 177.0 | 36 |
| 9 | | | | Mix-VI | 282.8 | 58 | 173.4 | 35 |
| 10 | | | 19 | Mix-VI | 310.0 | 64 | 197.0 | 40 |

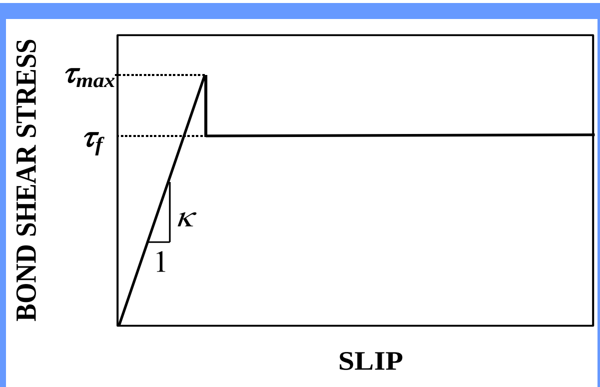
[a] Music steel wire; [b] Stainless steel wire # 1; [c] Commercial Dramix hooked fibers

# Analytical Models to Predict Pull-Out Curves of Steel Fibers

## For Smooth Steel Fibers

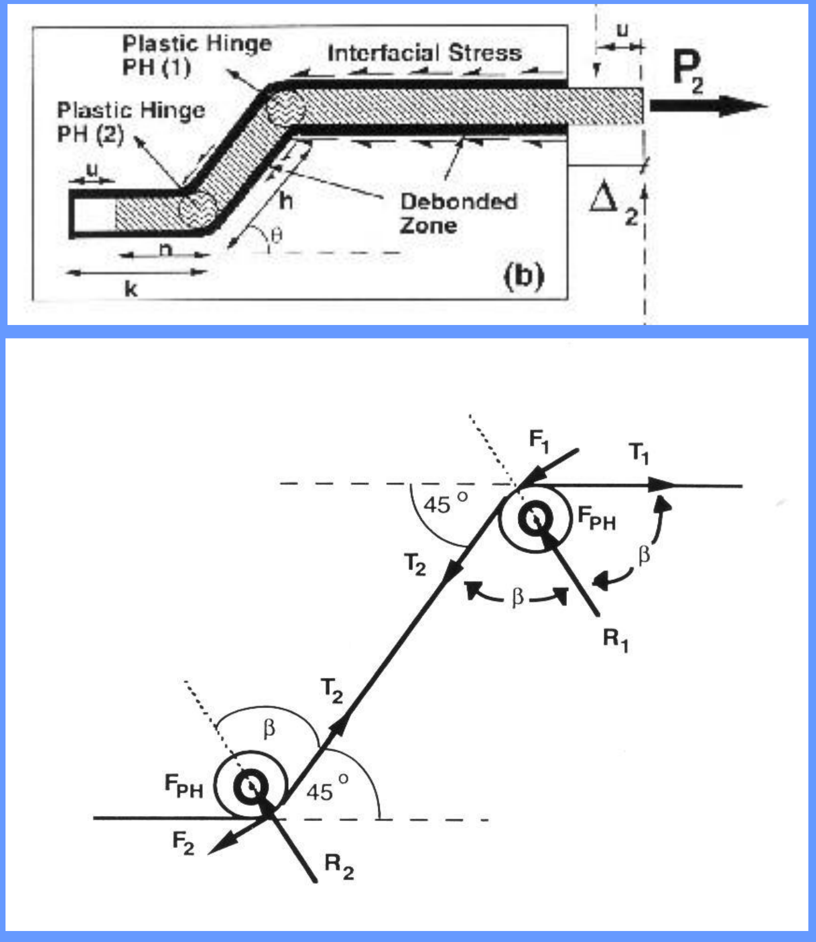
Naaman A. E., Namur G. G., Alwan J. M., and Najm H. S. (1991)




## For Hooked Steel Fibers

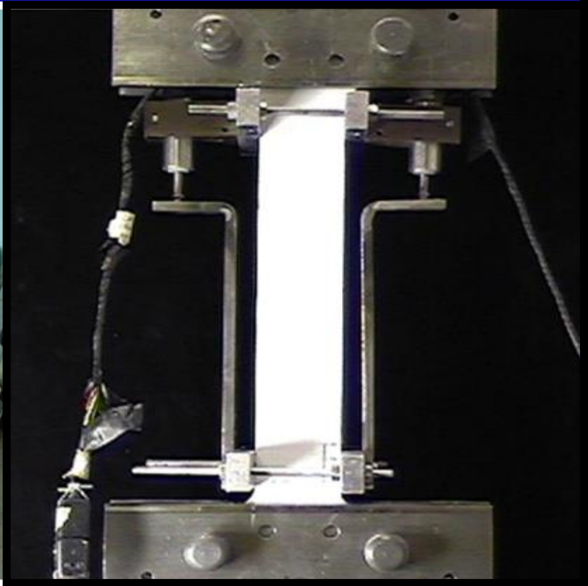
Alwan J. M., Naaman A. E., and Guerrero P. (1999)



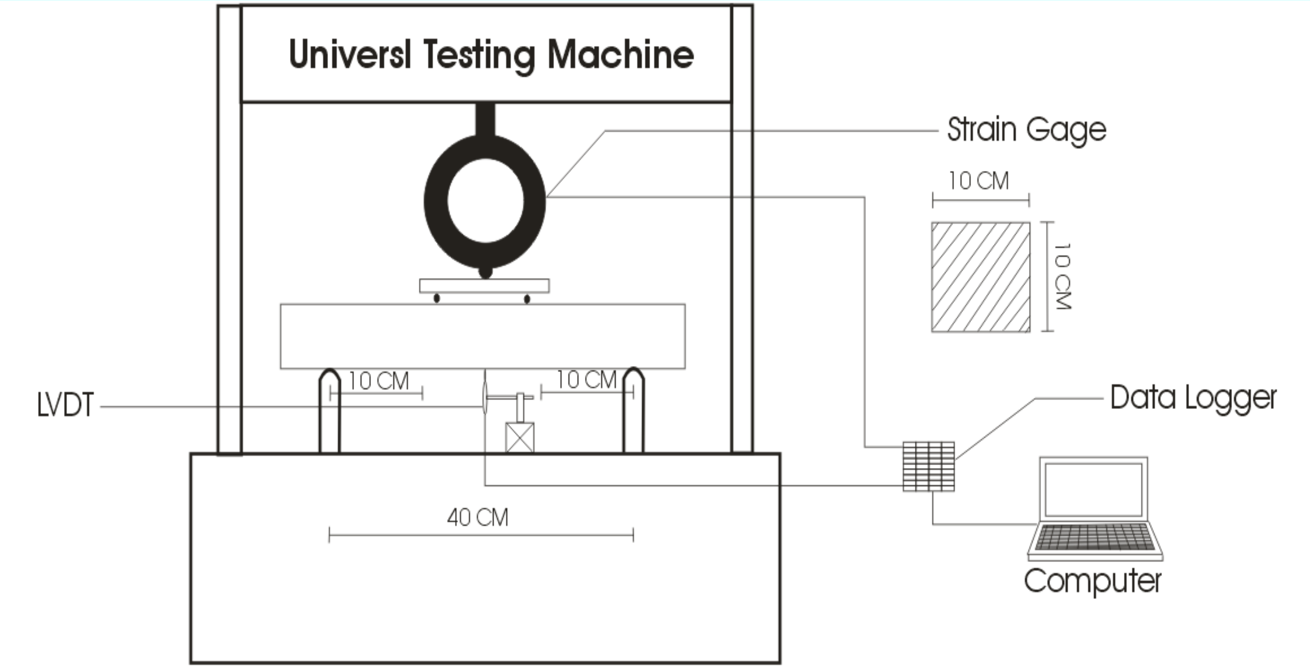
# Tension/ Flexural Mechanisms of Hooked Fiber Reinforced Concrete

# Tensile Test Setup

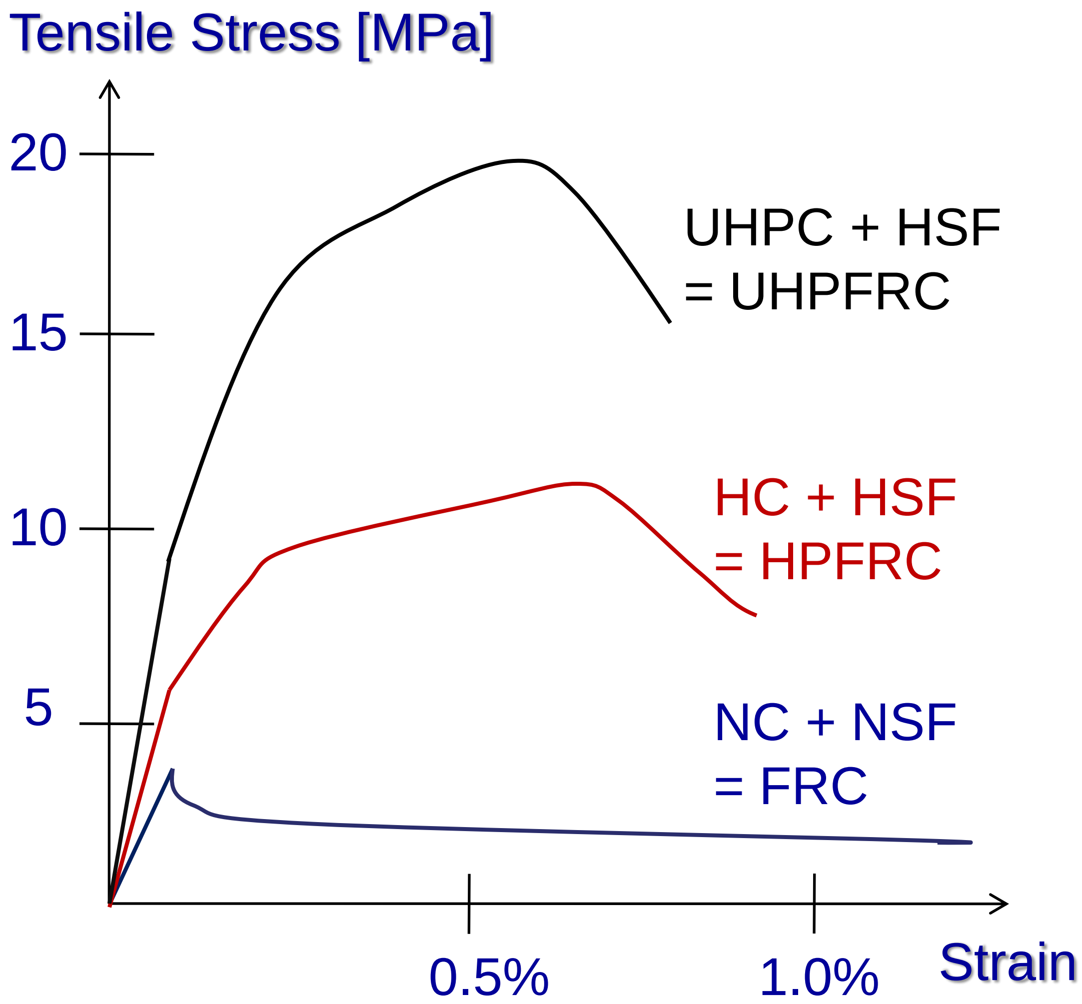
- The size are 5x5 cm in cross section and 50 cm in length
- All specimens are cured in water at 28 days
- The elongation of the tensile specimens was measured using the average recording of 2 symmetrically placed LVDTs over a gauge length of 20 cm.

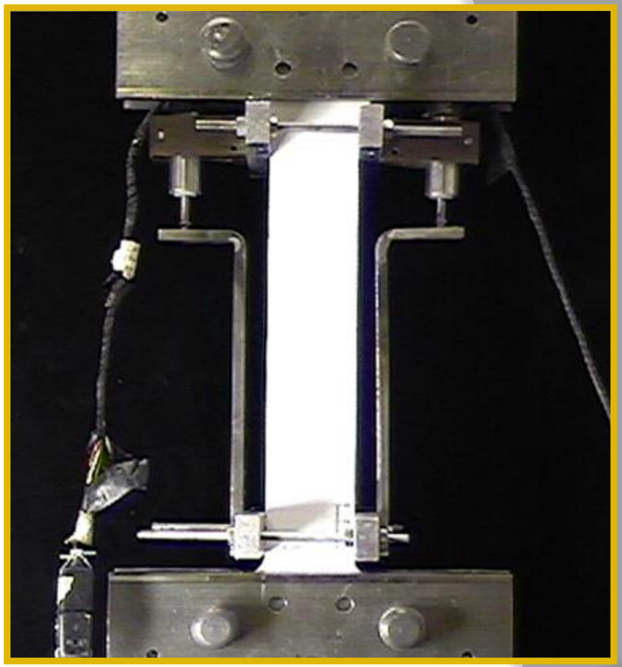


# Bending Test Setup




# Tensile Behavior: Concrete with Steel Fibers

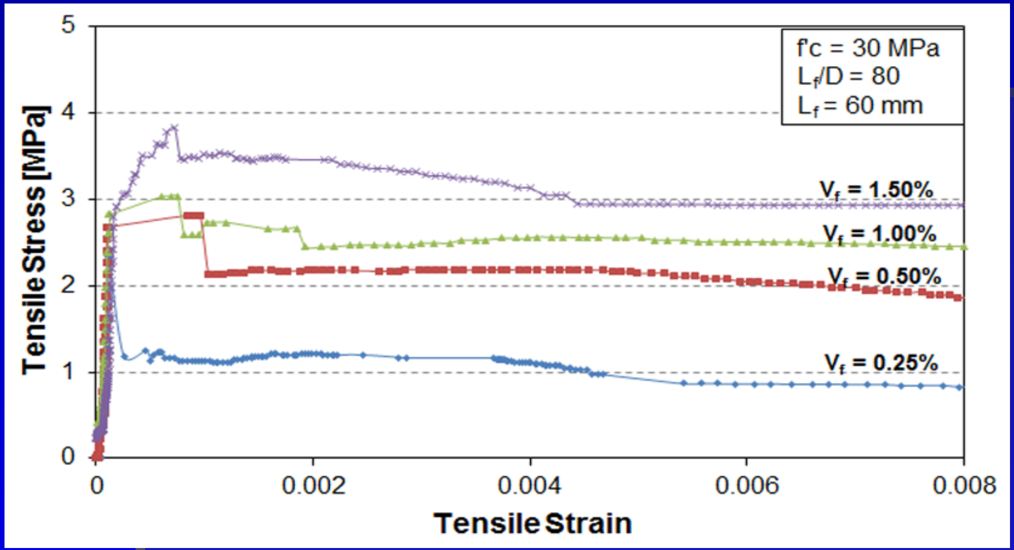


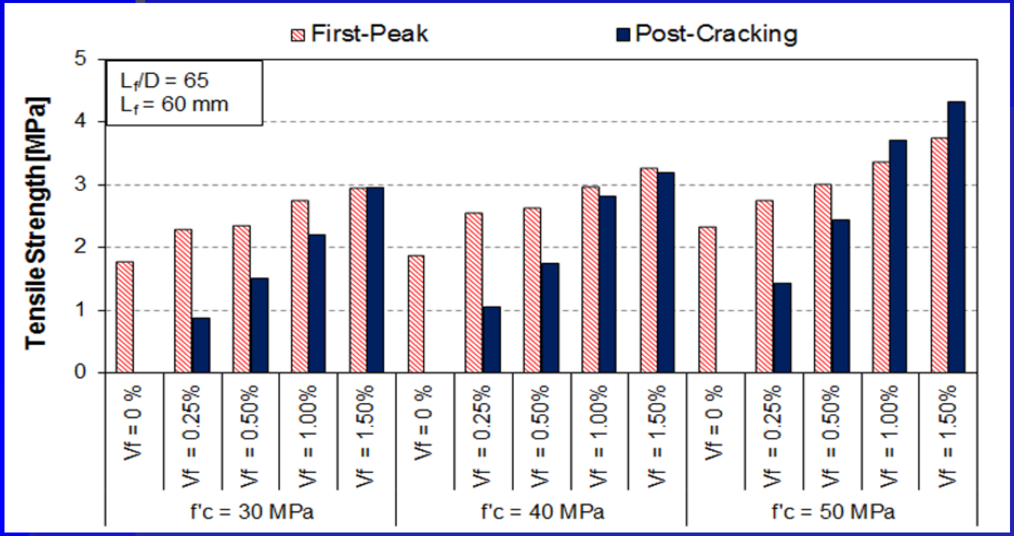



**NC = Normal Strength Concrete**
**HC = High Strength Concrete**

**NSF = Normal-Strength Steel Fibers**
**HSF = High-Strength Steel Fibers**

# Effect of Volume Fraction of Fibers



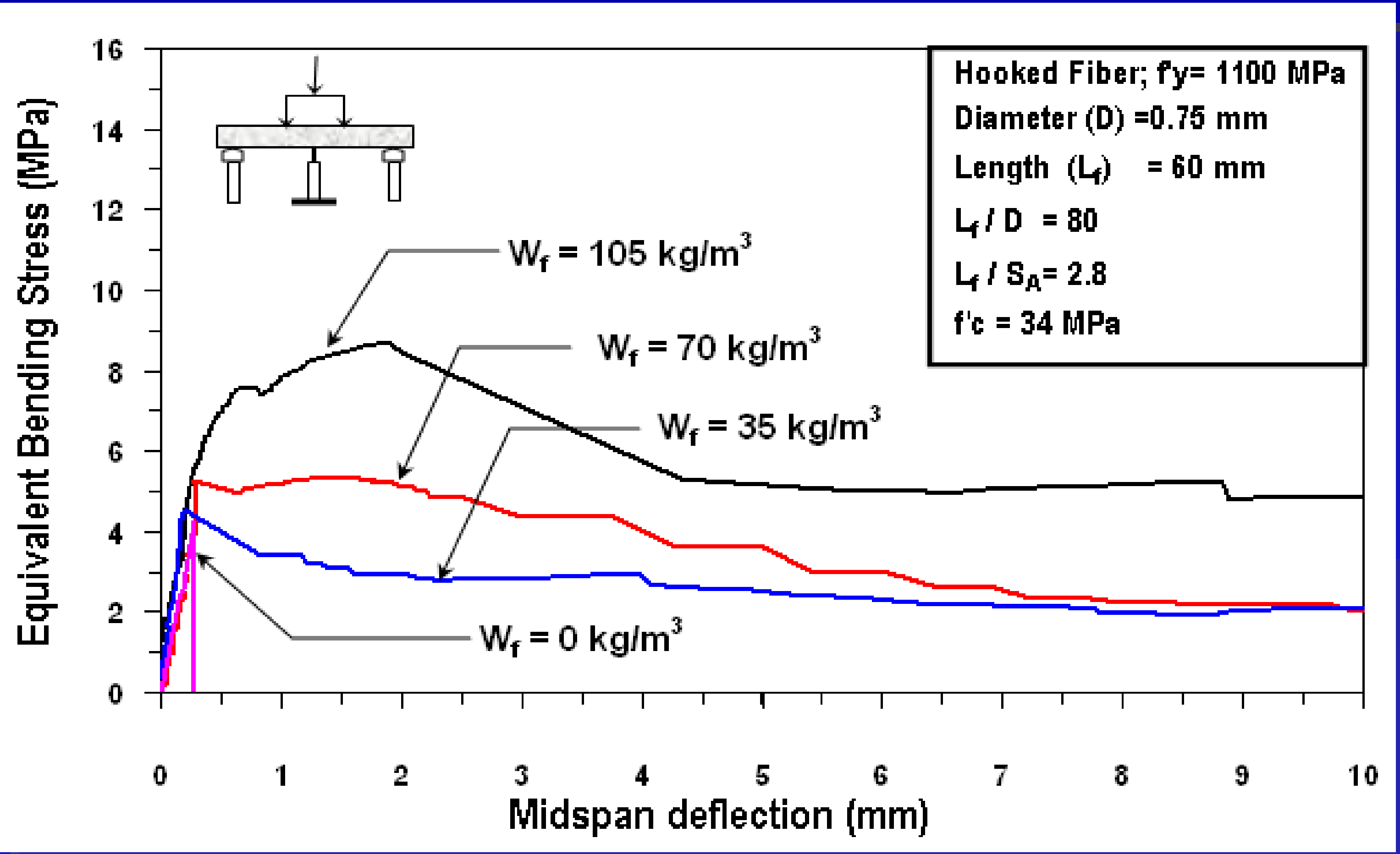

Increase in $V_f$ leads to

- an increase in first-peak strength
- a significant increase in post-cracking strength

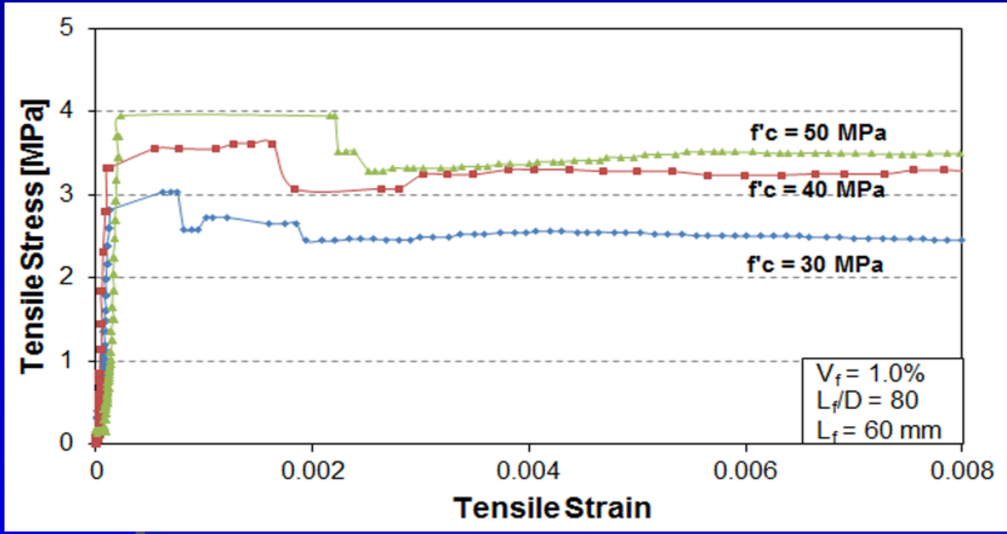
Linear relationship between post-peak strength and $V_f$ is NOT observed

HPFRCC can be obtained when higher $V_f$ and $f'_c$ are used

# Effect of Volume Fraction of Hooked Fibers

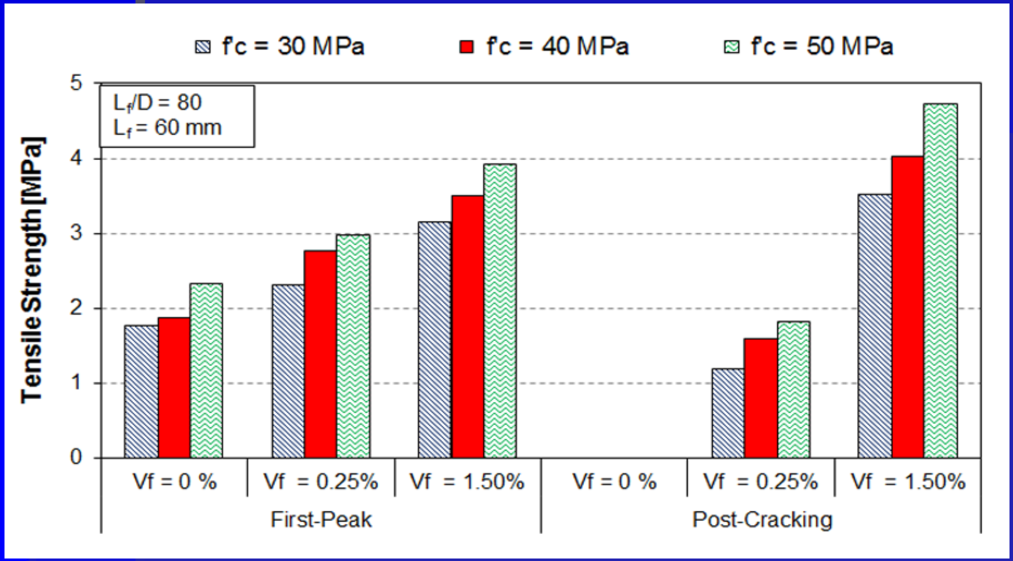


# Effect of Compressive Strength of Concrete



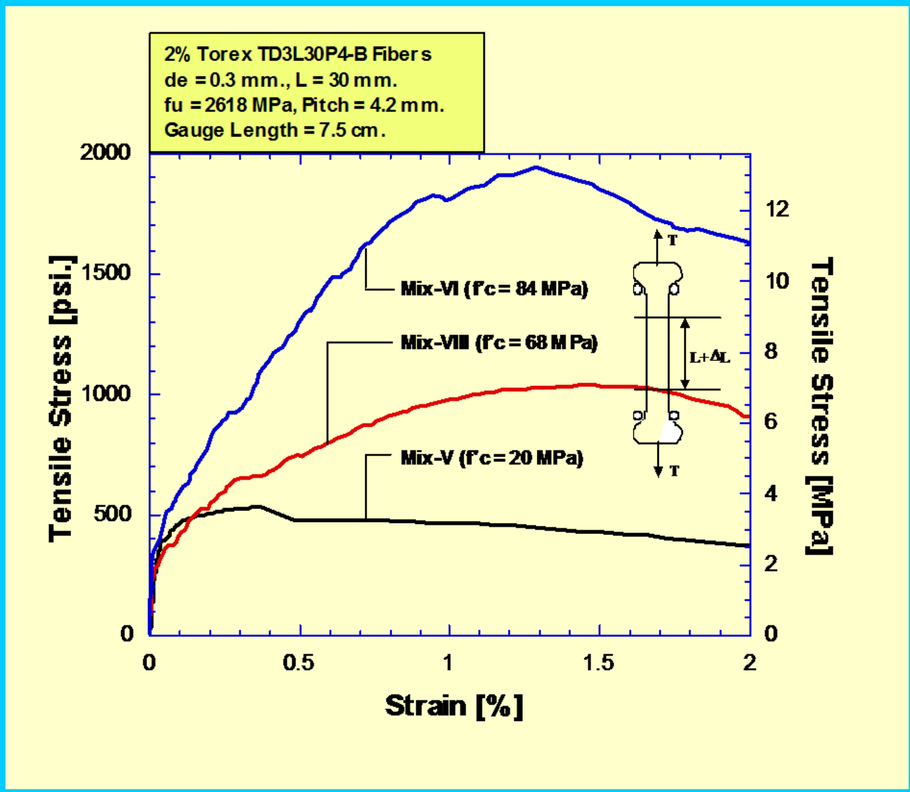

Increase in $f'_c$ leads to

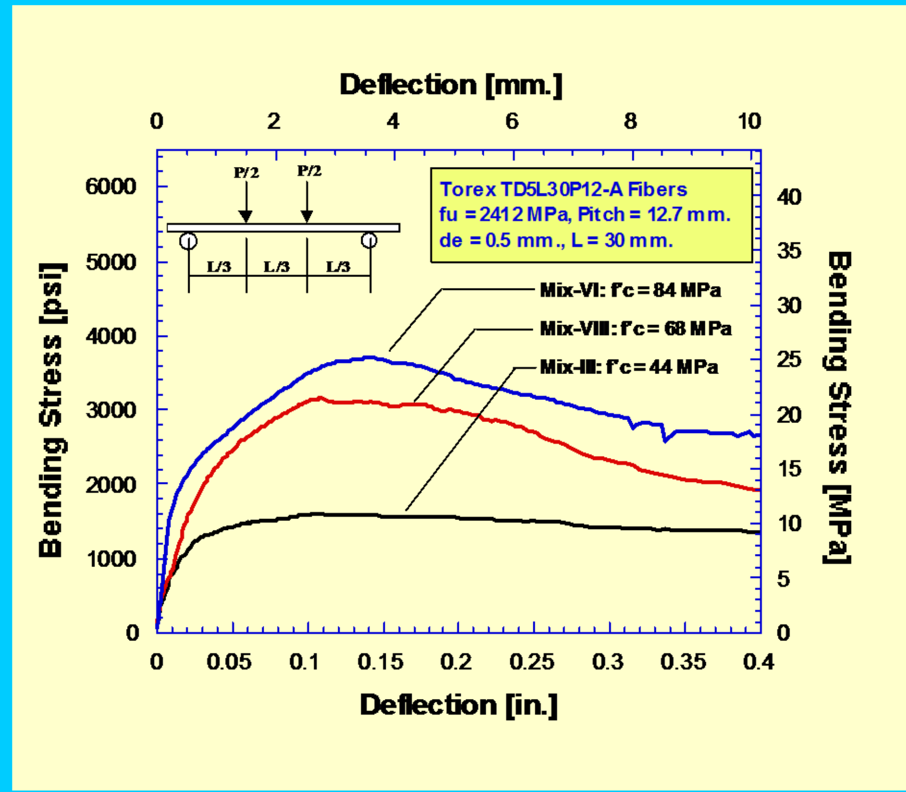
- increase in first-peak strength
- increase in post-cracking strength



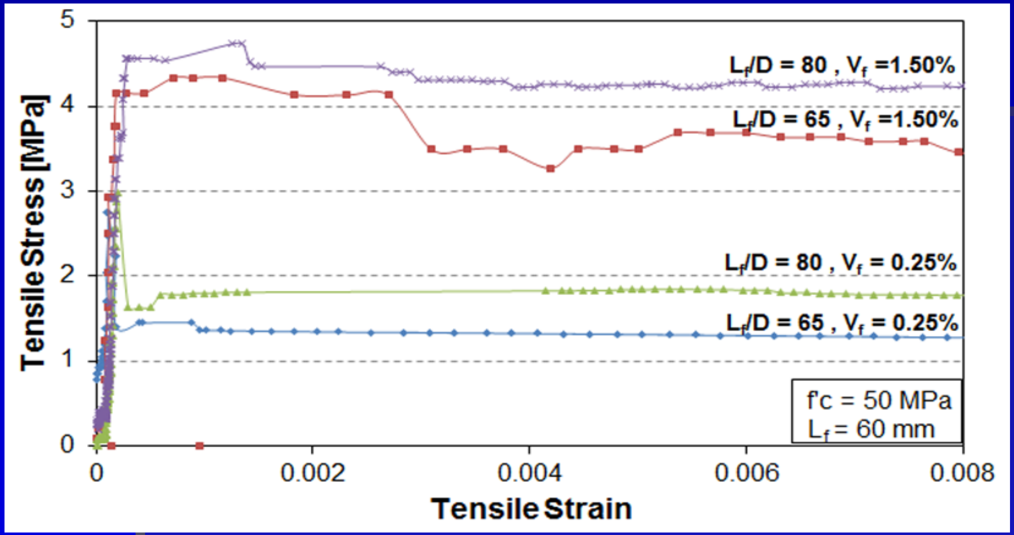

Post Strength increases Because an increase in compressive strength of concrete enhances the bond between fiber and concrete

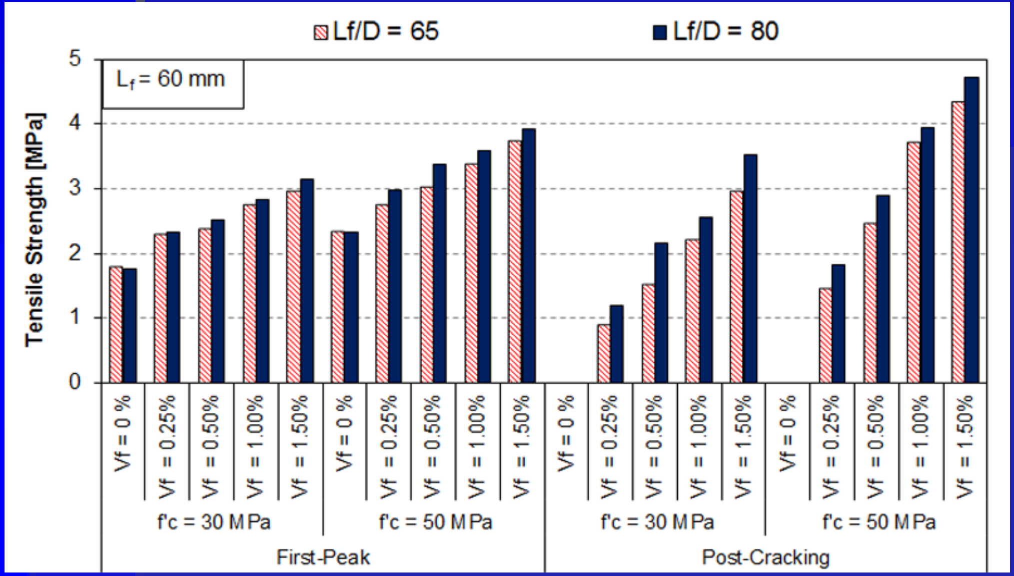
# Effect of Matrix Compressive Strength



# Effect of Aspect Ratio of Fibers ($L_f/D$)



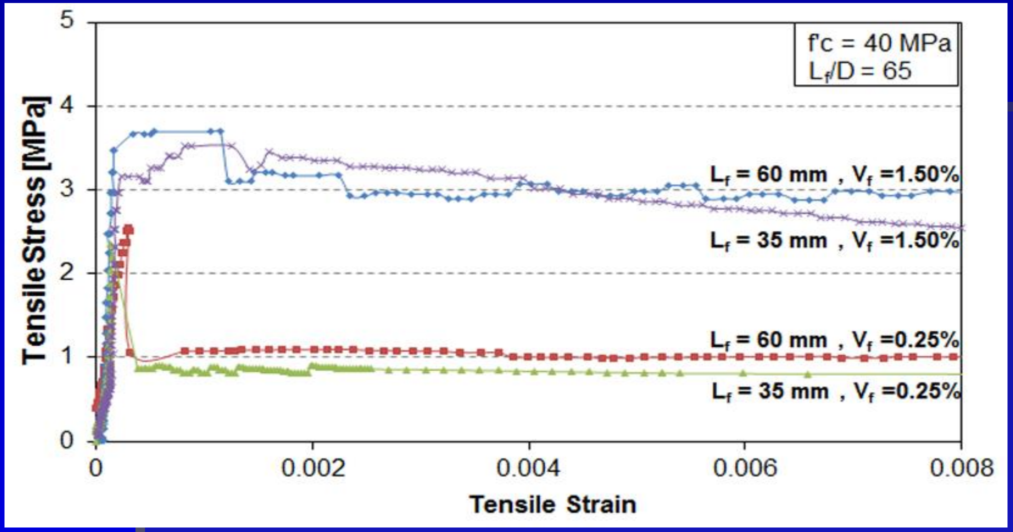



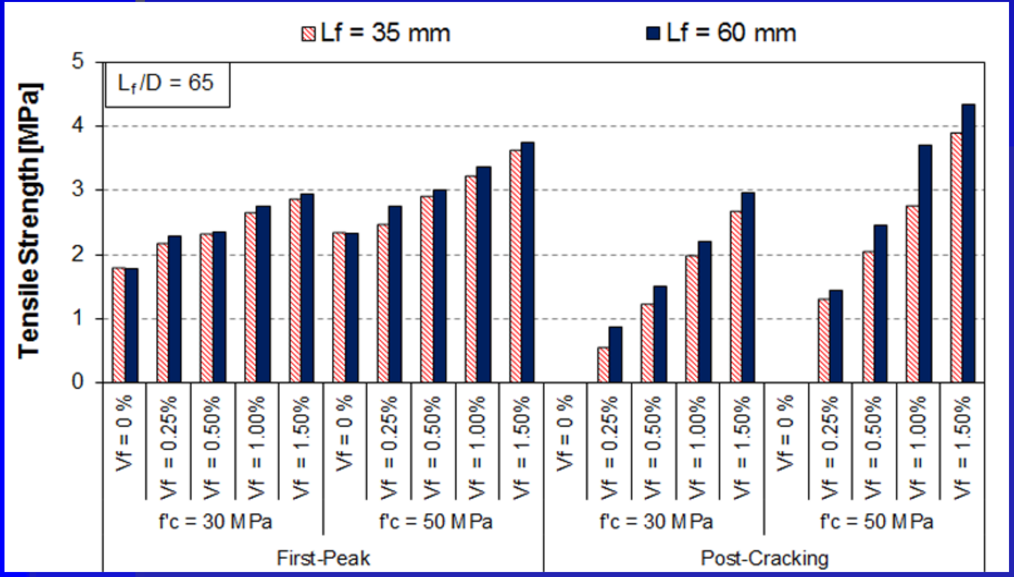

Increase in $L_f/D$ leads to

- A very slight increase in first-peak strength and some specimens do not present any improvement
- increase in post-cracking strength

The reason of improvement is related to an increase in frictional bond when the longer fiber is used

# Effect of Fibers Lengths ($L_f$)



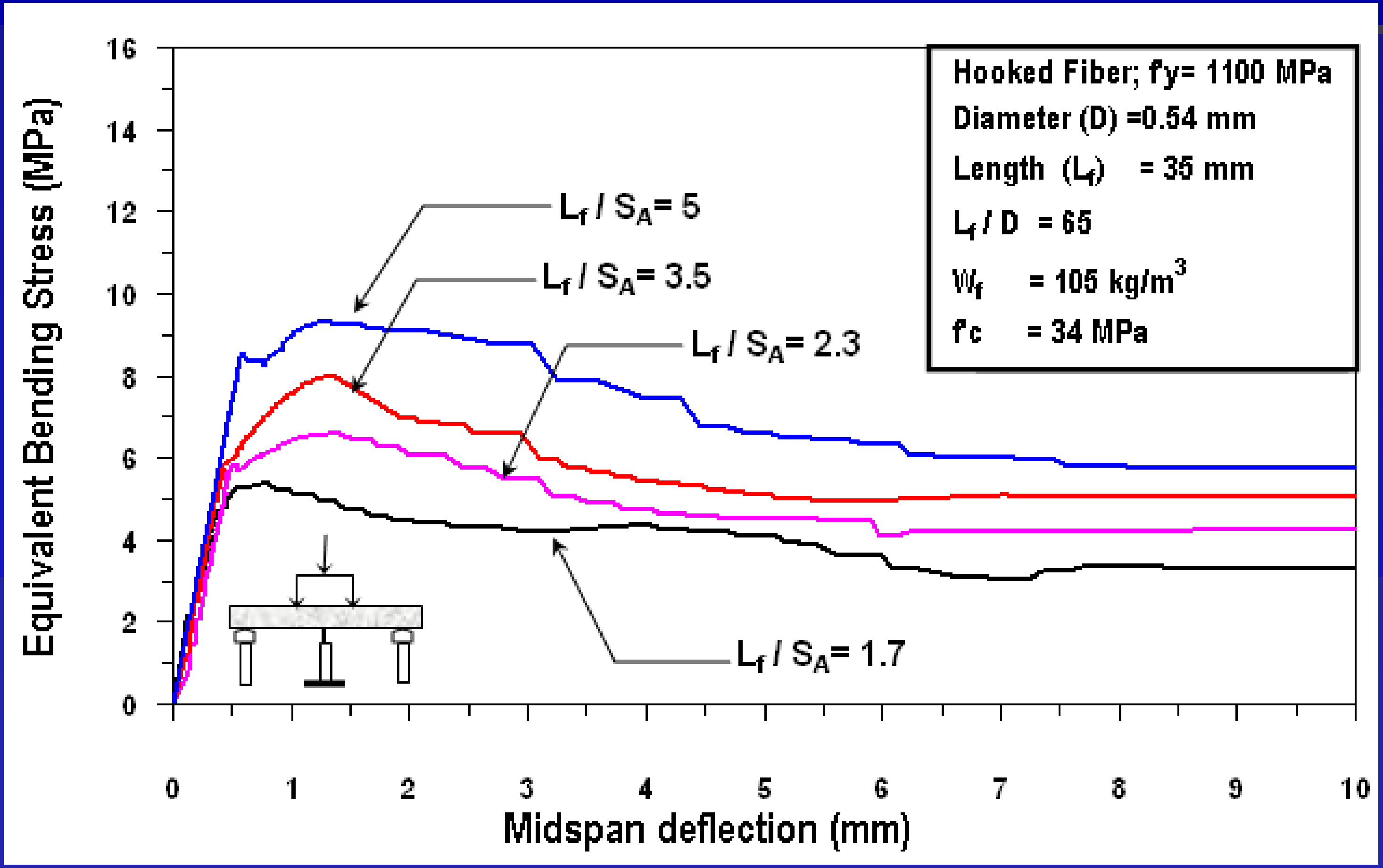




Increase in $L_f$ leads to

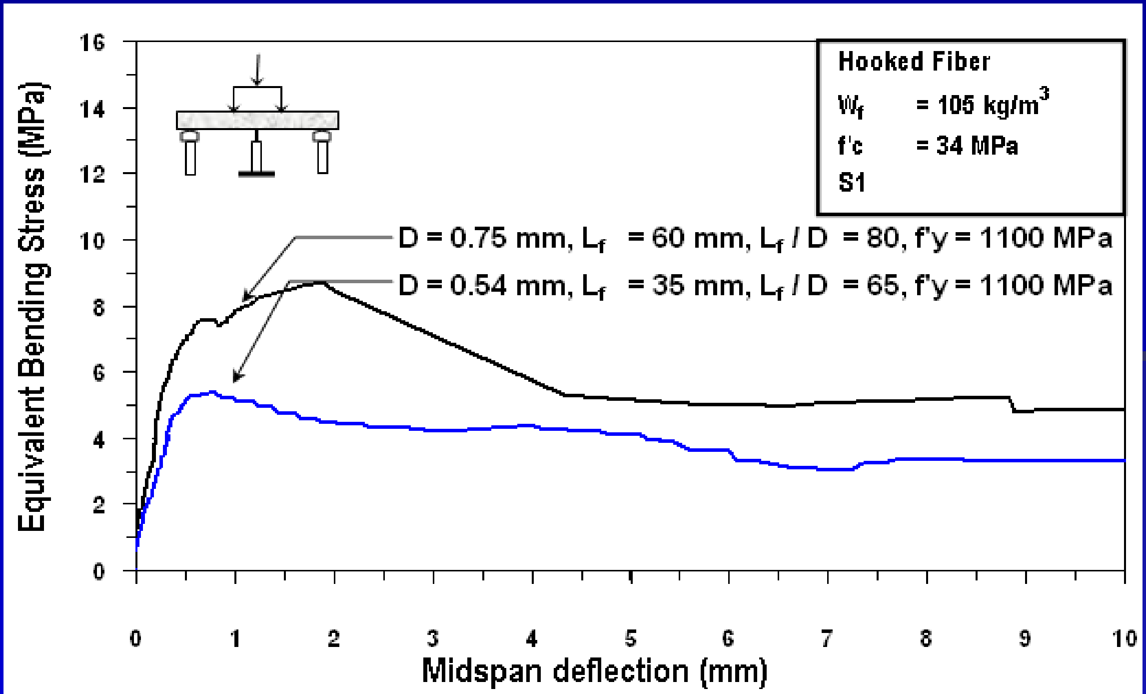
- Very slight increase in first-peak strength and some specimens do not present any improvement
- increase in post-cracking strength

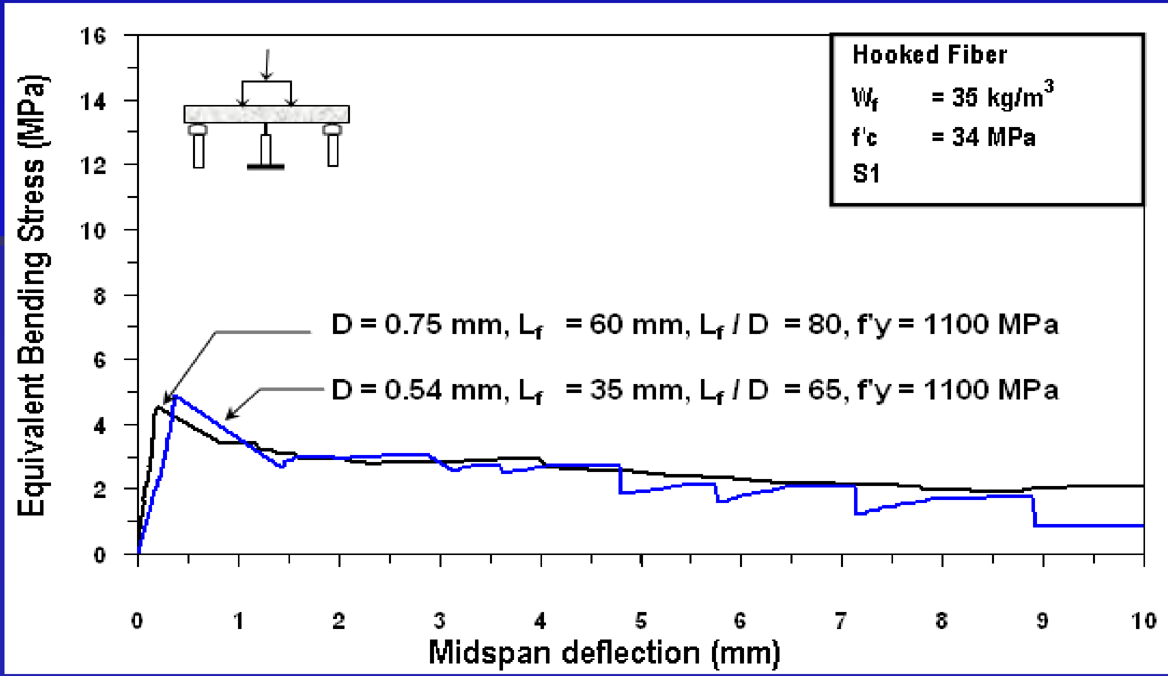
The reason of improvement is related to an increase in frictional bond when the longer fiber is used

# Effect of Fiber Length to Aggregate Ratio

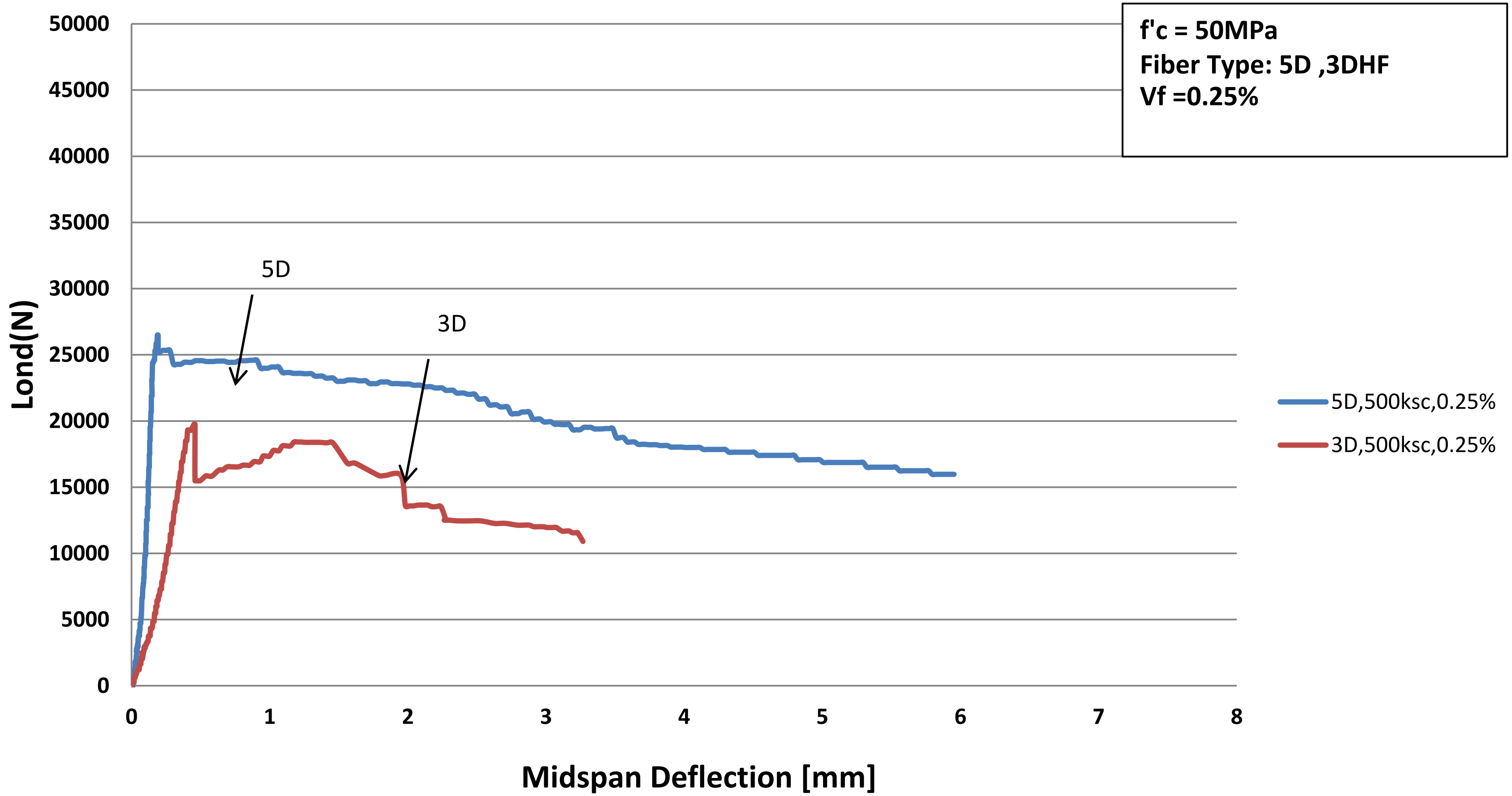


# Effect of Fiber Aspect Ratio (L/de)

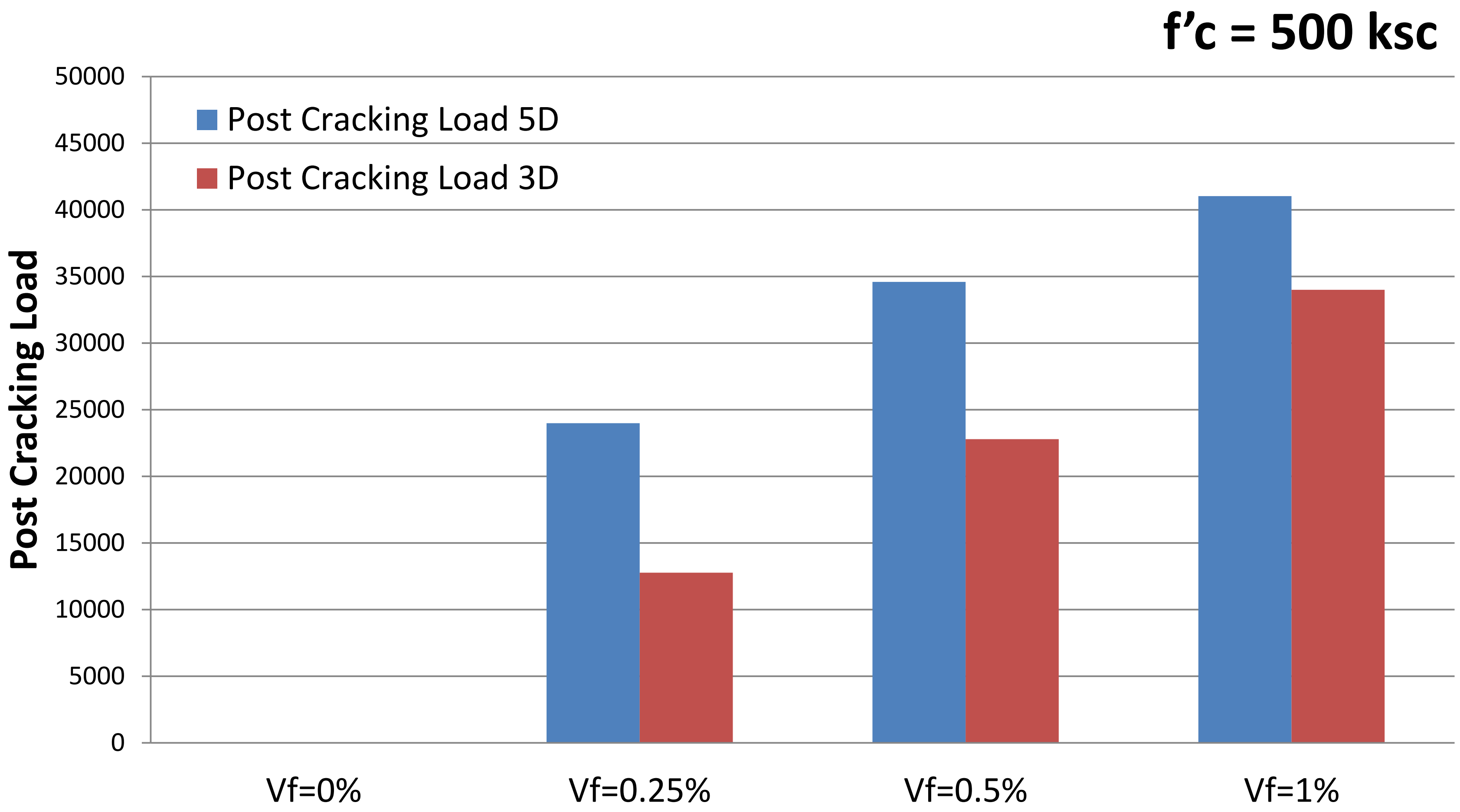


# Comparison of 3D and 5D

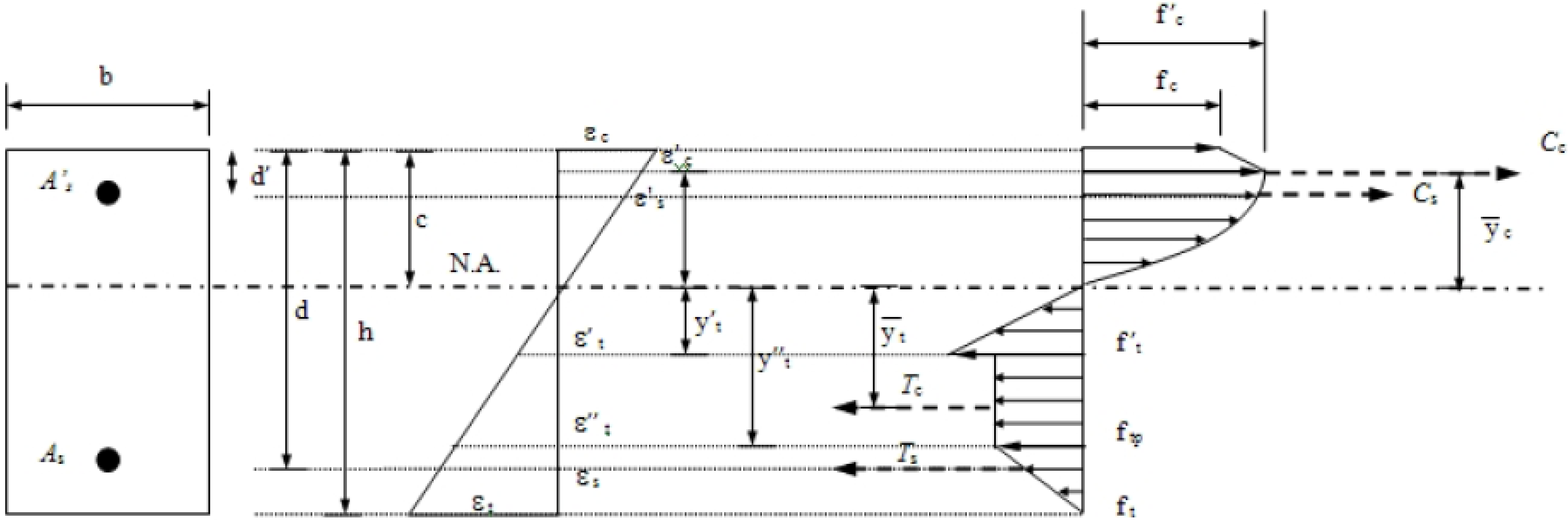


# Post Cracking Load



# Flexural Model of Doubly RC Beam Using HS-FRC

# Strain and Stress Distribution & Equilibrium of Forces



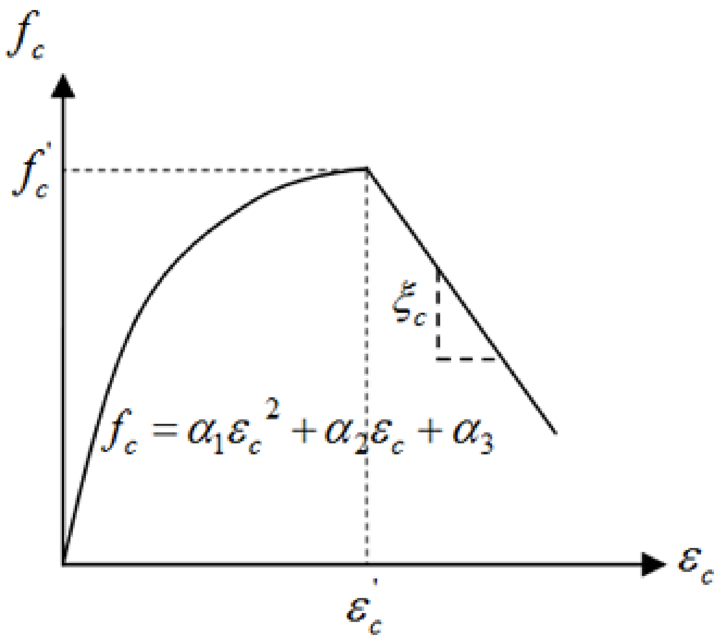

$$\sum F_x = 0:\quad C_c + C_s = T_s + T_c$$

$$\sum M = 0:\quad M = T_s\left(d - c + \bar{y}_c\right) + T_c\left(\bar{y}_c + \bar{y}_t\right) - C_s\left(\bar{y}_c - c + d'\right)$$

# Basic Concept and Assumptions

- Using **equilibrium of forces** obtained from **strain compatibility** to develop the flexural model

- The stress-strain relationship of HS-FRC in compression is assumed as shown in the figure below.



(a) Stress-Strain Relationship in Compression

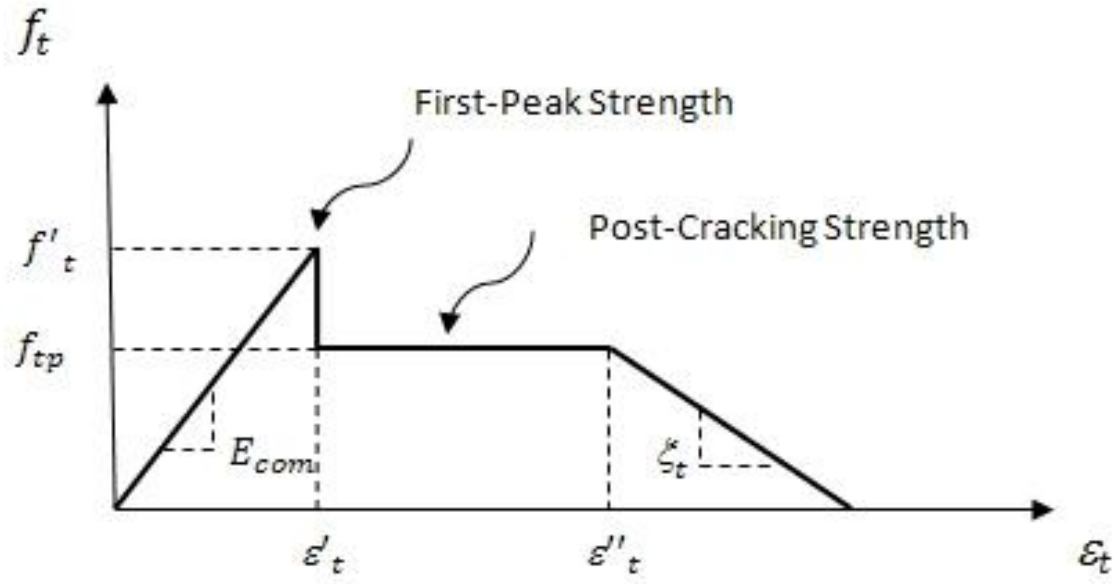
$$f_c = -\left(\frac{f_c'}{\left(\varepsilon_c'\right)^2}\right)\varepsilon_c^2 + \left(\frac{2f_c'}{\varepsilon_c'}\right)\varepsilon_c \quad \text{when} \quad \varepsilon_c \leq \varepsilon_c'$$

$$f_c = f_c' + \xi_c\left(\varepsilon_c - \varepsilon_c'\right) \quad \text{when} \quad \varepsilon_c > \varepsilon_c'$$

- The stress-strain relationship of HS-FRC in tension is assumed as shown in the figure below.

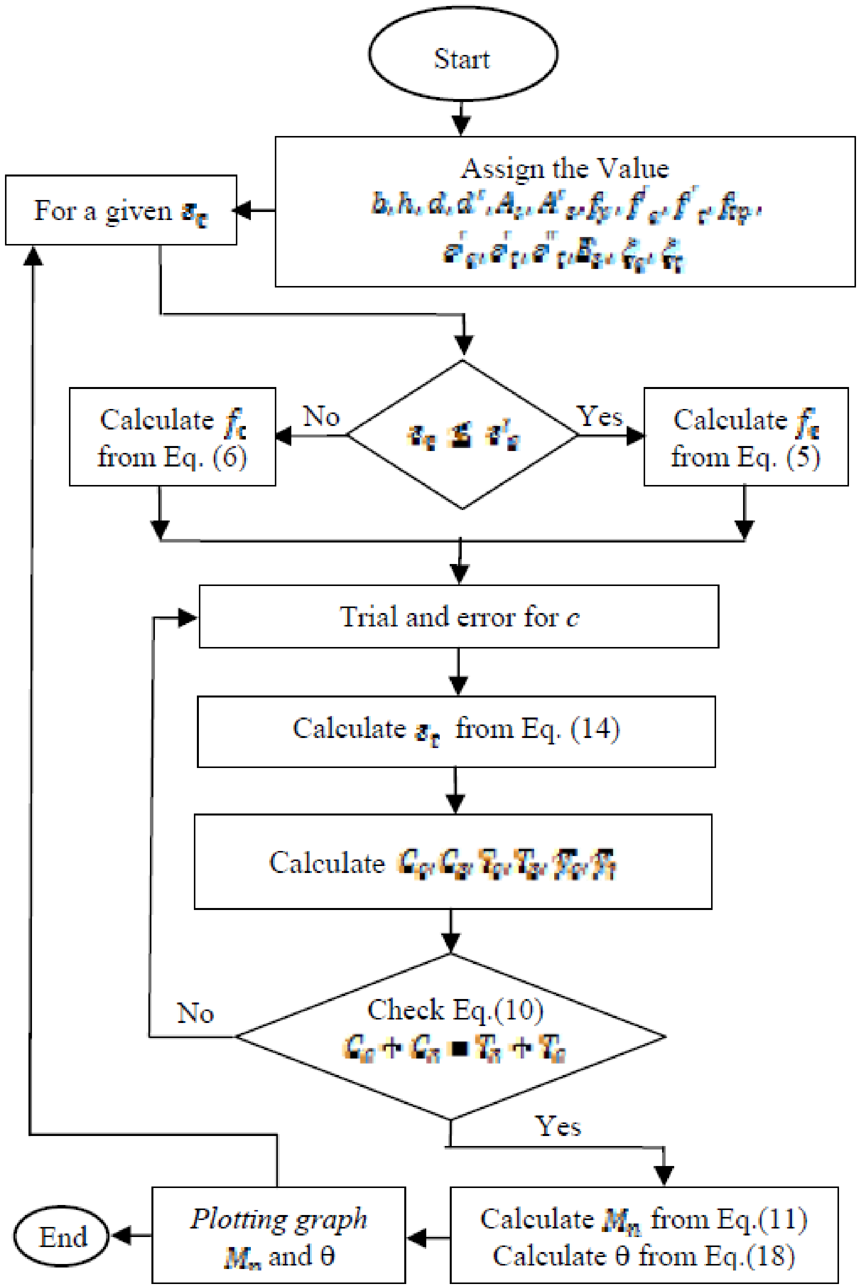
First-cracking strength and post-cracking strength adapted the model of Sujivorakul [2011], where

$$30 \text{ MPa} \le f_c' \le 50 \text{ MPa}$$



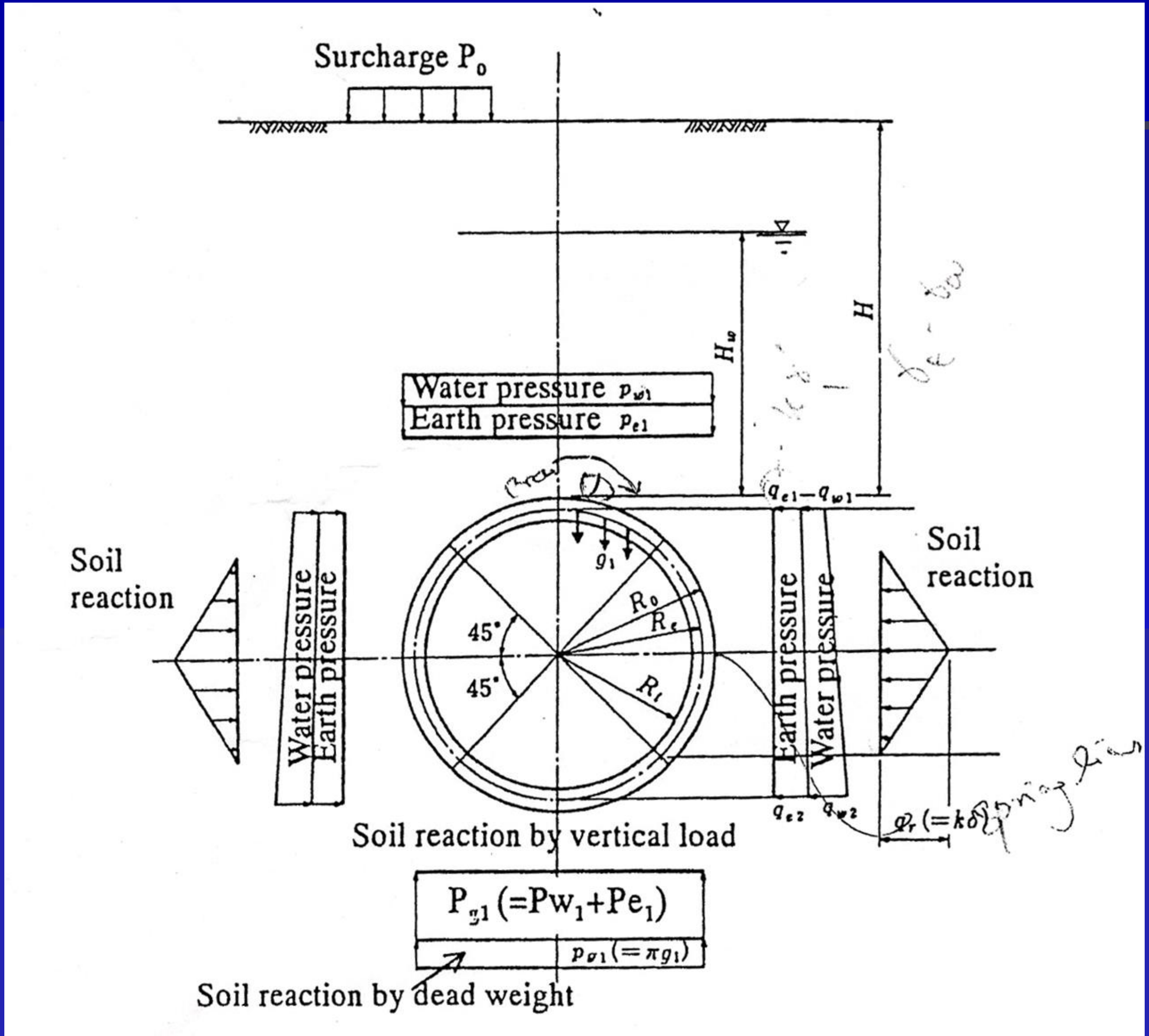

- Prefect bond between HS-FRC and steel rebar is assumed.
- Rebar has linear relationship equal to the elastic modulus of steel, until it reach yield strength.

$$f_s = E_s \varepsilon_s \le f_y \qquad f_s' = E_s \varepsilon_s' \le f_y$$




# Procedure for Obtaining Moment and Curvature Relationship

# Calculation Method for Tunnel Lining
## (JSCE 1996)



# Calculation for Vertical and Horizontal Pressure

Vertical Pressure = Soil Pressure + Water Pressure + Pressure from Surcharge Load

$$= (\gamma_{dry} H) + (\gamma_w H) + (P_o \times Disdribution\ Factor)$$

Horizontal Pressure = (Soil Pressure x λ) + Water Pressure

+ (Pressure from Surcharge Load x λ)

$$= (\gamma_{dry} H \times \lambda) + (\gamma_w H) + (P_o \times Disdribution\ Factor \times \lambda)$$

# Equations of Member Forces

| Load | Bending moment | Axial force | Shear force |
|---|---|---|---|
| Vertical load $(p_{e1}+p_{w1})$ | $M=\frac{1}{4}(1-2\sin^2\theta)(p_{e1}+p_{w1})R_c^2$ | $N=(p_{e1}+p_{w1})R_c\cdot\sin^2\theta$ | $Q=-(p_{e1}+p_{w1})R_c\cdot\sin\theta\cdot\cos\theta$ |
| Horizontal load $(q_{e1}+q_{w1})$ | $M=-\frac{1}{4}(1-2\cos^2\theta)(q_{e1}+q_{w1})R_c^2$ | $N=(q_{e1}+q_{w1})R_c\cdot\cos^2\theta$ | $Q=(q_{e1}+q_{w1})R_c\cdot\sin\theta\cdot\cos\theta$ |
| Horizontal triangular load $(q_{e2}+q_{w2}-q_{e1}-q_{w1})$ | $M=\frac{1}{48}(6-3\cos\theta-12\cos^2\theta+4\cos^3\theta)(q_{e2}+q_{w2}-q_{e1}-q_{w2})R_c^2$ | $N=\frac{1}{16}(\cos\theta+8\cos^2\theta-4\cos^3\theta)(q_{e2}+q_{w2}-q_{e1}-q_{w1})R_c$ | $Q=\frac{1}{16}(\sin\theta+8\sin\theta\cdot\cos\theta-4\sin\theta\cdot\cos^2\theta)(q_{e2}+q_{w2}-q_{e1}-q_{w1})R_c$ |
| Soil reaction $(q_r=k\cdot\delta)$ | $0\le\theta<\frac{\pi}{4}$<br>$M=(0.2346-0.3536\cos\theta)\,k\cdot\delta\cdot R_c^2$<br>$\frac{\pi}{4}\le\theta\le\frac{\pi}{2}$<br>$M=(-0.3487+0.5\sin^2\theta+0.2357\cos^3\theta)\,k\cdot\delta\cdot R_c^2$ | $0\le\theta<\frac{\pi}{4}$<br>$N=0.3536\cos\theta\cdot k\cdot\delta\cdot R_c$<br>$\frac{\pi}{4}\le\theta\le\frac{\pi}{2}$<br>$N=(-0.7071\cos\theta+\cos^2\theta+0.7071\sin^2\theta\cdot\cos\theta)\,k\cdot\delta\cdot R_c$ | $0\le\theta<\frac{\pi}{4}$<br>$Q=0.3536\sin\theta\cdot k\cdot\delta\cdot R_c$<br>$\frac{\pi}{4}\le\theta\le\frac{\pi}{2}$<br>$Q=(\sin\theta\cdot\cos\theta-0.7071\cos^2\theta\sin\theta)\,k\cdot\delta\cdot R_c$ |

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| Dead load $\left(P_{g1} = \pi \cdot g_1\right)$ | $0 \le \theta \le \frac{\pi}{2}$<br>$M = \left(\frac{3}{8}\pi - \theta \cdot \sin\theta - \frac{5}{6}\cos\theta\right) g \cdot R_c^2$<br>$\frac{\pi}{2} \le \theta \le \pi$<br>$M = \left\{-\frac{1}{8}\pi + (\pi - \theta)\sin\theta - \frac{5}{6}\cos\theta - \frac{1}{2}\pi \cdot \sin^2\theta\right\} g \cdot R_c^2$ | $0 \le \theta \le \frac{\pi}{2}$<br>$N = \left(\theta \cdot \sin\theta - \frac{1}{6}\cos\theta\right) g \cdot R_c$<br>$\frac{\pi}{2} \le \theta \le \pi$<br>$N = \left(-\pi \cdot \sin\theta + \theta \cdot \sin\theta + \pi \cdot \sin^2\theta - \frac{1}{6}\cos\theta\right) g \cdot R_c$ | $0 \le \theta \le \frac{\pi}{2}$<br>$Q = \left(\theta \cdot \cos\theta + \frac{1}{6}\sin\theta\right) g \cdot R_c$<br>$\frac{\pi}{2} \le \theta \le \pi$<br>$Q = \left\{(\pi - \theta)\cos\theta - \pi \cdot \sin\theta \cdot \cos\theta - \frac{1}{6}\sin\theta\right\} g \cdot R_c$ |
| Horizontal deformation of a ring at spring line $(\delta)$ | Without considering soil reaction derived from dead weight of lining:<br>$\delta = \frac{\{2(p_{e1} + p_{w1}) - (q_{e1} + q_{w1}) - (q_{e2} + q_{w2})\} R_c^4}{24\left(\eta \cdot EI + 0.0454k \cdot R_c^4\right)}$<br>Considering soil reaction derived from dead weight of lining:<br>$\delta = \frac{\{2(p_{e1} + p_{w1}) - (q_{e1} + q_{w1}) - (q_{e2} + q_{w2}) + \pi g\} R_c^4}{24\left(\eta \cdot EI + 0.0454k \cdot R_c^4\right)}$<br>However EI: Bending rigidity in unit width | | |