Fiber-reinforced cement-based composite materials (FRCCs)

Reference Books

- Balaguru, P.N., Shah, S.P., «Fiber-reinforced cement composites», McGraw-Hill, Inc., 1992.
- Bentur, A., Mindess, S., «Fiber-reinforced cementitious composites», Modern Concrete Technology Series, Taylor & Francis, 2nd Edition, 2007.

Contents

Composite Materials - Introduction

COMPOSITE MATERIAL?

Composite Materials - Introduction

Composite material:

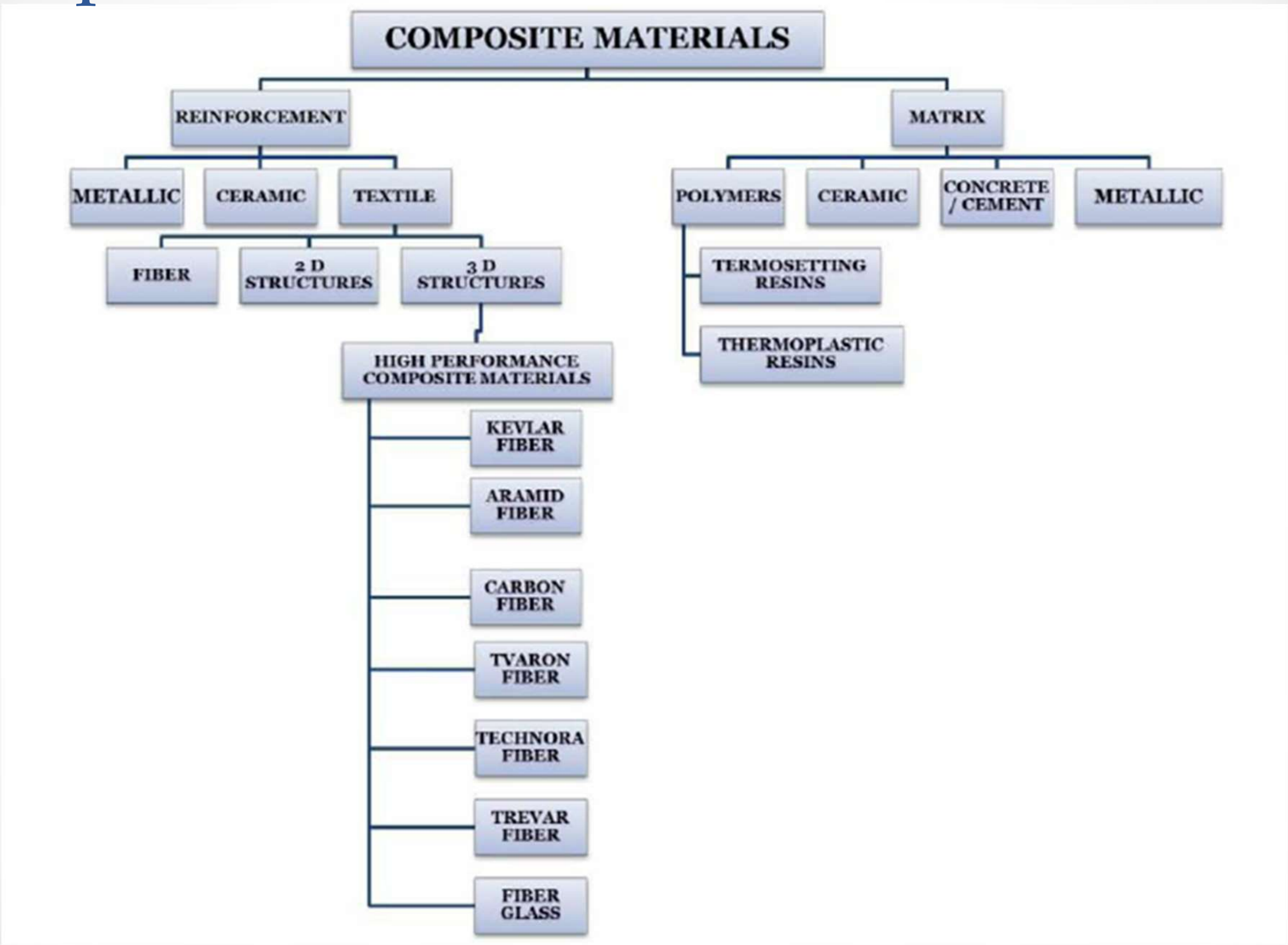
Composed of at least 2 materials to obtain superior properties than those of the individual materials.

General definition;

Composite material = **Matrix phase** + **distributed phase**

ex; Concrete, fiber – reinforced concrete, fiber – reinforced polymers.

Composite Materials - Classification



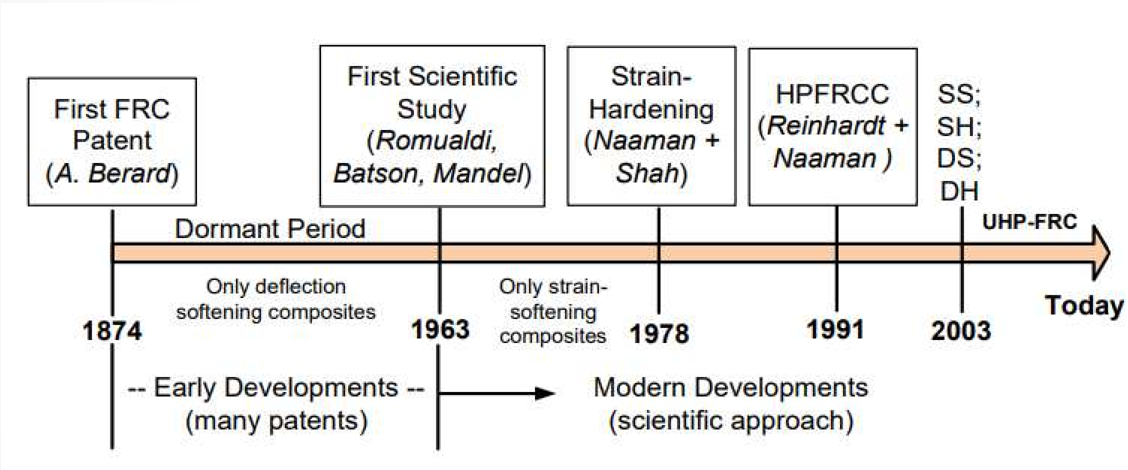
https://www.researchgate.net/publication/283344021_Experimental_Analysysis_of_Cutting_Tool%27s_Wear_Evolution/figures?lo=1

Composite materials - History

- Fibers made of straw and horsehair + bricks ; dates back to thousands of years

FRC History

- *Fiber-reinforced concrete (FRC); concrete with suitable discontinuos fibers added to it to achieve a desired level of performance in a particular property (or properties)*[5]



Milestones in the development of fiber reinforced concrete

[5]Naaman, A., Fiber reinforced concrete: Five decades of progress, 4th Brazilian conference on composites Materials. Rio de Janeiro, July 22nd-22th, 2018

FRCCs

FIBER-REINFORCED CEMENT-BASED COMPOSITES

OR

FIBER-REINFORCED CEMENTITIOUS COMPOSITES

FRCCs - Introduction

Definition for FRCCs

FRCC = Cement based matrix + fibers

- Cement – based matrix; cement paste, mortar, concrete
- Fibers; metallic, polymeric, mineral, natural, etc.

FRCCs – History

- Use of FRCCs began in early 1960s
- Major improvement reported by several researchers
- Major problems were mixing and workability
- These problems were overcome with the advent of high-range water-reducing admixtures
- Use of FRCCs increased with new developments in fibers and cement based matrix

FRCCs – History of applications

- In the beginning, FRC was primarily used for pavements and industrial floors.
- Later, the applications increased to cover bridges, tunnels, hydraulic structures, pipes, explosion resistant structures, safety vaults, cladding, roller compacted concretes, etc.

FRCCs - Applications

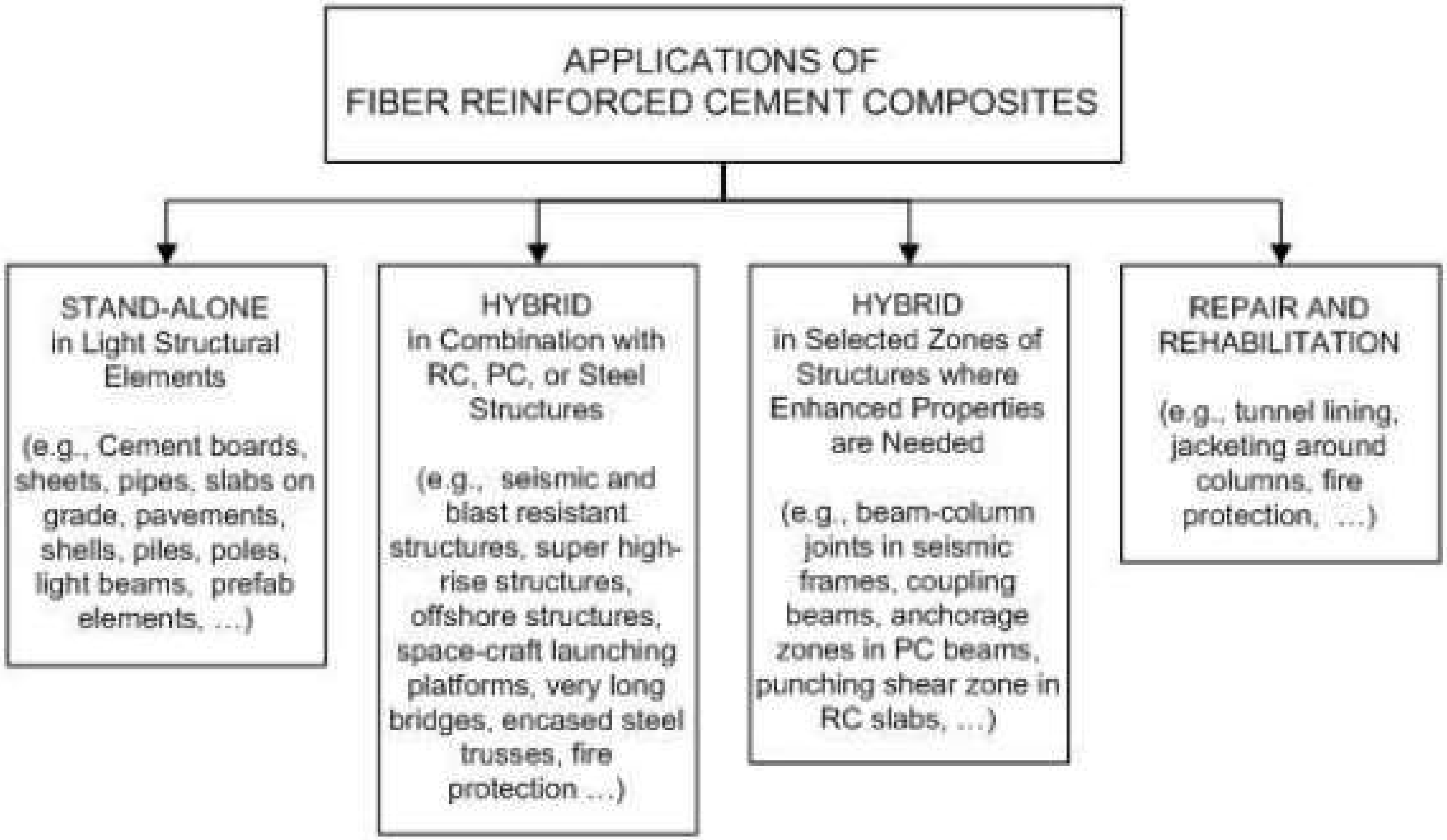


Figure 6.1 Classes of applications of fiber reinforced cement composites.

Naaman, High performance fiber reinforced cement composites

Need for reinforcement

Brittleness of plain cement-based materials

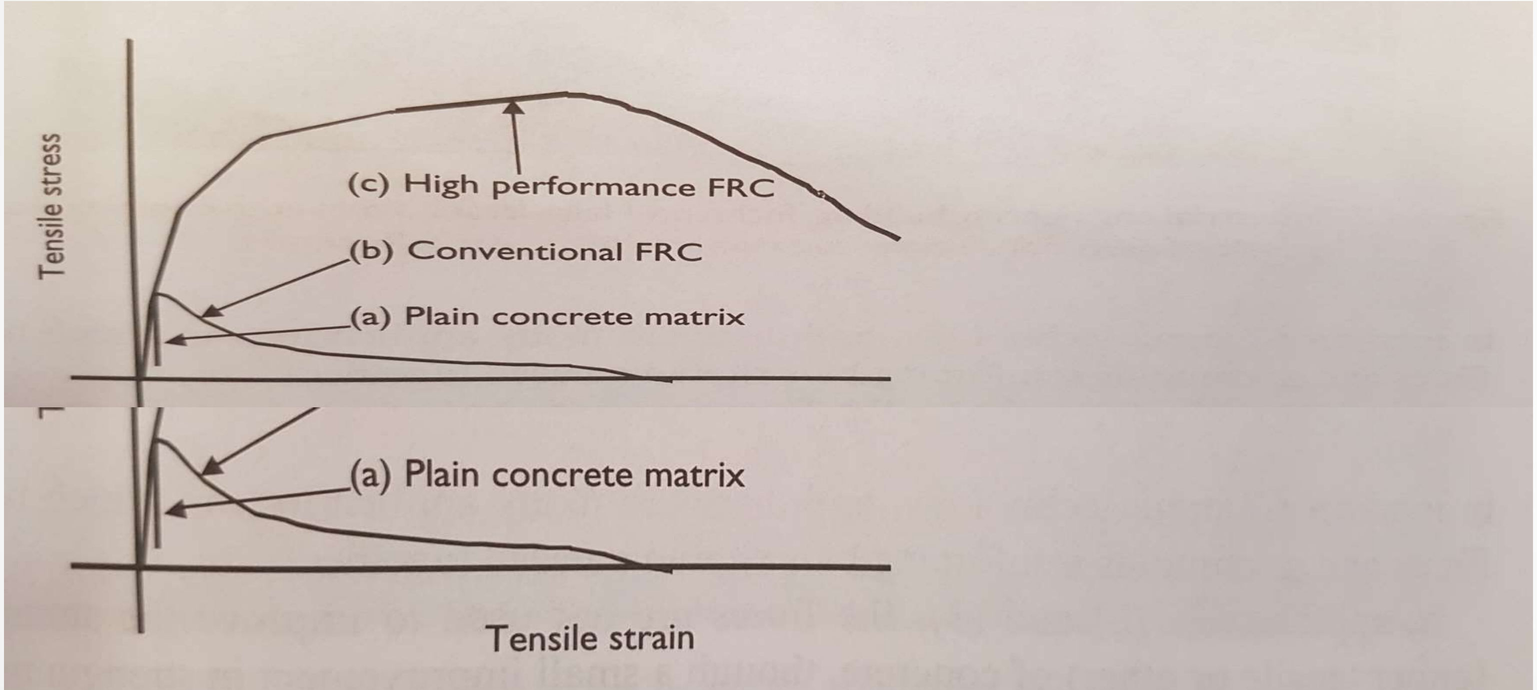


Figure 1.1 Typical stress–strain curves for conventional and high performance FRC (after ACI 544 [2]).

- Bentur, and Mindess, Fiber –reinforced cementitious composites

Need for reinforcement – RC vs. FRC

Reinforced concrete; concrete reinforced using continuous rebars for increased load bearing capacity.

Placed in the structure at the appropriate locations to withstand the imposed tensile and shear stresses.

Fiber – reinforced concrete; fibers are discontinuous and randomly distributed (most of the time) throughout the matrix.

Their efficiency in withstanding the tensile stresses relatively low. However, since they are more closely packed, they are more effective in controlling cracks.

FRC is not a substitute for RC!

- Bentur, and Mindess, Fiber –reinforced cementitious composites

The main structural applications

- Many different structural applications of FRC are possible

1.3.1 Slabs

- One of the applications in which FRCs are most used.
- Other reinforcement systems are also used in slabs (traditional reinforcement, precast or post-tensioned)
- Advantages of FRC slab systems include primarily the economic aspects, followed by the improved strength and ductility, increased speed of construction, reduction of joints, and crack width control in continuous joint-free slabs.

Slabs

- The slabs can be founded on grade, on piles and can be elevated.
- The bearing capacity of a continuously supported slab can be significantly increased with respect to a simply supported slab.

Slabs

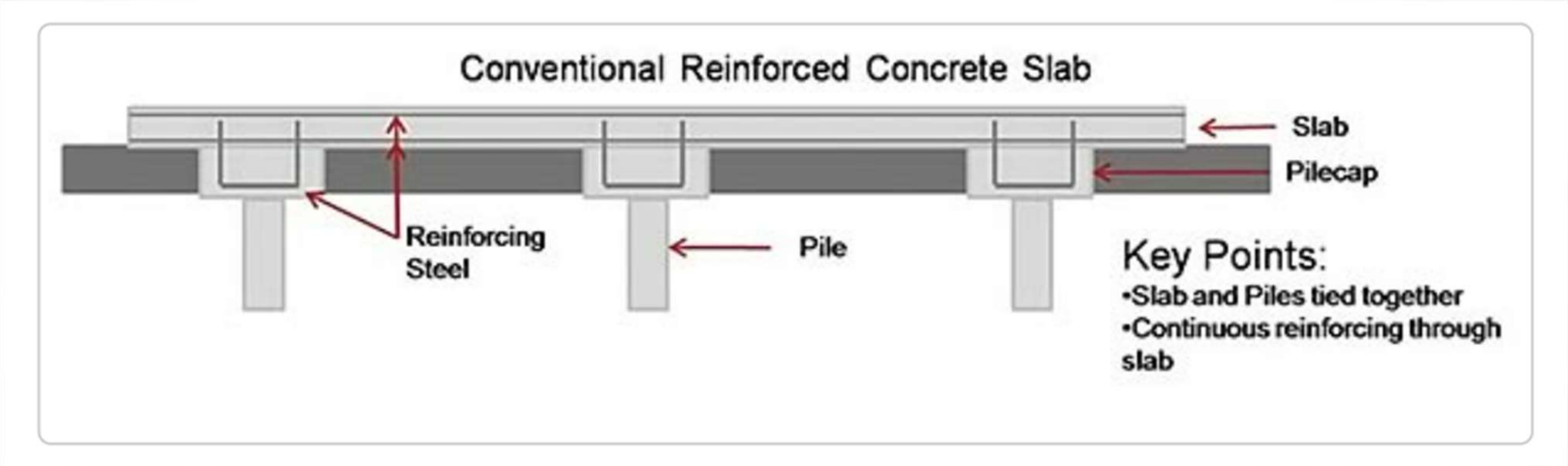
- Foundation slabs are most commonly thicker and the loads are higher. FRC with localized traditional reinforcement around columns and piles is typically used.
- Raft slabs are a special type of foundation slab where the foundation can be a combination of piles and the normal subgrade as a balanced interaction.
- The loads on the slab construction are distributed partly by the piles and partly by the subgrade. In that sense, the foundation piles can be seen as a settlement reduction system.

Slabs on grade

- The most adopted application for FRC.
- Depending on the amount and type of fibers, the shrinkage and load effects can be handled with a varying depth and joint length.

Pile supported slabs

- Widely adopted application all over the world.
- In Europe large logistic centres are built on piles. The loads are often much higher than the dead weight (50 kN/ m2 is a normal load), with spans typically ranging from 1.5 to 3.0 m and slab thickness ranging from 150 mm to 250 mm, as an approximate economic optimum.



[Figure ref: Pile Supported Slab - CoGripedia - CoGri Group Ltd]

Pile supported slabs

The slabs are not likely to provoke a sudden progressive collapse of the structural frame above them.

These slabs can be made flat or with column heads with different fibre solution options.

- Fibres only
- Fibres with an upper mesh above the piles
- Fibres with a top mesh over the total area

Pile supported slabs

Fibre reinforcement reduces micro-cracking and early-age cracking. Conventional reinforcement reduces the macro cracking and creep after cracking.

Besides the substitution of rebars, significant advantages of using fibers in this application are the crack width reduction as well as shear and punching capacity increase.

Road slabs on piles

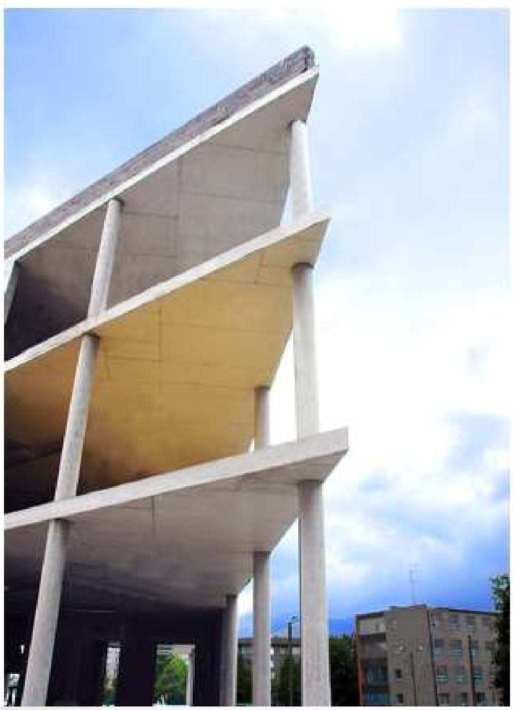
- Used where settlements of slabs supported on grade are too large
- Ex: A road N463 near Woerden Verlaat (Netherlands) is built on piles. The road runs through a part of the Dutch green hart. The peat layer in this area has a typical thickness of around 10 meters.
- Settlement of roads supported on grade are typically around 2 meters after a few decades of use. To stop the settlement of the road, piles were used.

Elevated slabs

- Elevated suspended slabs could have a sudden progressive collapse; therefore, these slabs contain a set of minimum continuity reinforcing bars, also known as anti-progressive collapse (APC) reinforcing bars.
- This traditional reinforcement could, for instance, be placed in the bottom of the slab from column to column in both directions (as shown in Fig.1-3).

Elevated slabs

The floor in Fig.1-3b was cast as a part of a 5 story structure with 5'000 m² total floor space in Mondragon (Spain), with a 8.30 m span, 280 mm thick slab, and uniformly distributed load (UDL) of 7 kN/m², using 100 kg/m³ of steel fibres (hooked end with a tensile strength of 1'500 MPa).



Wind turbine rafts

- In Eemshaven, the Netherlands, a hybrid reinforced foundation for a 3MW wind turbine was designed and constructed (Fig. 1-6).
- Hub height: 91,5m
- Rotor diameter: 117m
- The foundation diameter: 13,5m
- Thickness: 1,6m at the edge to 3,5m at the center
- Founded on 26 piles with a length of 25m each
- The reinforcement bars in combination with SF (a total of 35kg/m3).

Wind turbine rafts

Fig. 1-6 Wind turbine at Eemshaven (ABT Netherlands).

Retaining structures

- Hybrid reinforced concrete is very suitable for watertight dock structures.
- The dry dock of Fig.1-7 is constructed by using an estimated 10'000 m3 of hybrid reinforced concrete. The dock is located in the west of the Netherlands near the harbor of Rotterdam and the heritage site Kinderdijk.

Retaining structures

Fig. 1-7 Retaining walls at Kinderdijk, the Netherlands.

Retaining structures

- Because of the thickness and long straight length (140 m), hybrid reinforcement was used. The combination of fibers and rebars is very suitable for controlling crack width.
- The stresses created by restrained deformation in these structures are enormous, especially for the walls (hydration cooling and shrinkage).
- These walls are insulated from the outside and the formwork restrains the heat flow from the inner side. These walls reached a temperature of over 50 degrees after pouring.

Retaining structures

- Because of the hydration heat and the subsequent cooling, the walls could be severely cracked. Since the walls were hybrid reinforced, the cracks have a small width and most cracks are watertight.
- The amount of reinforcement used is significantly lower than that of a traditionally reinforced wall.

Shell structures

- Shell structures can have a very complicated shape with e.g. double curvatures and the use of traditional reinforcement is very labor intensive.
- In these structures, FRC makes these projects possible. The following examples show the amazing projects that can be achieved.

Shell structures

The thin shell structure in Valencia consists of several lobes of about 12 m (Fig.1-9). The thickness of the shells ranges between 225 mm (at the bottom) to 60 mm at the top[1-5].
The reinforcement consists of a combination of traditional reinforcement and steel fibers (RC/SFRC).

Fig. 1-9 Oceanographic aquarium Valencia, Spain.

Shell structures

The Mushroom museum in the Netherlands is also a hybrid construction (RC/SFRC) for a dome of about 30 m diameter with a thickness of 150 to only 50 mm (Fig.1-10).

The addition of traditional reinforcement was necessary mainly to ensure the watertight design of the dome. The combination was extremely effective against shrinkage strain.

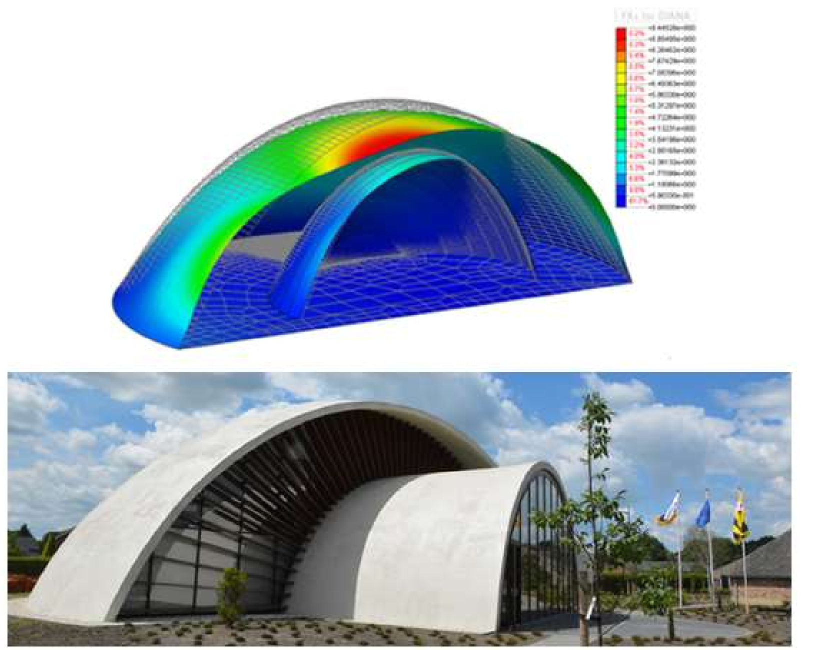


Fig.1-10 Mushroom museum Melderslo (pictures provided by DIANA FEA Netherlands).

Bridge decks

- Decks are one of the most vulnerable structural components of bridges in terms of durability.
- Because bridge deck replacement is expensive and is a source of major traffic disruption, in urban areas or on roads, where no alternative routes are available, bridge owners have been looking at many options for improving bridge deck durability.
- In bridge deck construction, a hybrid reinforcement (RC/SFRC) is introduced: in fact, a high dosage of steel fibers can contribute structurally to the strength of lightly reinforced concrete members.

Bridge decks

- Five cast-in-place SFRC bridge decks on girders were built between 1998 and 2002 in Quebec Canada following an intensive experimental research program carried out at Polytechnique Montreal aimed at developing and evaluating the potential of using SFRC with reduced conventional reinforcement[1-6].

Bridge decks

- The experimental and analytical investigations indicated that, with a dosage of 80 kg/ m3 of high performance steel fibres, the expected deck performances at serviceability, fatigue and ultimate limit states exceed those obtained with current design involving conventional reinforcement.
- The final design enabled reducing by half the amount of conventional reinforcement using only one single reinforcement layer located at the bottom third of the deck, in both positive and negative moment regions (Fig.1-12).

Bridge decks

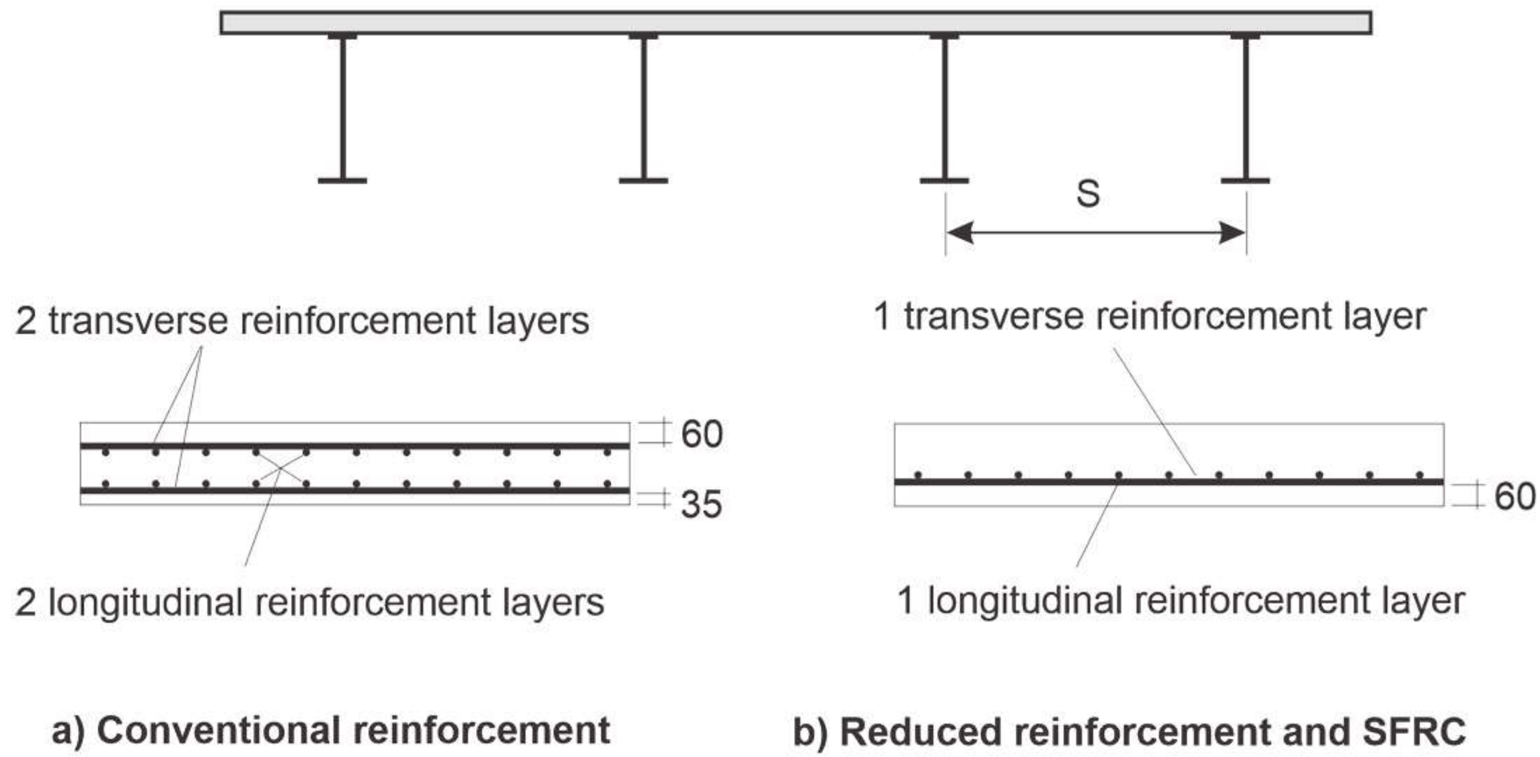


Fig. 1-12 Reinforcement options for typical composite bridge decks.

Bridge decks

a) Reduced reinforcement.

b) Final deck finish.

Fig.1-13 St-Antoine bridge deck with reduced reinforcement.

Shotcrete in tunnelling and mining

- Shotcrete or sprayed concrete in tunnelling and mining applications is often fibre-reinforced. Tunnels in soft ground or poor rock conditions are often build according the principles of the New Austrian Tunnelling method (NATM). In this case, shotcrete is one of the most important supporting tools.
- Mostly shotcrete is for temporary use then, but permanent applications are increasing. Tunnels in hard rock are often designed according the Q-method (Norwegian). Shotcrete is then a permanent lining.

Shotcrete in tunnelling and mining

- Fibre reinforced shotcrete is the standard material as the application of mesh reinforcement is costly under these conditions. Applications in mining follow one of these methods, but often allow higher deformations of the lining, as the linings usually are for temporary use only.
- Nowadays, mainly the wet-mix method is used, as the rebound during spraying is lower than for the dry-mix method, which is used for tricky applications (e.g. high water ingress, downtown sites).

Shotcrete in tunnelling and mining

- Fibre rebound will reduce the fibre content from the base-mix to the applied shotcrete by 10 to 30%. Steel fibres used, never are longer than 40 mm, 35 mm being a standard.
- Structural synthetic fibres may be somewhat longer. Most suppliers offer special fibres for shotcrete applications. Typical fibre content in the base mix is 25 to 55 kg/m³ of steel fibres, 4 to 7 kg/m³ of synthetic macro fibres.

Tunnel segments

- Despite the wide use of FRC as shotcrete for temporary lining, in the last two decades FRC was used in many precast tunnel segments in combination or not with conventional rebars, (the state of art report of the International Tunnelling Association (ITA, 2016), fib Bulletin 83).
- FRC tunnels are build all over the world from 1980's. The functions vary from Metro, railway, water, gas and electric supply to sewer and cable lines. The diameters varying from 2 to 12 m and a thickness of 200-500 mm Di / h = 15-25.

Tunnel segments

In the case studies of ITA, several type of fibres and their contents are specified. It should be noticed that steel fibre reinforcement solution was used for the vast majority of the alignment. Hybrid solution have been used only in highly loaded tunnel sections and at the cross-passages location

Tunnel segments

Fig.1-14 Example of tunnel lining segments[1-8].

Tunnel segments

The data collected in the study show that FRC is a competitive material for tunnel segmental lining for the following main reasons:

- Fibre reinforcement enables better crack control, especially in combination with traditional reinforcing bars. Hence, smaller crack openings are expected at SLS, resulting in a considerable improvement of the durability of the structure.
- Fibres provide higher resistance to impact loading.

Tunnel segments

- The industrial production process is improved, since a partial or complete substitution of conventional rebars can be achieved, which means time reduction in handling and placing curved rebars. A considerable reduction or elimination of storage areas for traditional reinforcement can be achieved.
- Fibre reinforcement is distributed everywhere in the segment, including the concrete cover which, in RC segments, often needs to be considerably thick for the fulfilment of the fire protection and durability requirements.

Tunnel segments

- Watertightness is improved. This is associated with permeability but also depends on microcracks or cracks related to internal and external strain experienced by structures. In this regard, fibre reinforcement can considerably reduce the cracking phenomena and control permeability of concrete under stress.
- Fibre reinforcement enhances a sustainable use of structural concrete, due to a low environmental impact and to the resulting mechanical performance of such structures.

Tunnel inner linings

- Tunnel lining is a very significant application of FRC made of metallic and/or macro synthetic fibres mostly in combination with conventional reinforcement.
- During a tunnel fire, the concrete inner lining may reduce in cross-section due to explosive spalling. The addition of 1 to 2 kg/m^3 Polypropylene microfibres can delay spalling.

U shaped box-culvert and channel structures

- An interesting application of FRC can be found in box culverts. The idea is to partially substitute the reinforcement introduced in the longitudinal direction of each segment and/or the transverse reinforcement at the extrados with FRC.

U shaped box-culvert and channel structures

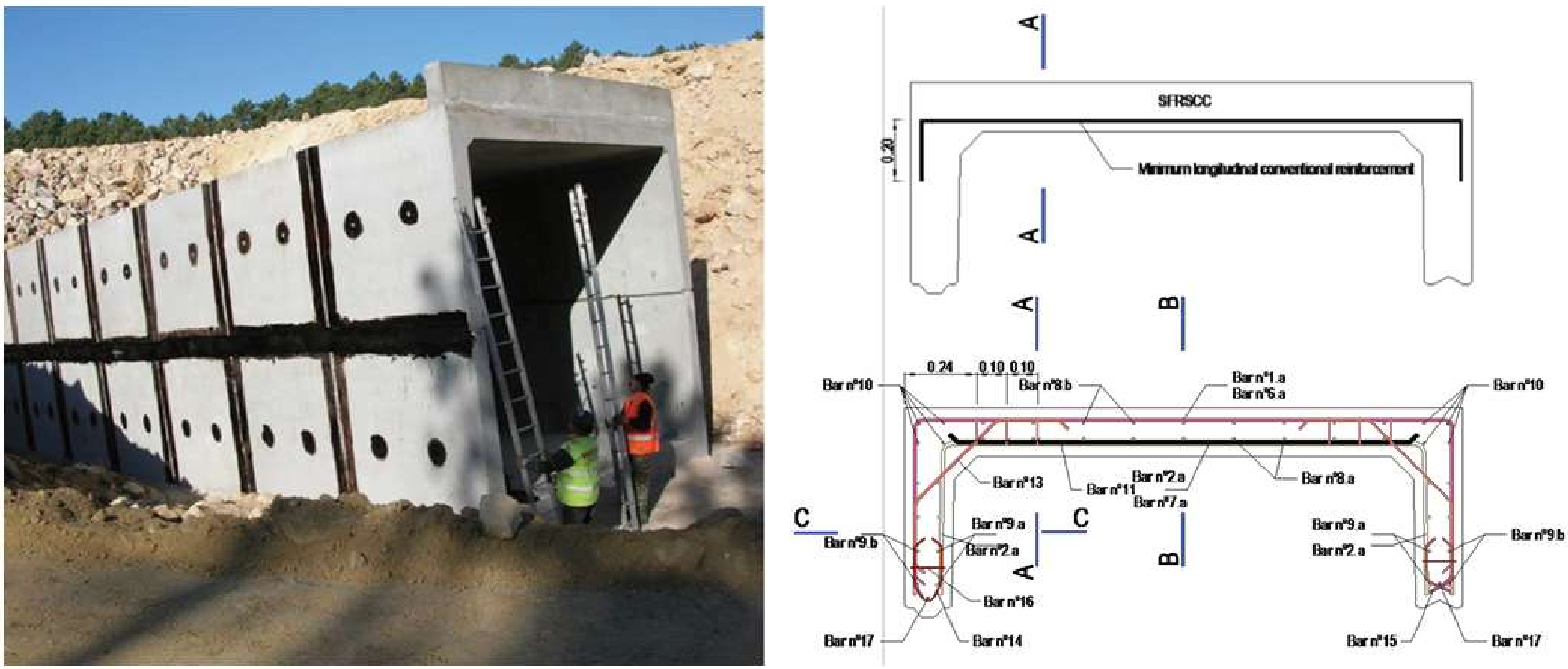


Fig. 1-15 FRC box culvert[1-9].

Prestressed and HPFRC roof element

- FRC used in precast elements is considered very interesting from the economical point of view as alternative, or complementary, to the welded-wire meshes and to traditional transverse reinforcement.
- Mid-plane positioning of the reinforcement suggested by a careful durability design can rarely be guaranteed in thin-walled sections: therefore, fibre reinforcement, especially when used in prefabricated roof elements, is a promising technique since the nineties.

Prestressed and HPFRC roof element

Fig. 1-17 FRC precast prestressed roof elements[1-11, 1-12, 1-13].

Prestressed and HPFRC roof element

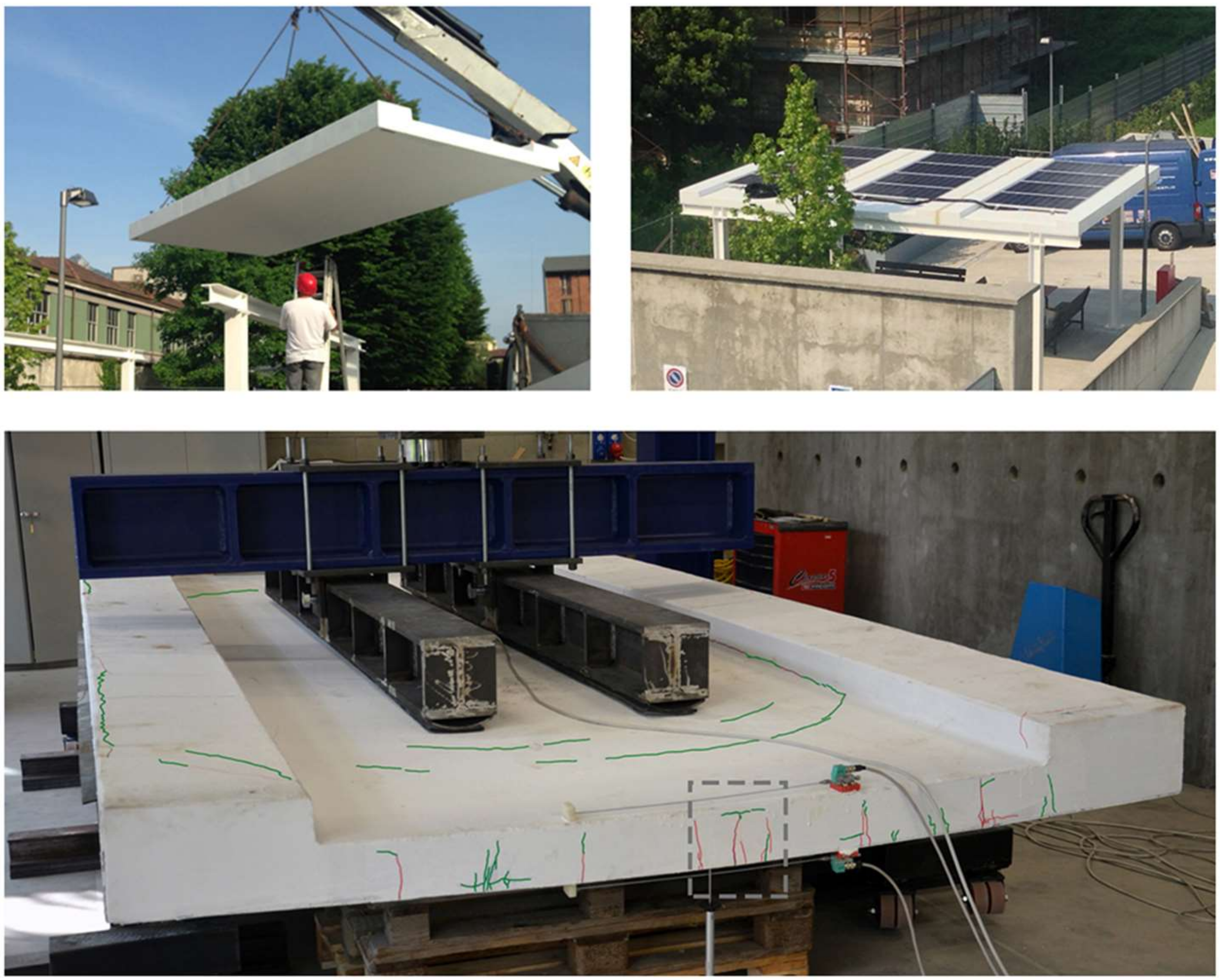


Fig. 1-18 FRC precast roof elements[1-14].

Contents

2. Structure of FRCCs

- The structure of the bulk cementitious matrix
- The shape and distribution of the fibers
- The structure of the fiber-matrix interface

2. Structure of FRCCs

2.1. MATRIX

i) Cement paste/Mortar (cement + sand + water)

ii) Concrete (cement +sand +coarse agg + water)

2. Structure of FRCCs

2.2. FIBERS; wide range of fibers

Table 1.1 Typical properties of fibres

Fibre	*Diameter (μm)*	*Specific gravity*	*Modulus of elasticity (GPa)*	*Tensile strength (GPa)*	*Elongation at break (%)*
Steel	5–500	7.84	200	0.5–2.0	0.5–3.5
Glass	9–15	2.6	70–80	2–4	2–3.5
Asbestos					
Crocidolite	0.02–0.4	3.4	196	3.5	2.0–3.0
Chrysolite	0.02–0.4	2.6	164	3.1	2.0–3.0
Polypropylene	20–400	0.9–0.95	3.5–10	0.45–0.76	15–25
Aramid (kevlar)	10–12	1.44	63–120	2.3–3.5	2–4.5
Carbon (high strength)	8–9	1.6–1.7	230–380	2.5–4.0	0.5–1.5
Nylon	23–400	1.14	4.1–5.2	0.75–1.0	16.0–20.0
Cellulose	—	1.2	10	0.3–0.5	—
Acrylic	18	1.18	14–19.5	0.4–1.0	3
Polyethylene	25–1000	0.92–0.96	5	0.08–0.60	3–100
Wood fibre	—	1.5	71.0	0.9	—
Sisal	10–50	1.5	—	0.8	3.0
Cement matrix (for comparison)	—	1.5–2.5	10–45	0.003–0.007	0.02

2. Structure of FRCCs

2.2. FIBERS;

i) Shapes of the individual fibers
   a. Discrete fibers
   b. Bundled fibers

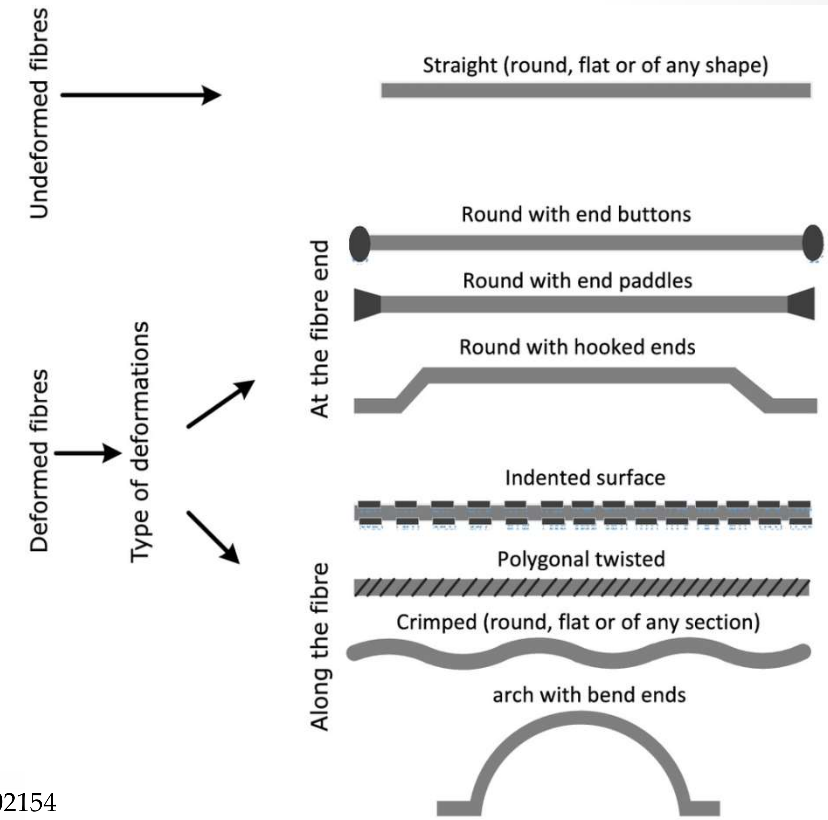
ii) Dispersion of the fibers

2. Structure of FRCCs

2.2. FIBERS;

i) Shapes of the individual fibers

a. Discrete fibers (monofilament fibers)



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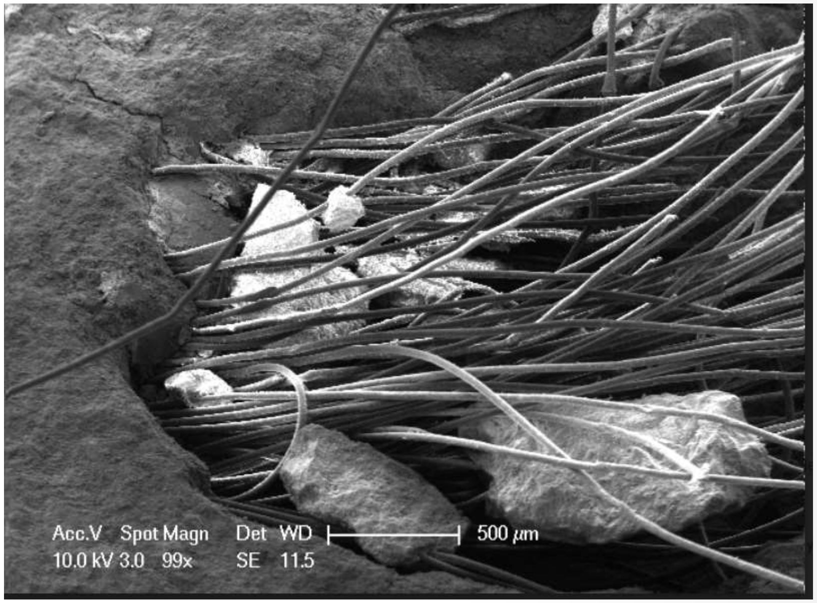
2. Structure of FRCCs

2.2. FIBERS;

i) Shapes of the individual fibers

a. Discrete fibers

b. Bundled fibers



ii) Dispersion of the fibers

3. Fiber-Matrix Interaction

The structure of fiber – matrix interface

Interfacial transition zone (ITZ) – vicinity of the reinforcing inclusion, microstructure of the paste matrix is considerably different from that of the bulk paste

Structure of transition zone highly affects fiber – matrix bond!

3. Fiber-Matrix Interaction

2.3. The structure of fiber – matrix interface

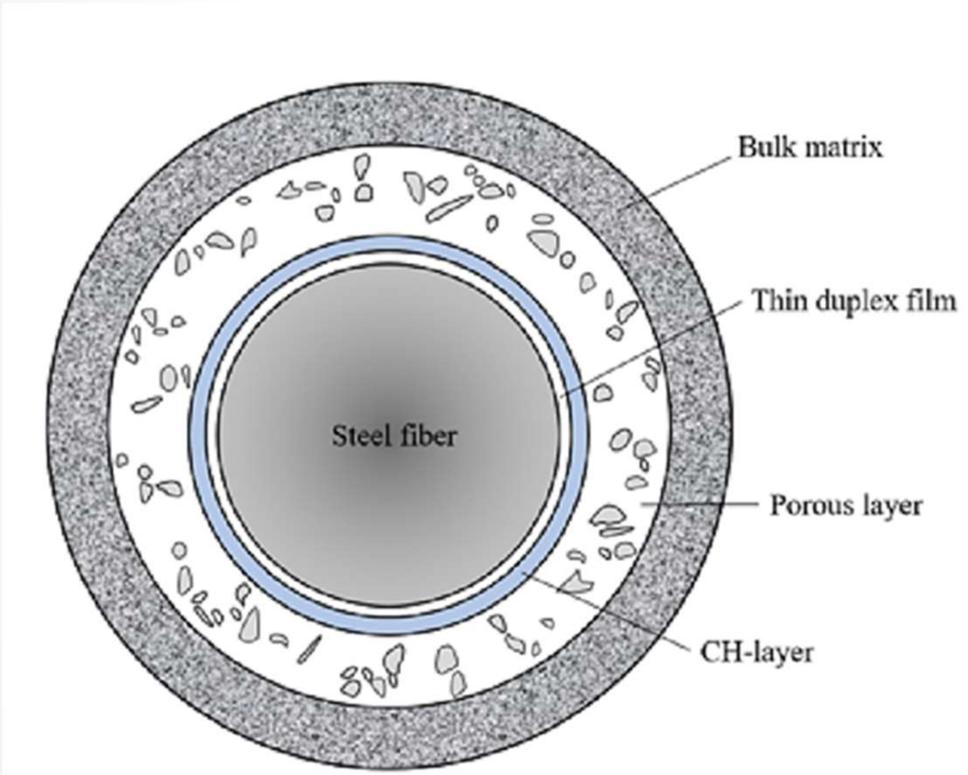
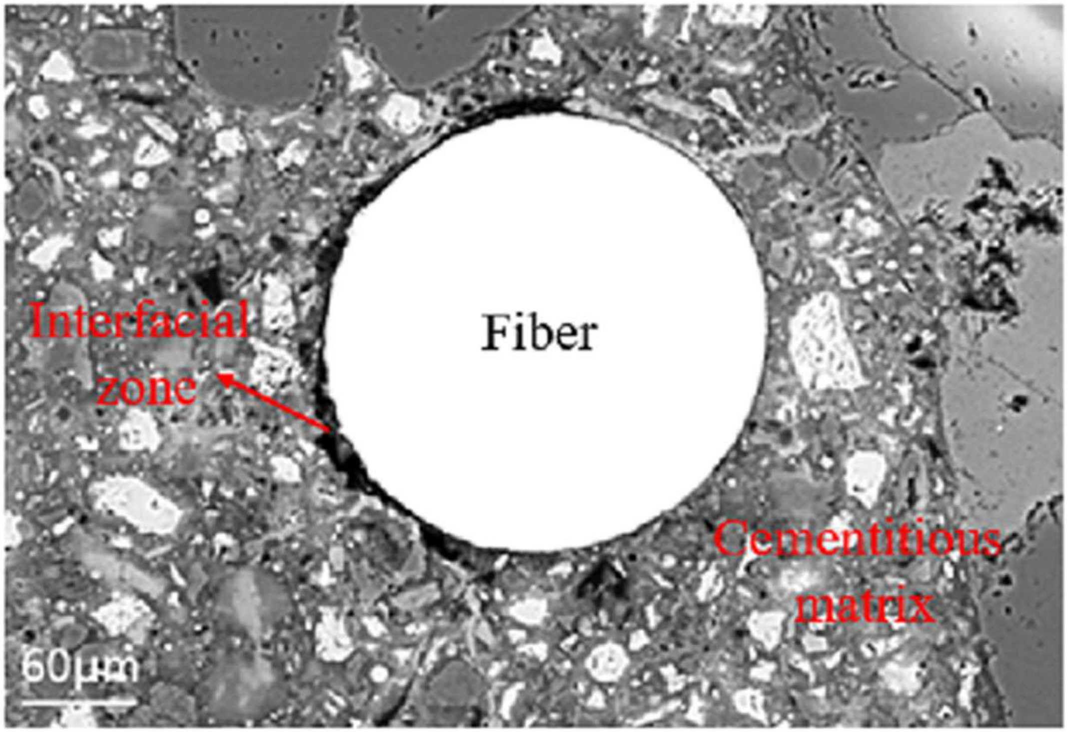


Figure ref: A. Bentur, S. Mindess, Fibre reinforced cementitious composites, CRC Press (2006)

3. Fiber-Matrix Interaction

The structure of fiber – matrix interface



ITZ between fiber and matrix

Figure ref: Z. Pi, H. Xiao, J. Du, M. Liu, H. Li, "Interfacial microstructure and bond strength of nano-SiO2-coated steel fibers in cement matrix", Cem. Concr. Compos., 103 (2019), pp. 1-10

3. Fiber-Matrix Interaction

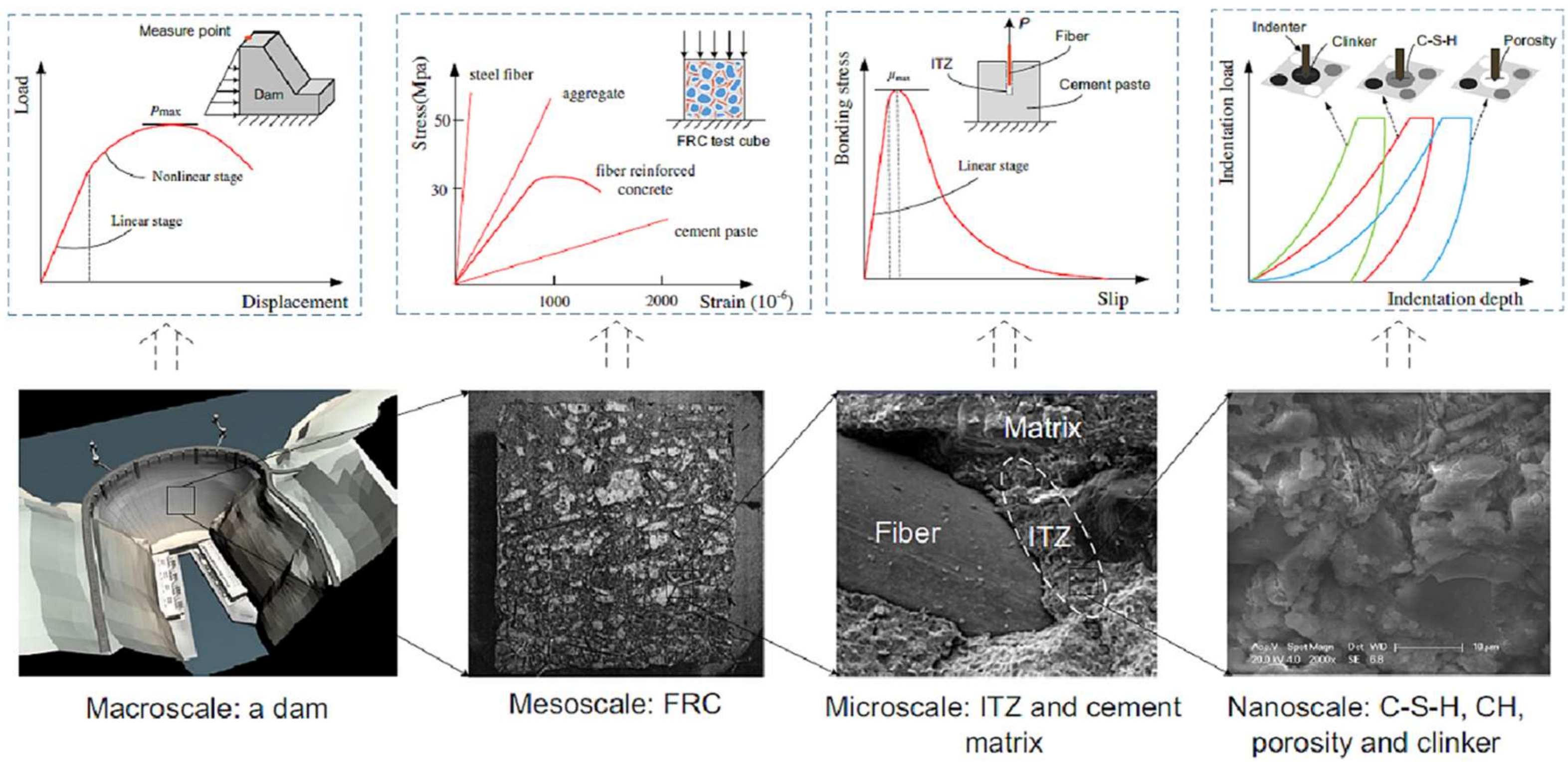


Fig. 2. Multiscale concept of FRC [19].

Figure ref: Nano-mechanical behavior of the interfacial transition zone between steel-polypropylene fiber and cement paste, Construction and Building Materials, Vol 145, August 2017, pp.619-638

The structure of fiber – matrix interface

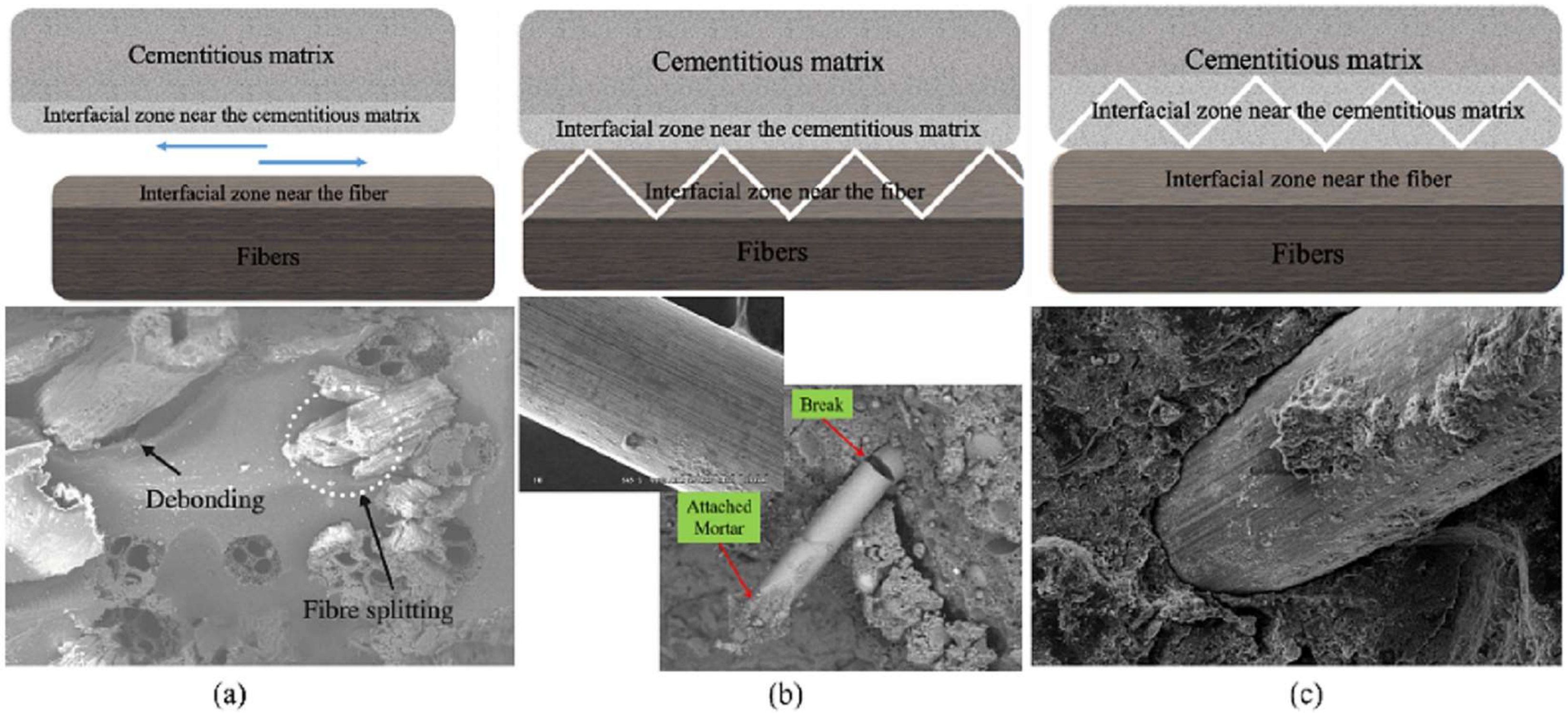


Fig. 3. Failure modes of fiber–matrix interface: (a) debonding failure, (b) failure in fibers, (c) failure in cementitious matrix. Reproduce from [22–24,26,35,36].

Chen Lin, Terje Kanstad, Stefan Jacobsen, Guomin Ji, "Bonding property between fiber and cementitious matrix: A critical review, Construction and Building Materials", Vol 378, May 2023, 131169

The structure of fiber – matrix interface

- When structures are subjected to tensile load, cracks develop until they reach the interface and continue to grow when the fiber is fractured or pulled out.
- During this process, forces to prevent slip between fiber and matrix are developed due to the friction, adherence, and the anchoring force between fibers and matrix.
- A weak bond between matrix and fiber surface will lead to the pullout phenomenon of fiber at lower loads, and fibers cannot contribute much to against crack development.

Chen Lin, Terje Kanstad, Stefan Jacobsen, Guomin Ji, "Bonding property between fiber and cementitious matrix: A critical review, Construction and Building Materials", Vol 378, May 2023, 131169

The structure of fiber – matrix interface

- Conversely, a relatively strong bonding property would allow the stress transfer from concrete matrix to fiber, thus improving the FRC's mechanical performance.
- But when the fiber–matrix bond becomes too strong, fiber cannot contribute fully to the post-crack strength due to the rupture of fibers. Therefore, the efficiency of force transfers between fiber and matrix plays a critical role in the overall performance of FRC structures.

Chen Lin, Terje Kanstad, Stefan Jacobsen, Guomin Ji, "Bonding property between fiber and cementitious matrix: A critical review, Construction and Building Materials", Vol 378, May 2023, 131169

Methods to improve fiber matrix bond

Table 1
Different improvement methods for bonding between fiber and cementitious matrix.

Author-Ref.	Improvement method	Type of fiber and matrix	Related bonding mechanism	Improvement of bonding
D.-Y. Yoo et al. [81]	Geometric modification	Deformed steel fiber/UHPC	Mechanical interlocking	2.8–4.1
H. Zhang et al.[82]	Geometric modification	Deformed steel fiber/UHPC	Mechanical interlocking	1.8–4.1
T. Sugama et al.[83]	Zinc phosphating	Steel fiber/Cement paste	Mechanical interlocking	1.4
D. Zhang et al.[17]	Microbially induced calcite precipitation treatment	Steel fiber/UHPC	Mechanical interlocking	2.5
Ali et al.[84]	Treatment with boiling water and chemicals	Coconut fiber/Concrete	Mechanical interlocking	2.8
C. Asasutjarit et al.[85]	Boiled and washed	Coconut fiber/Light weight concrete	Mechanical interlocking	6.7
L. Yan et al.[86]	Alkali-treated	Coir fiber/Cement composites	Mechanical interlocking	\
M. Azeem et al.[60]	Chemical group functionalization	Carbon nanotube/Cement paste	Electrostatic attraction	
Ao Zhou et al.[63]	Silane coupling agent (SCA) treatment	Steel fiber/cementitious composites	Chemical bonding	1.6
T. Liu, R. Bai, Z. Chen et al.[87]	SCA treatment	Polyethylene fiber/Strain hardening cementitious materials	Chemical bonding	1.6
M. Lu et al.[61]	Nanomaterial coating	SiO_2 coated carbon fiber/cement matrix	Chemical bonding	3.0
K. H. Khayat[62]	Nanomaterial coating	Steel fiber/UHPC	Chemical bonding	1.3
Schneider K et al.[88]	Plasma treatment	Carbon fiber/Concrete	Both chemical and mechanical bonding	1.8–2
H-C. Wu et al.[89]	Plasma treatment	Polyethylene fiber/Cement paste	Both chemical and mechanical bonding	1.5
H. D. Miller et al.[90]	Plasma treatment	Steel fiber/Cement mortar	Both chemical and mechanical bonding	1.3
A. Beglarigale et al.[1]	Improvement of cementitious matrix (Mineral admixtures)	Steel fiber/Mortar	Mechanical interlocking	1.7–3.2
Z. Yunsheng et al.[91]	Improvement of cementitious matrix (Curing condition)	Steel fiber/Reactive powder concrete (RPC)	Mechanical interlocking	2.0
Antonova [11]	Increased roughness by sanding vs electropolishing	Steel fiber/Cement paste	Reduced ITZ thickness	2.5

Methods to improve fiber matrix bond

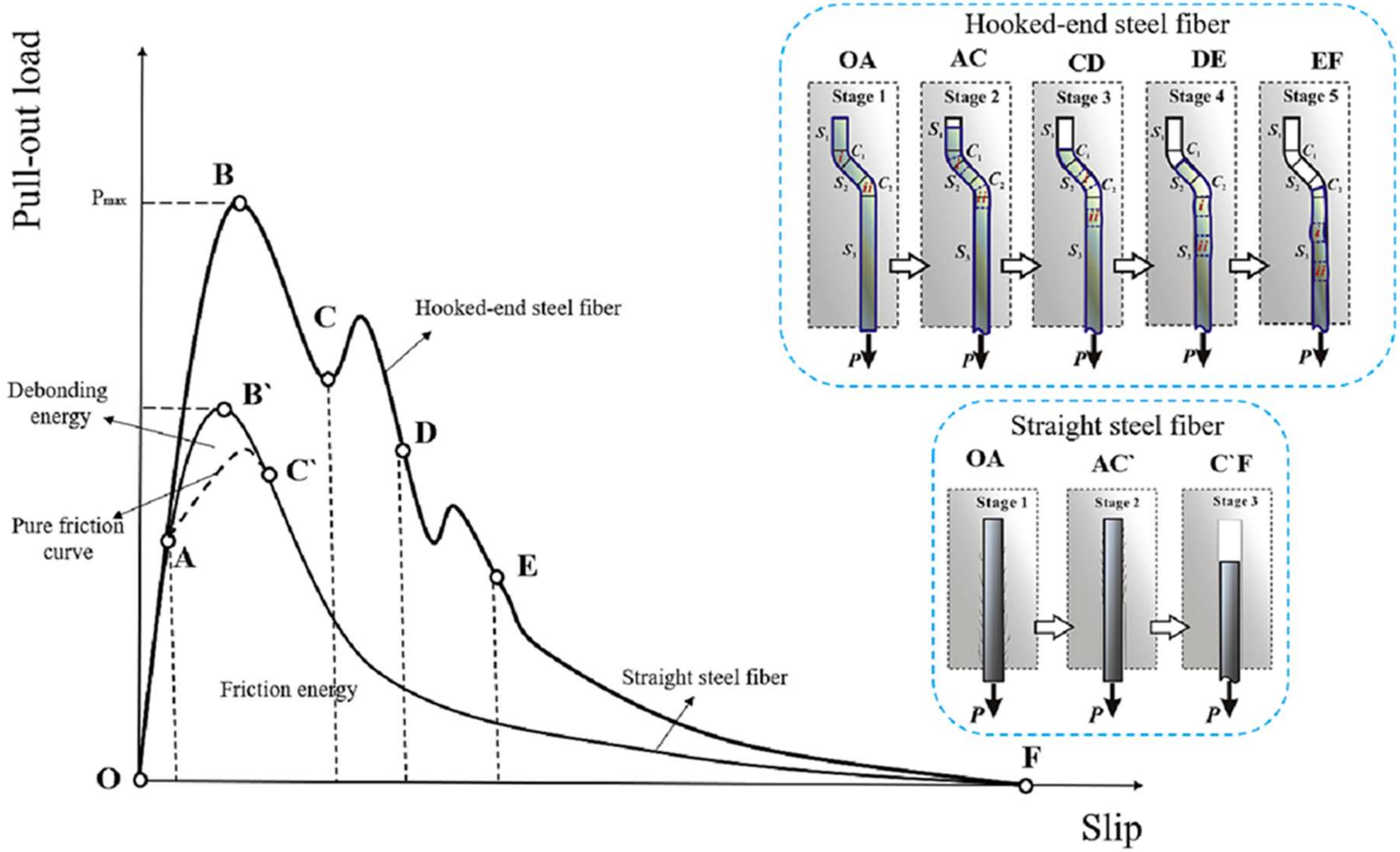


Fig. 6. Pullout behavior of single hooked-end steel fibers and straight steel fibers. Reproduce from [98].

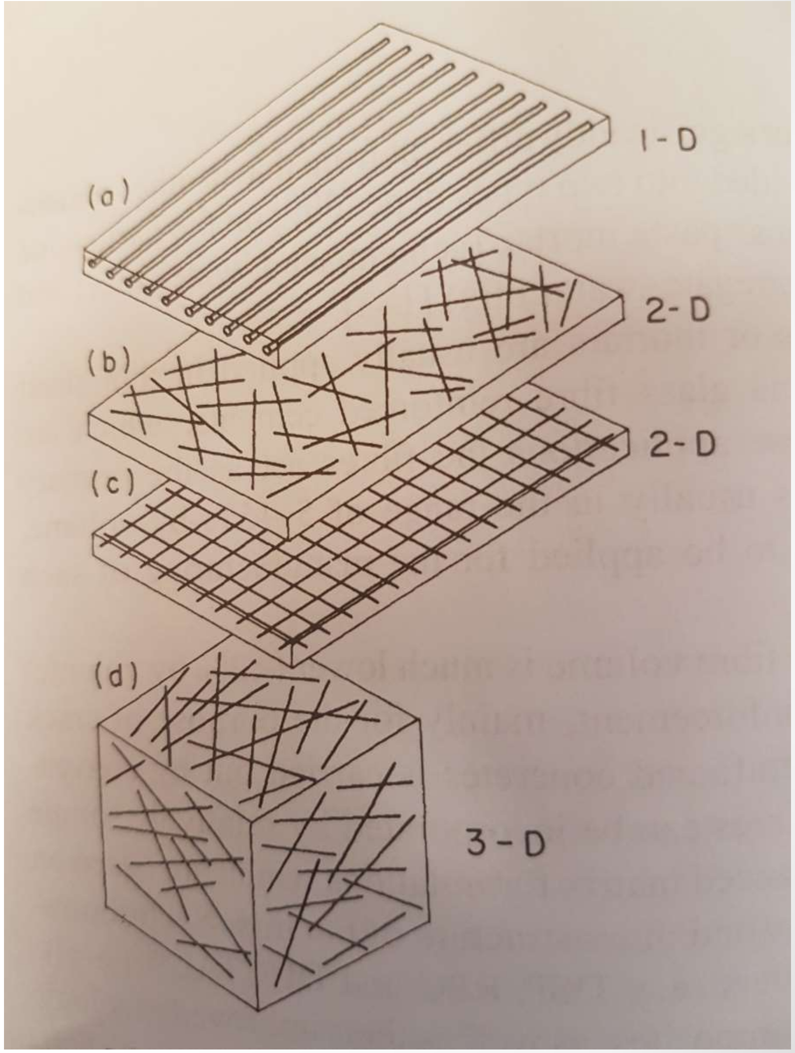
2. Structure of FRCCs

2.2. FIBERS;

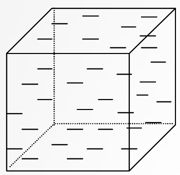
i) Dispersion of the fibers

  a. Continuous
  b. Discontinuous

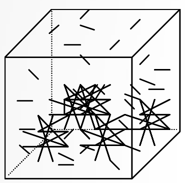
Fibers can be dispersed in 1-D, 2-D or 3-D!



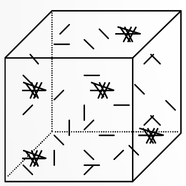
Fiber dispersion state



Orientation of fibers



Segregation
(i.e. settlement)



Local Clumping
(especially for small fibers)

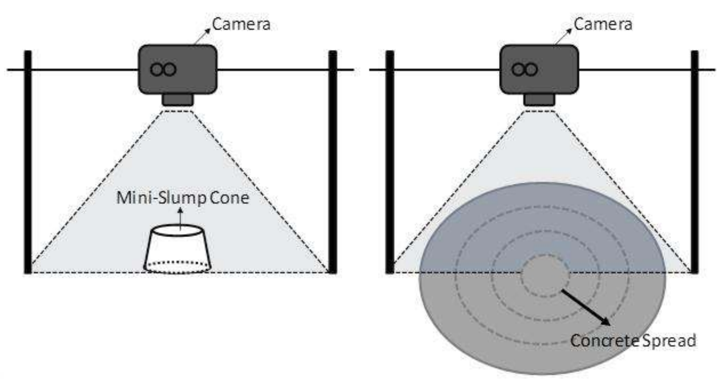
FIBER DISPERSION STATE!!!

Ozyurt, N., Correlating fiber dispersion, rheology and mechanical performance for fiber-reinforced cement-based materials, PhD Thesis, Feb 2006, Istanbul Technical University, Graduate Institute

Evaluating fiber dispersion in the fresh state

Mini-Slump Flow Test and particle image velocimetry – Clumping and orientation!

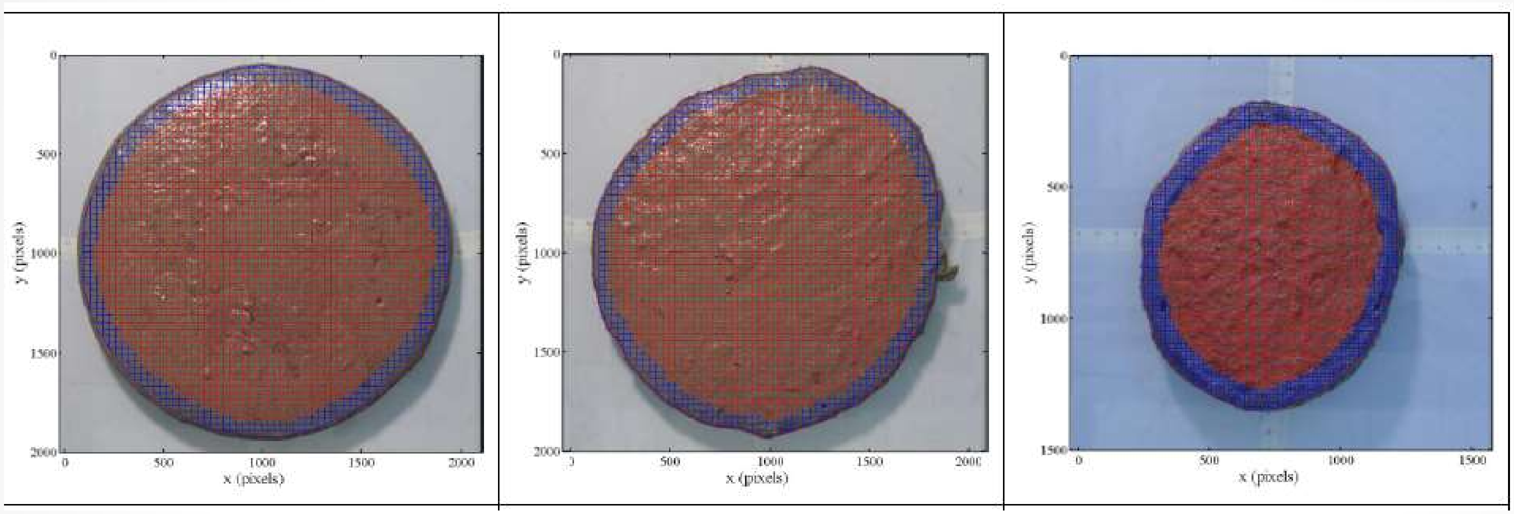
- *Mini-slump cone flow diameters were measured*
- *A digital camera was mounted right above the slump plate*
- *Images captured every sec.*
- *The resulting images were divided into a grid of test patches*
- *Displacement vectors are found by comparing the two following images*

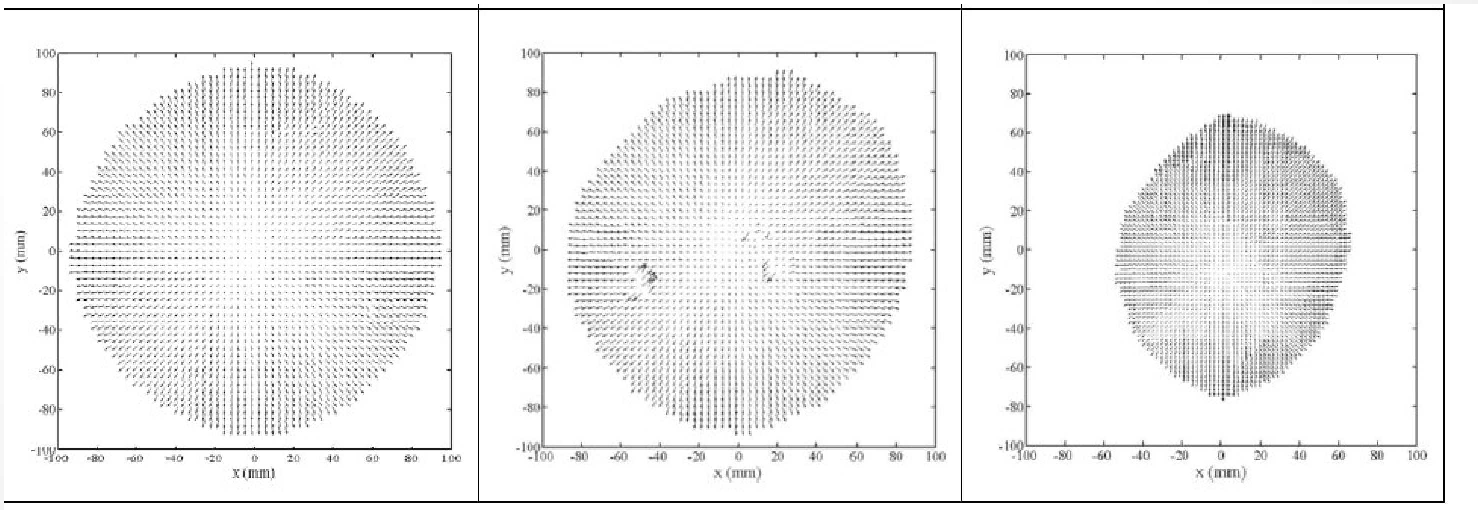


Schematic view of the digital camera location and mini-slump test setup

Sanal, I, et al., Particle image velocimetry (PIV) to evaluate fresh and hardened state properties of self compacting fiber reinforced cementitious composites (SC-FRCCs), Construction and Building Materials, 78 (2015) 450-463

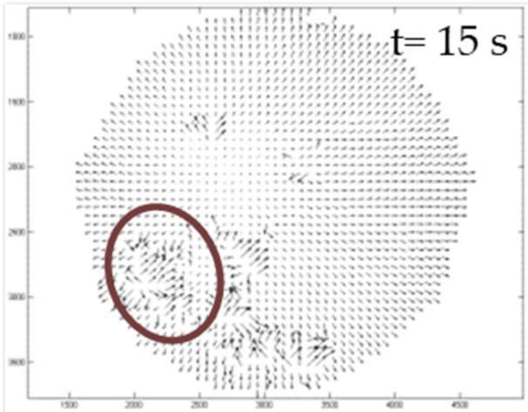
Evaluating fiber dispersion in the fresh state



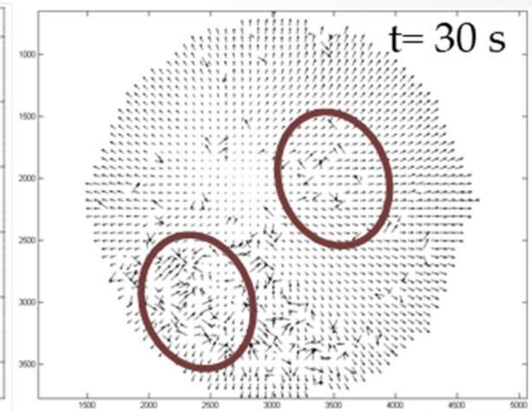


Evaluating fiber dispersion in the fresh state

Grids for the PIV analysis



PIV Analysis Results
(Strain Vector Plot)

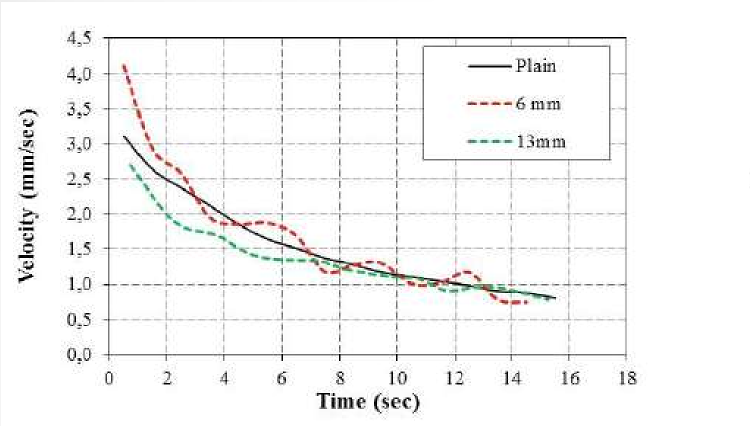


PIV Analysis Results
(Strain Vector Plot)

- As the result of PIV analysis, vector plots and strain distributions were obtained
- Vector plot showed the flow of fresh concrete
- As a result, flow of conrete in each time interval can be analyzed
- Driving ability of the fresh concrete can be examined
- If there is any fiber clumping or inhomogenity, it can be observed.

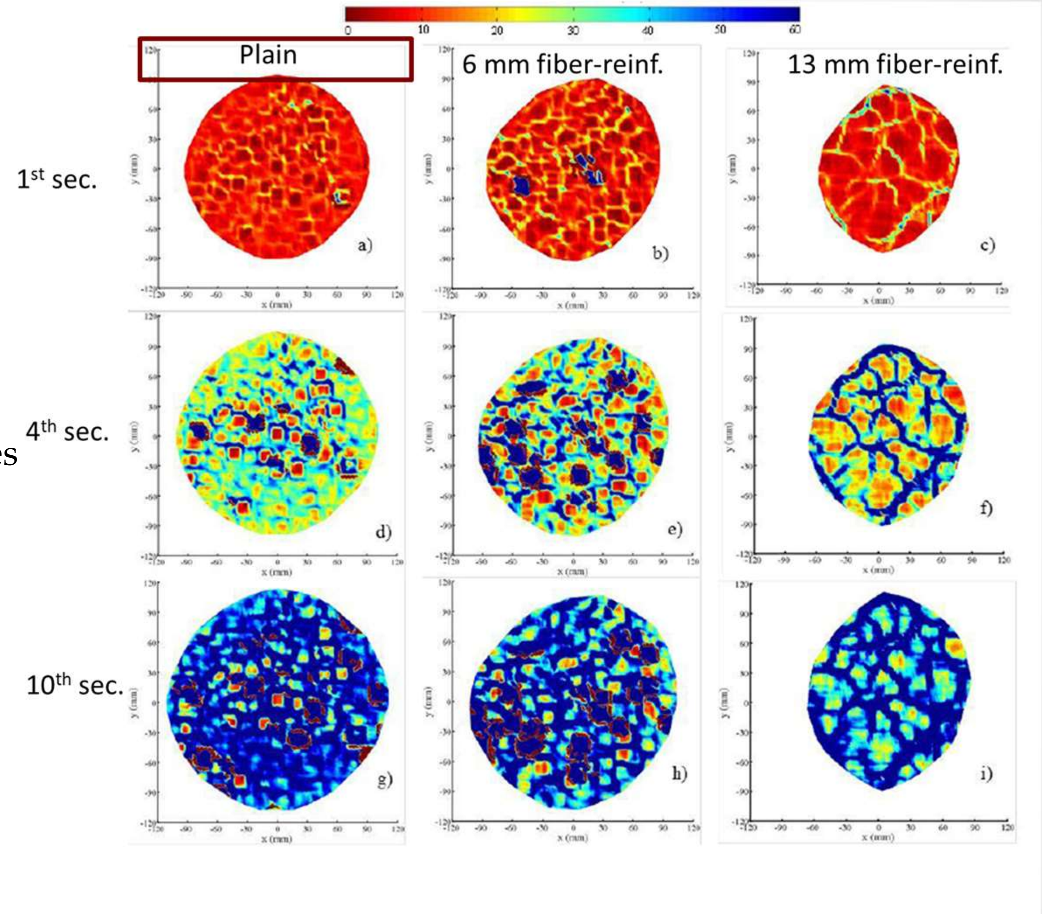
Mesh generation using 128x128 pixel patches spaced at 32 pixels center-to-center

Evaluating fiber dispersion in the fresh state



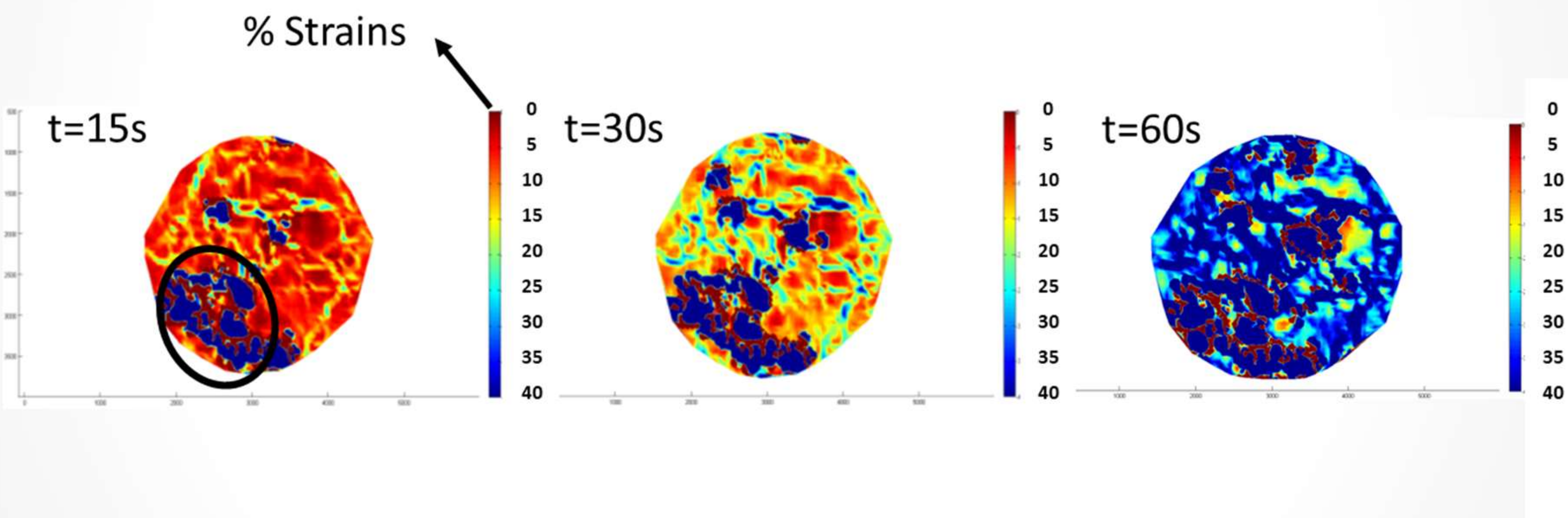
Velocity vs. time relation of the mixes

Mini slump flow (PIV analysis)

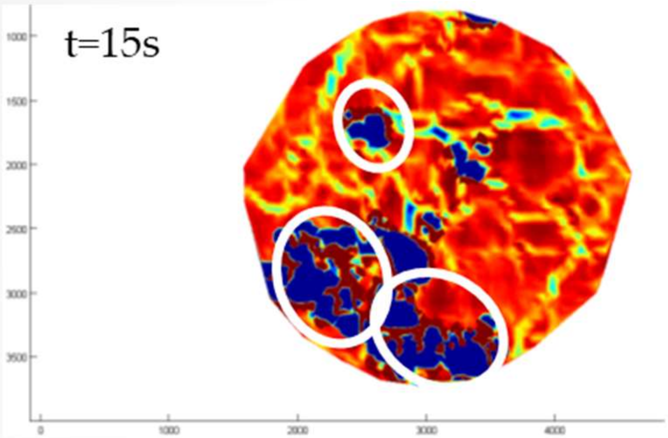


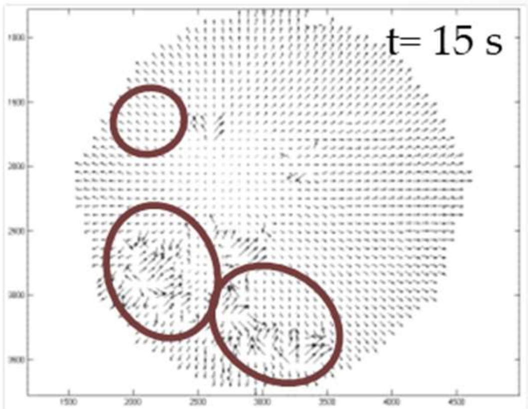
Evaluating fiber dispersion in the fresh state

- Strain distributions in fresh concrete can also be observed with PIV technique for each time interval,
- The flowing parts and the blocked parts can be visually observed from these images



Evaluating fiber dispersion in the fresh state





- Results of the vector plot and strain distributions were compared in order to verify the fiber clumping and flowing observations

Evaluating fiber dispersion in the fresh state

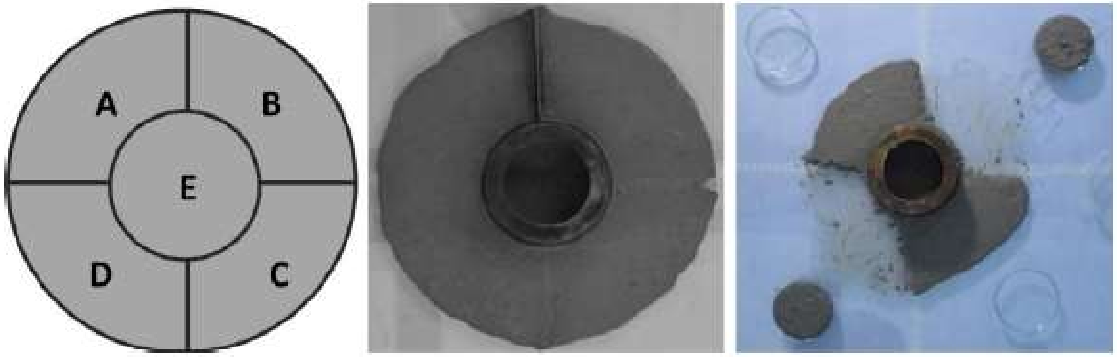
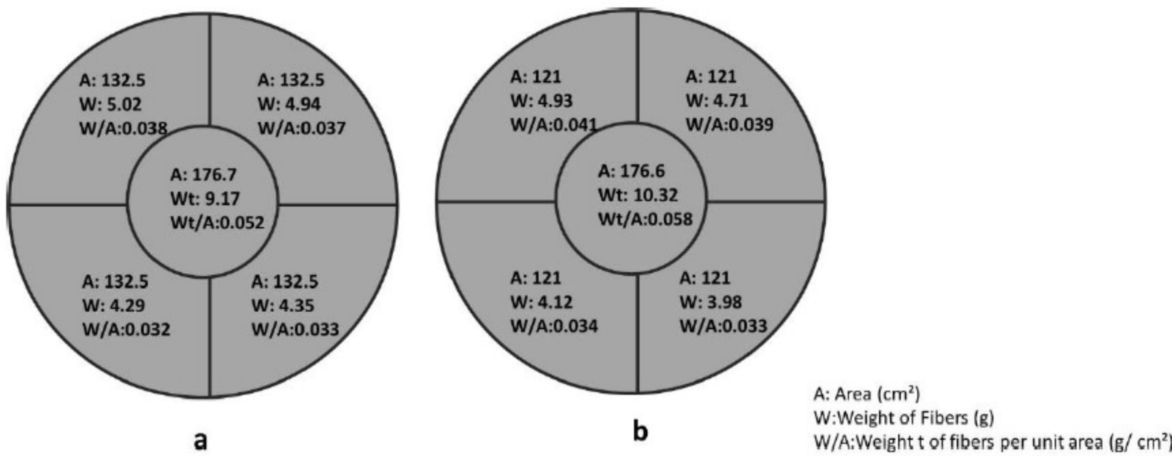


Figure 2. Divided regions of mini-slump flow putty for fiber counting



Evaluating fiber dispersion in the fresh state

Table 1
Concrete mix designs and vibration times

Fiber type	Mix design		Vibration time
6 mm fibers $w/c = 0.40$ Fiber content: 1% vol.	A_0	sp	No vibration
	A_2		2 min
	A_8		8 min
	B_8	sp + vma	8 min
	C_8	vma	8 min
40 mm fibers $w/c = 0.40$ Fiber content: 1% vol.	A_2	sp	2 min
	SCC	sp	No vibration

Table 6
Rheological characteristics of cement pastes

		Mix Design	Viscosity (Pa s)	Standard deviation (Pa s)	Yield stress (Pa)	Standard deviation (Pa)
Paste	sp	A	1.20	0.15	46.73	5.05
	sp + vma	B	3.52	0.18	110.65	2.31
	vma	C	5.45	0.29	76.73	2.07
	scc	SCC	7.22	0.51	19.48	2.80

- Ozyurt N., et al. Correlation of fiber dispersion, rheology and mechanical performance of FRCs, Cement and Concrete Composites, (29), 2007, 70-79

Evaluating fiber dispersion in the fresh state

Table 4
Fiber content distribution in specimens for different mix designs and vibration times

	6 mm fibers					40 mm fibers	
	A_0	A_2	A_8	B_8	C_8	A_2	SCC
a	0.99	0.90	0.38	0.89	0.97	0.70	0.92
b	0.99	0.92	1.02	0.88	1.00	0.97	1.19
c	0.96	1.02	1.20	0.97	1.00	0.98	1.08
d	0.89	1.15	1.44	0.98	1.01	1.30	1.13

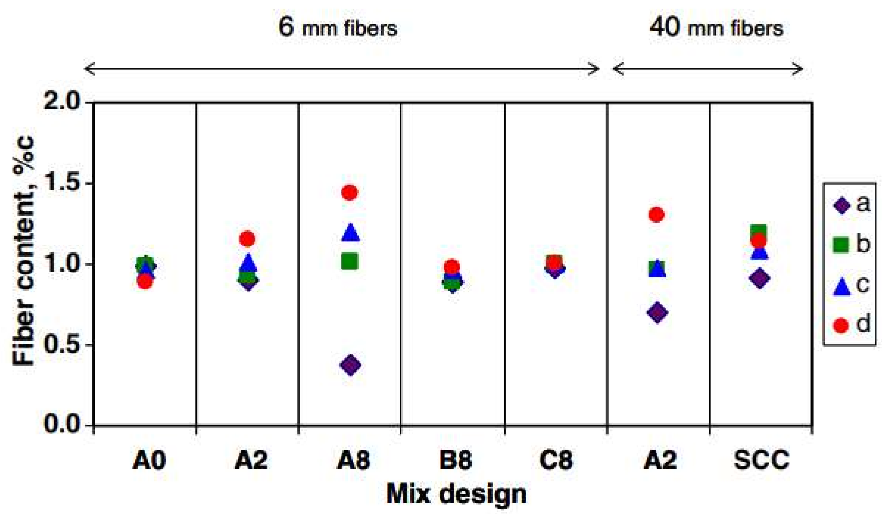


Fig. 6. Fiber content distribution in specimens for different mix designs and vibration times.

- Ozyurt N., et al. Correlation of fiber dispersion, rheology and mechanical performance of FRCs, Cement and Concrete Composites, (29), 2007, 70-79

Evaluating fiber dispersion in the fresh state

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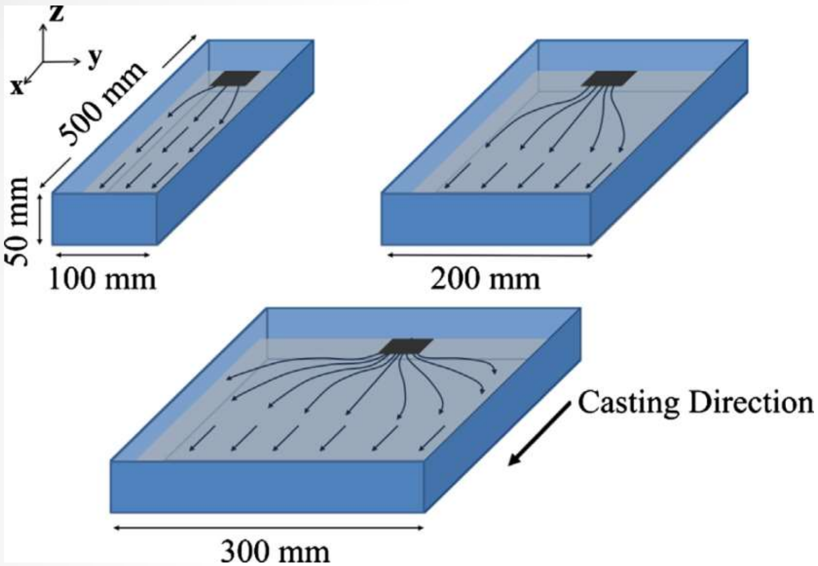
	scc	SCC	7.22	0.51	19.48	2.80

	A	**B**	**C**	**SCC**
Segregation Resistance	Low	**High**	**High**	**Medium**
Placeability (without vibration)	Poor	Poor	Poor	**Good**
Density	**High**	Low	Low	**High**

- Ozyurt N., et al. Correlation of fiber dispersion, rheology and mechanical performance of FRCs, Cement and Concrete Composites, (29), 2007, 70-79

Fiber dispersion in the hardened state



Variation of pre-defined parameters

- **First parameter, ''flow width/fiber length'' (w/fL)**
- **Second parameter, ''flow thickness/fiber length'' (w/fL)**

Parameters investigated in the scope of the study.

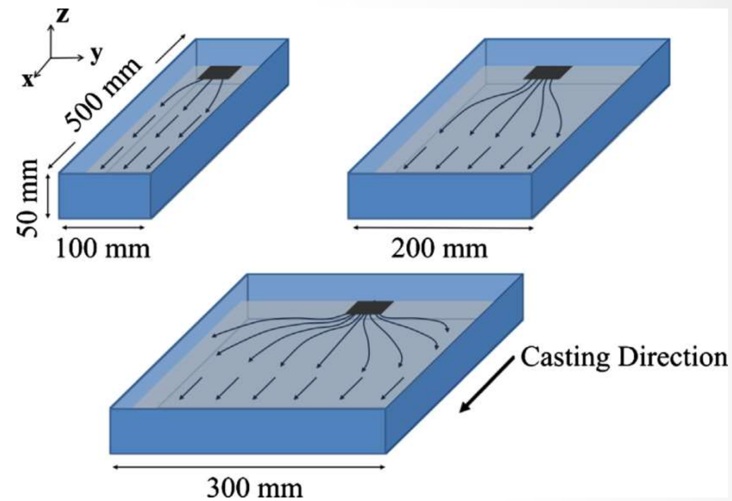
Fiber length (mm)	6	13
Flow width (mm)	Flow width/fiber length (w/f_L)	
100	16.7	7.7
200	33.3	15.4
300	50	23.2
Flow thickness (mm)	Flow thickness/fiber length (t/f_L)	
25	4.2	1.9
50	8.3	3.9

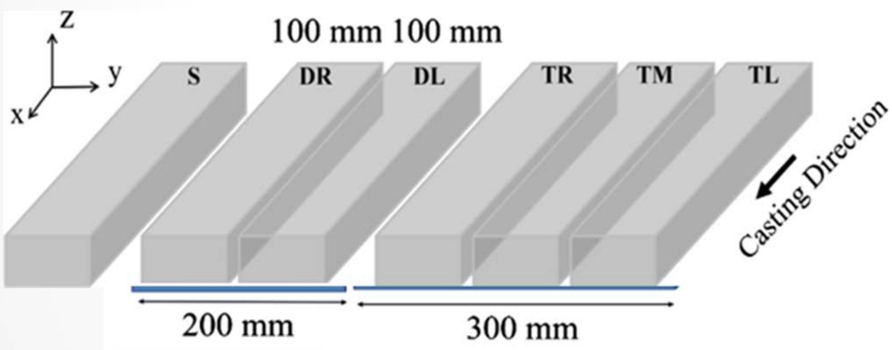
- Sanal, I and Ozyurt N., To what extent does the fiber orientation affect mechanical performance, Construction and Building Materials, 44 (2013), 671-681

Fiber dispersion in the hardened state

- In order to obtain various flow behaviors
  - Flow width was varied to be 100, 200 and 300 mm
  - Flow thickness was varied to be either 25 mm or 50 mm

- Two mixes were cast by varying fiber length
- Before 4-point flexural testing, specimens were cut out, in order to have same width of 100 mm





Sanal, I and Ozyurt N., To what extent does the fiber orientation affect mechanical performance, Construction and Building Materials, 44 (2013), 671-681

Fiber dispersion in the hardened state

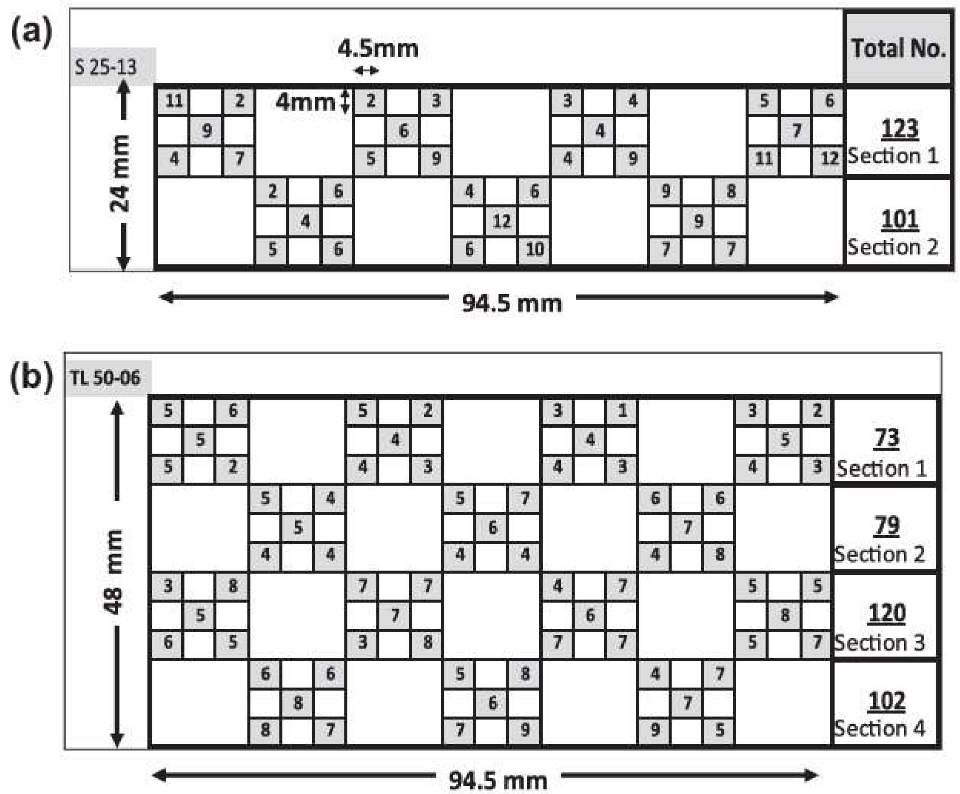


Fig. 7. Fiber numbers in each square of (a) S 25–13 and (b) TL 50–06 specimens. (Top 1 mm for 25 mm thick section and top 2 mm for 50 mm thick section was not studied since a clear picture could not be taken due to rough surface).

Fiber dispersion in the hardened state

Table 4
Number of fibers and percentages of fibers in different sections of the specimens.

Specimen	Section	Total no. of fibers	Total square area (mm^2)	No. of fibers per unit area	% of fibers in different sections
S 25-13	Sec 1	123	320	0.384	47.7
	Sec 2	101	240	0.421	52.3
TL 25-13	Sec 1	124	320	0.388	48.4
	Sec 2	99	240	0.413	51.6
S 25-06	Sec 1	109	320	0.341	44.3
	Sec 2	103	240	0.429	55.7
TL 25-06	Sec 1	107	320	0.334	41.5
	Sec 2	113	240	0.471	58.5
S 50-06	Sec 1	78	320	0.244	19.4
	Sec 2	67	240	0.279	22.2
	Sec 3	105	320	0.328	26.1
	Sec 4	97	240	0.404	32.2
TL 50-06	Sec 1	73	320	0.228	16.8
	Sec 2	79	240	0.329	24.2
	Sec 3	120	320	0.375	27.6
	Sec 4	102	240	0.425	31.3
S 50-13	Sec 1	151	320	0.472	20.3
	Sec 2	148	240	0.617	26.5
	Sec 3	191	320	0.597	25.7
	Sec 4	153	240	0.638	27.5
	Sec 1	65	320	0.203	17.7
	Sec 2	75	240	0.313	27.2
TL 50-13	Sec 3	123	320	0.384	33.4
	Sec 4	61	240	0.250	21.7

Fiber dispersion in the hardened state

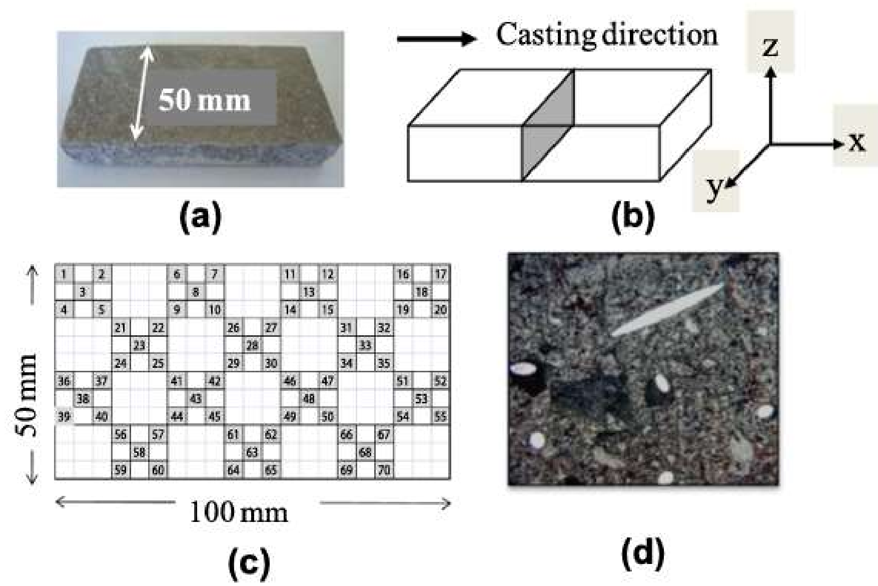


Fig. 8. (a) 50 mm thick cross-section examined for the fiber alignment analysis, (b) casting and cutting directions of sections, (c) sub-sections selected for analyses and (d) an optical microscope image used for analysis.

Fiber dispersion in the hardened state

Table 6
Fiber orientation density results and variation of w/f_L and t/f_L for the specimens.

Specimen	*X*	*Y*	*Z*	w/f_L	t/f_L
S 25-06	0.703	0.165	0.132	16.7	4.2
DL 25-06	0.672	0.177	0.151	33.3	
TL 25-06	0.659	0.184	0.156	50	
TM 25-06	0.660	0.177	0.163	50	
S 50-06	0.707	0.148	0.144	16.7	8.3
DL 50-06	0.664	0.158	0,177	33.3	
TL 50-06	0.618	0.199	0.183	50	
TM 50-06	0.626	0.197	0.177	50	
S 25-13	0.568	0.235	0.197	7.7	1.9
DL 25-13	0.588	0.197	0.216	15.4	
TL 25-13	0.496	0.311	0.193	23.2	
TM 25-13	0.562	0.223	0.214	23.2	
S 50-13	0.632	0.151	0.217	7.7	3.9
DL 50-13	0.601	0.177	0.223	15.4	
TL 50-13	0.547	0.206	0.247	23.2	
TM 50-13	0.551	0.234	0.215	23.2	

2. Structure of FRCCs

2.3. The structure of fiber – matrix interface

Interfacial transition zone (ITZ) – vicinity of the reinforcing inclusion, microstructure of the paste matrix is considerably different from that of the bulk paste

Structure of transition zone highly affects fiber – matrix bond!

Contents

3. Tensile behavior

Fiber - matrix interaction

- Fundamental property that affects performance
- Many factors are effective
  - Condition of matrix
  - Matrix composition
  - Geometry of the fiber
  - Type of fiber
  - Surface characteristics of the fiber
  - Relative stiffness of fiber and matrix
  - Orientation of fibers
  - Volume fraction of fibers
  - Rate of loading
  - Durability of the fiber and long term effects

3. Tensile behavior

Fiber - matrix interaction

- Fiber length should be at least twice the largest aggregate diameter to prevent crack propagation in bridging cracks beyond the coarse aggregates.
- UHPFRC is usually produced by using straight short steel fibers (0,5-2 cm) since aggregate size is quite small for UHPFRC.

3. Fiber - matrix interaction

- 3 types of interactions are important
  - Physical and chemical adhesion; only important when very thin fibers (10μm) and cement matrices with very refined microstructure (very low porosity)
  - Friction
  - Mechanical anchorage induced by deformations on the fiber surface or by geometry (hooks, crimps, etc.)

3. Fiber matrix interaction
General summary

- **Pre-cracking stage;** no cracking, elastic stress transfer is the dominant mechanism; longitudinal deformations of the fiber and the matrix at the interface are compatible. This mode is used when predicting limit of proportionality and the 1st crack stress of the composite.
- **Post-cracking stage;** increased load results in debonding across the surface, process becomes frictional slip. Great importance in the post – cracking zone, ultimate strength and composite strain are controlled by this mode of stress transfer.

3. Fiber matrix interaction General summary

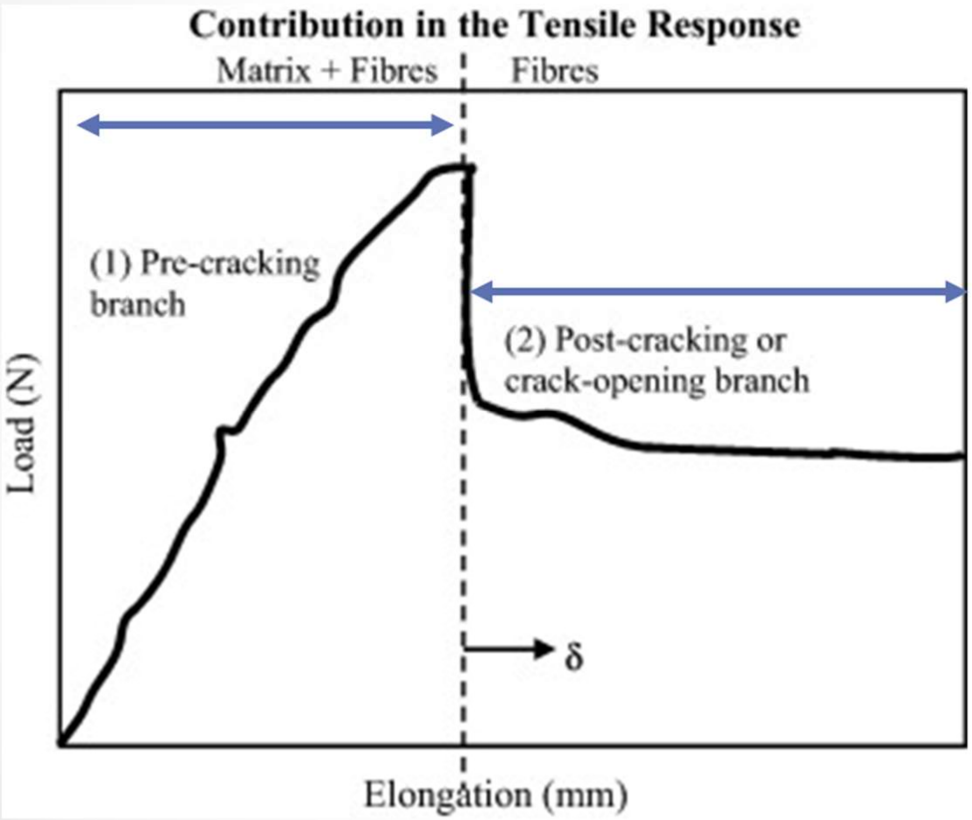


Fig. 3. General response of concrete under direct tension.

- Khan and Ayub, «Modelling of the pre and post-cracking response of the PVA fibre reinforced concrete subjected to direct tension», Construction and Building Materials, Vol 120, pp.540.

3. Fiber matrix interaction
General summary

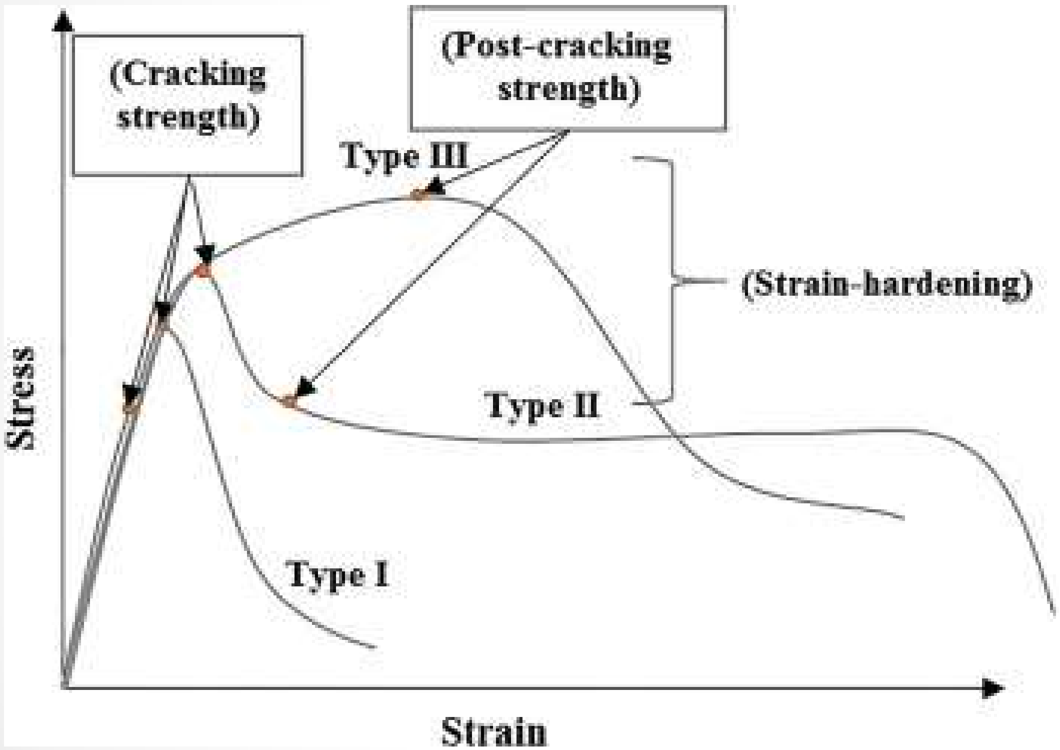


Fig. 1. Generalised stress-strain behaviour under direct tension and failures (pva fibers)

- Khan and Ayub, «Modelling of the pre and post-cracking response of the PVA fibre reinforced concrete subjected to direct tension», Construction and Building Materials, Vol 120, pp.540.

3. Fiber matrix interaction
General summary

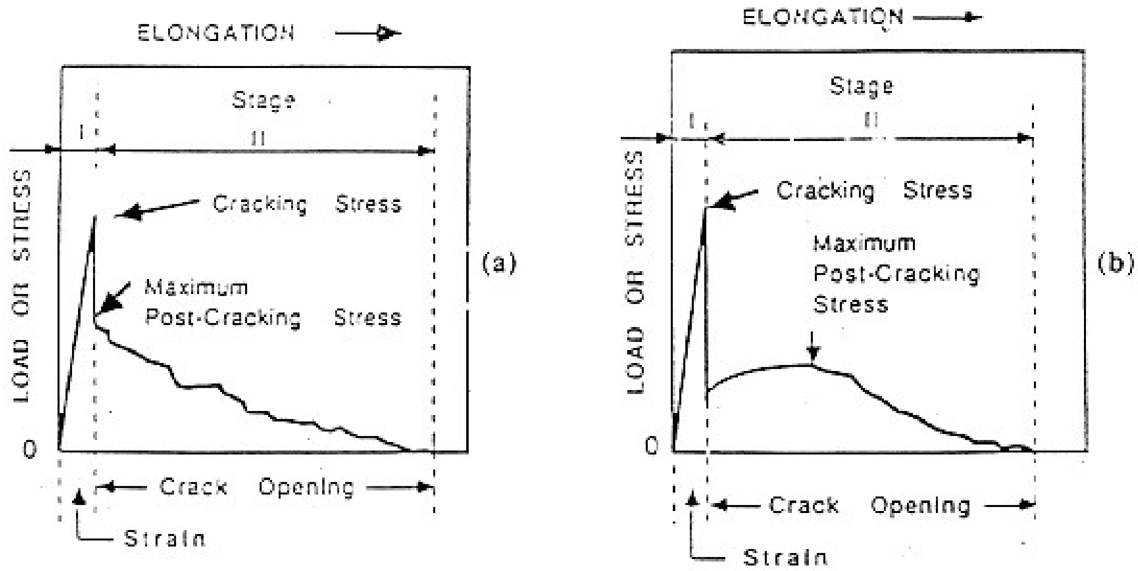


Figure 5.14 Comparison of experimentally observed stress-elongation curves of steel reinforced mortar and SIFCON [Naaman 1985]

REASONS for the DIFFERENT BEHAVIORS OBTAINED?

- https://www.fhwa.dot.gov/publications/research/infrastructure/structures/hpc/97030/chap5.cfm

3. Fiber – matrix interaction – Theory
i) Pull – out behavior

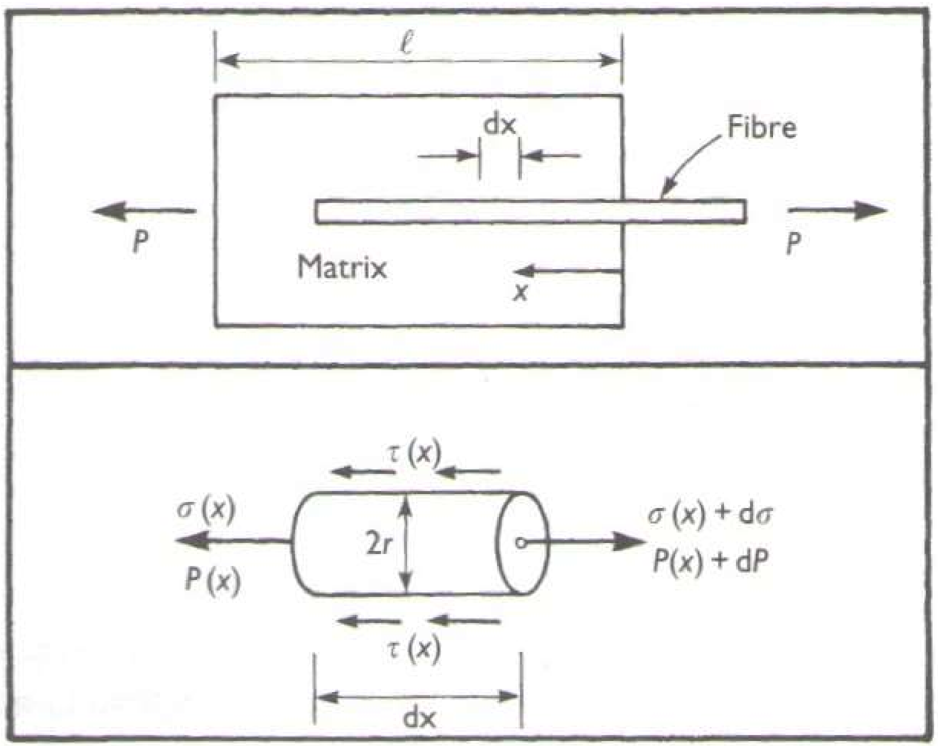


Figure 3.1 Pull out geometry to simulate fibre–matrix interaction.

3. Fiber – matrix interaction – Theory

i) Stress transfer in the uncracked composite (pre-cracking)

- Elastic stress transfer in the uncracked matrix
- Combined elastic and frictional stress transfer

ii) Stress transfer in the cracked composite (post-cracking)

3. Fiber – matrix interaction – Theory
i) Stress transfer in the uncracked composite

- Possible during initial stages of loading
- Practical applications is limited since in most cases matrix cracks during the service life

3. Fiber – matrix interaction – Theory
i) Stress transfer in the uncracked composite

Upon load application to matrix;

i. Part of the load is transferred to fiber along its surface.
ii. Shear stress develops along the surface of the fiber because of the difference in the stiffness between the fiber and the matrix. Some of the load is transferred to the fiber.

3. Fiber – matrix interaction – Theory

i) Stress transfer in the uncracked composite (pre-cracking)

- Elastic stress transfer
- Combined elastic and frictional stress transfer

ii) Stress transfer in the cracked composite (post-cracking)

Fiber – matrix interaction – Theory

i) Stress transfer in the uncracked composite

Elastic stress transfer

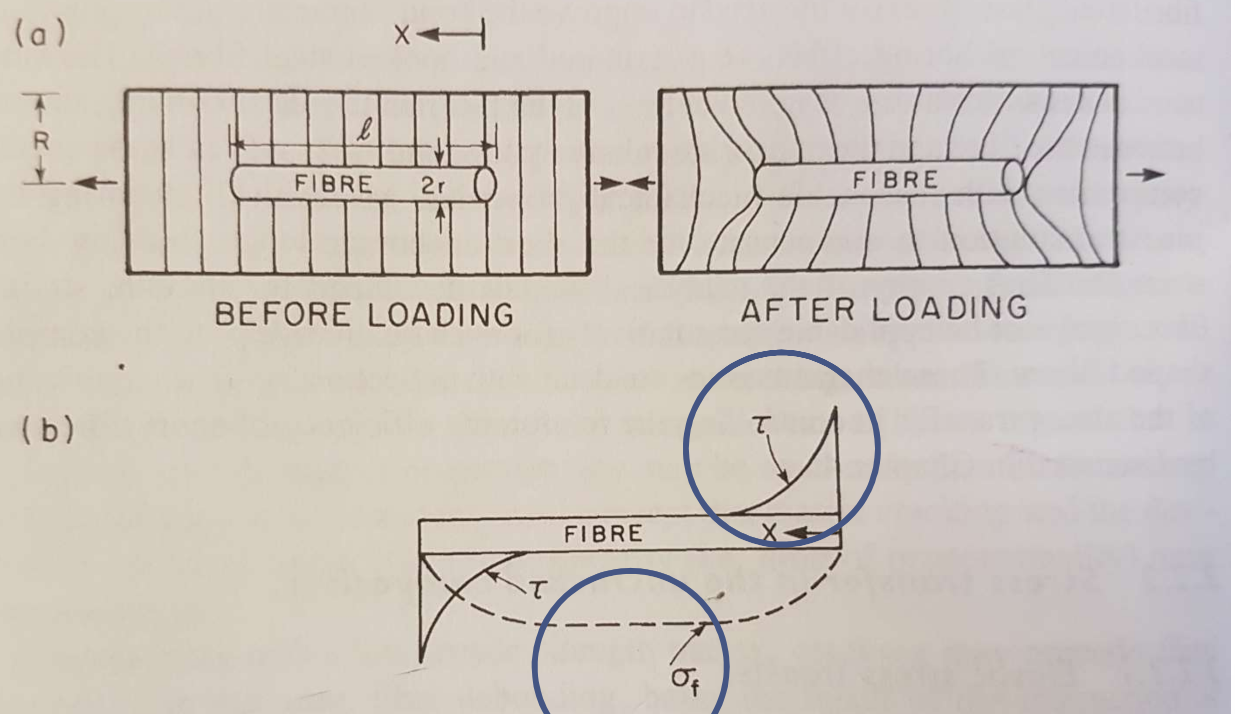
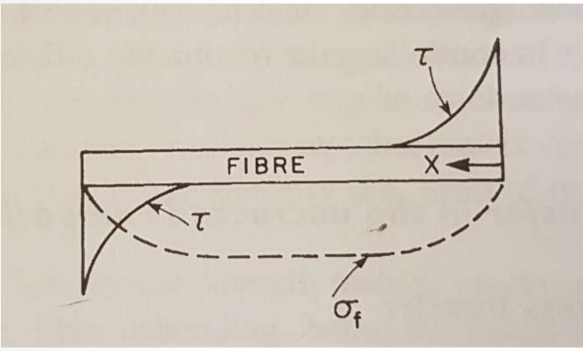


Figure 3.3 Schematic description of a fibre embedded in a matrix, and the deformation and stress fields around it: (a) geometry of the fibre and the deformation in the matrix around the fibre prior to and after loading; (b) elastic shear stress distribution at the interface (τ) and tensile stress distribution in the fibre (σ).

Fiber – matrix interaction – Theory

i) Stress transfer in the uncracked composite

Elastic stress transfer



τ = elastic shear stress distribution at the interface

τ has a maximum value at the ends and drops to zero at the center of the fiber.

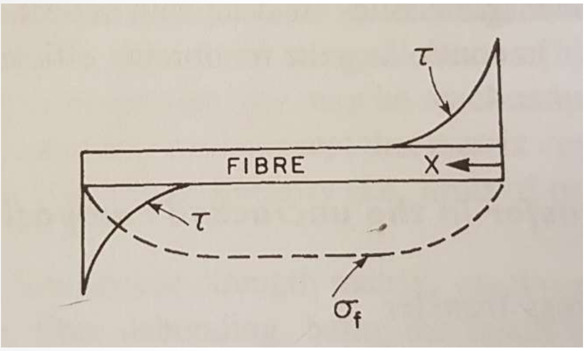
[τ (max) = τ (x = 0)]

σ = tensile stress distribution in the fiber

Stress is transferred from matrix to fiber at the end zone. σ increases from the fiber end moving inwards.

[σ_f (max) = σ_f (x = L/2)]

3. Fiber – matrix interaction – Theory
i) Efficiency of fiber reinforcement



Efficiency of fiber depends on the maximum tensile stress (σ) that can be transferred to fiber.

Maximum possible value; tensile strength of the fiber

Research show that maximum tensile stress develop in the fiber is well below the tensile strength of the fiber!!! FULL CAPACITY of the FIBERS are NOT USED!!!

Fiber – matrix interaction – Theory
i) Stress transfer in the uncracked composite

Elastic stress transfer

Mathematical models for shear stress and stress along the fiber – shear lag models

Assumptions;

i. Linear elastic behavior of fiber and matrix
ii. A perfect bond between fiber and matrix
iii. The interface being extremely thin and its property the same as the property of the matrix elsewhere
iv. The fibers having straight and regular cross-sections

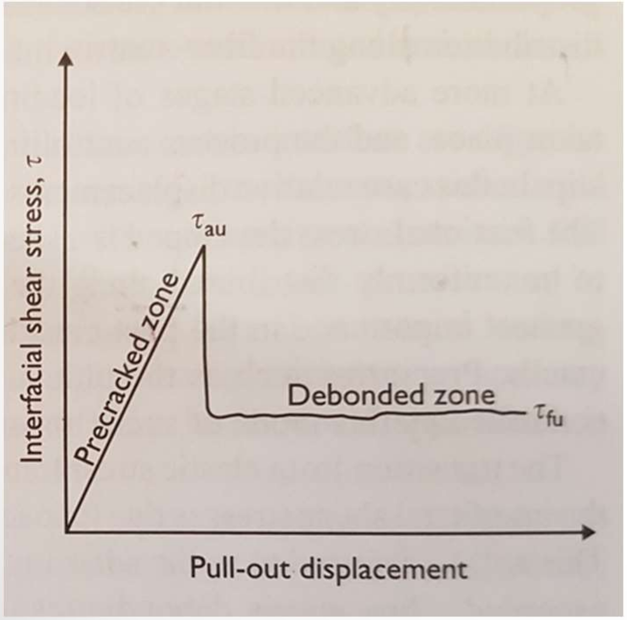
Fiber – matrix interaction – Theory

i) Stress transfer in the uncracked composite

From elastic stress transfer to frictional stress transfer

Limit value in elastic stress transfer?
DEBONDING occurs when $\tau_{max} > \tau_{au}$

τ_{au} ---- ADHESIONAL SHEAR BOND STRENGTH
τ_{fu} ..... FRICTIONAL SHEAR STRESS



Frictional resistance to slip will be activated

Fiber – matrix interaction – Theory
i) Stress transfer in the uncracked composite

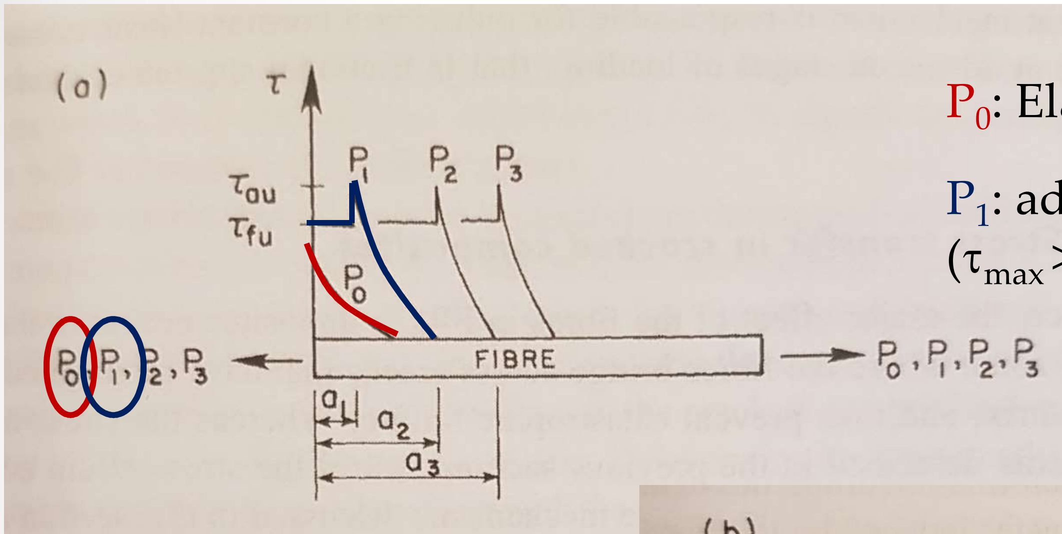
Combined elastic stress and frictional stress transfer

- 1st mechanism; DEBONDING
- 2nd mechanism ; FRICTIONAL RESISTANCE

Fiber – matrix interaction – Theory

i) Stress transfer in the uncracked composite

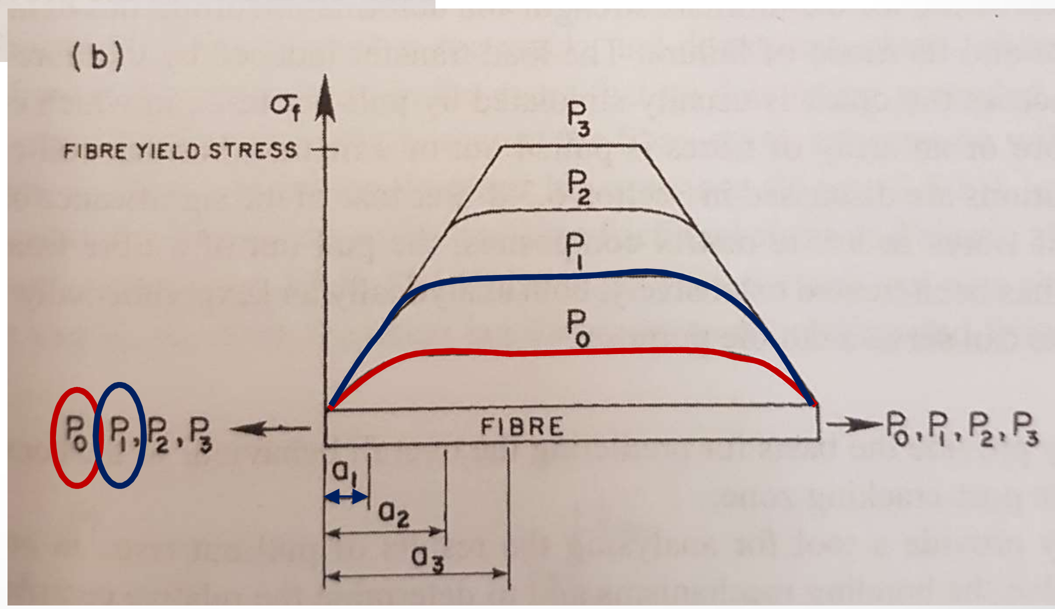
Combined elastic stress and frictional stress transfer



P_0: Elastic shear bond stress ($\tau_{max} < \tau_{au}$)

P_1: adhesional shear stress is exceeded ($\tau_{max} > \tau_{au}$)

τ_{fu} =Frictional shear bond strength



Fiber – matrix interaction – Theory
i) Stress transfer in the uncracked composite

Combined elastic stress and frictional stress transfer

Stages ;

1) P_0: Elastic shear bond stress ($\tau_{max} < \tau_{au}$)
2) P_1: adhesional shear stress is exceeded ($\tau_{max} > \tau_{au}$)
   Debonded zone a_1 is formed
3) P_2: load furhter increase, debonded zone a_2 is formed
4) P_3: extreme case; debonded zone a_3 is formed, tensile stress is equal to the strength of fiber (stress distribution becomes linear)

3. Fiber – matrix interaction – Theory

i) Stress transfer in the uncracked composite (pre-cracking)

- Elastic stress transfer
- Combined elastic and frictional stress transfer

ii) Stress transfer in the cracked composite (post-cracking)

Fiber – matrix interaction – Theory
iii) Stress transfer in the cracked composite

Upon loading, matrix cracks at a certain stage.
Fiber carries the load across the crack, transferring load from one part of the matrix to the other. In practice several fibers will bridge the crack.

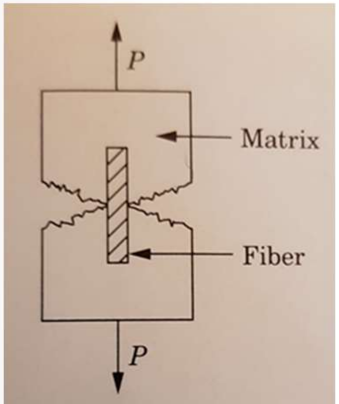


Figure 2-2 Fiber-matrix interaction, cracked matrix.

Fiber – matrix interaction – Theory
iii) Stress transfer in the cracked composite

Stress transfer mechanisms during pull-out or bridging over an opening crack are similar to the uncracked composite.

Main difference is where τ_{max} occurs;

In the cracked composite τ_{max} occurs at the point the fiber enters the matrix.

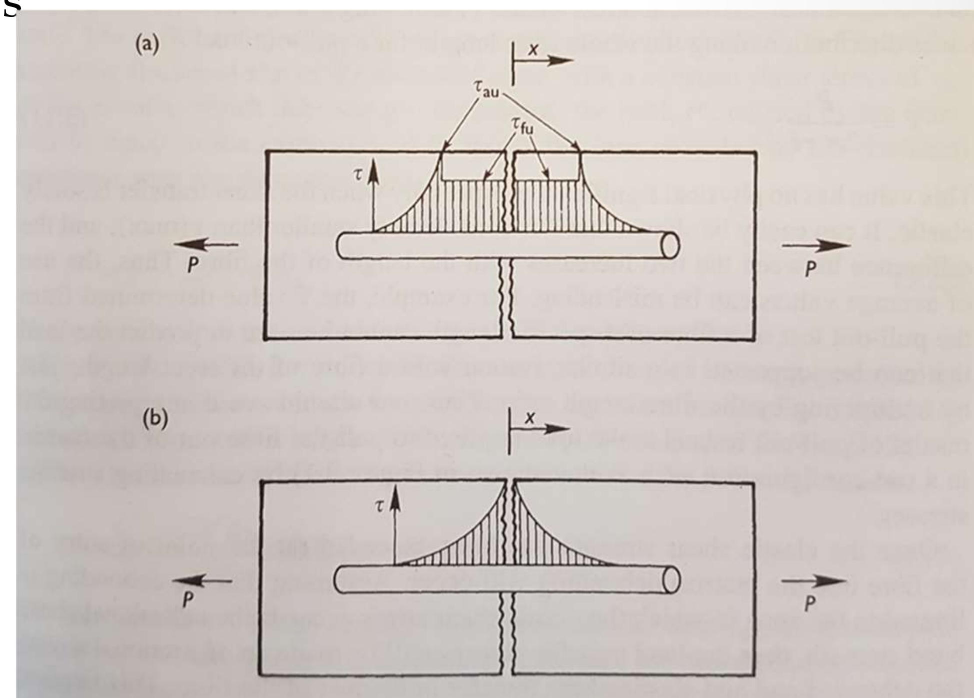
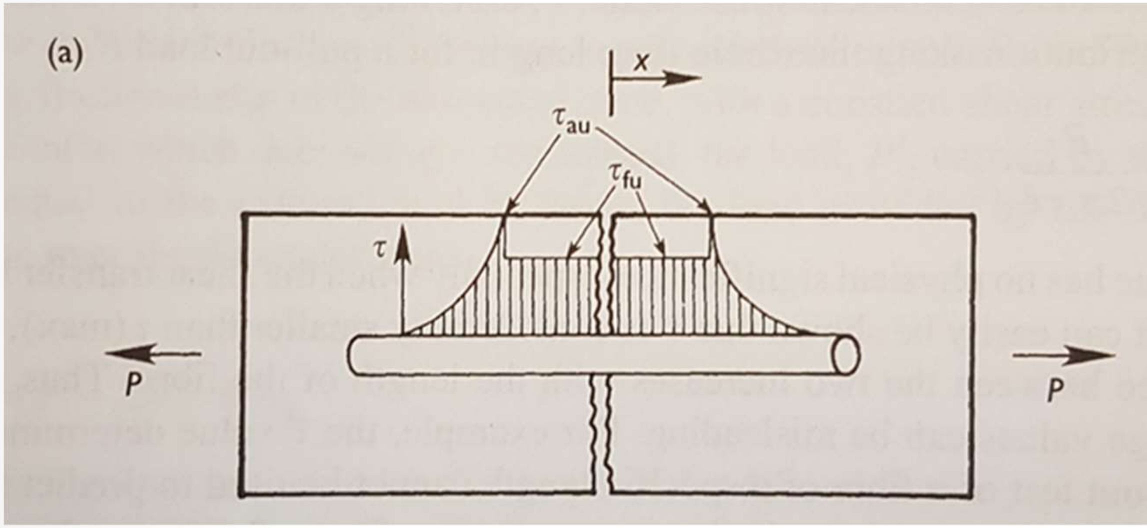


Figure 3.5 Interfacial shear stress distribution along a fibre intersecting a crack immediately after cracking: (a) debonding preceded cracking; (b) no debonding prior to cracking.

Fiber – matrix interaction – Theory
iii) Stress transfer in the cracked composite

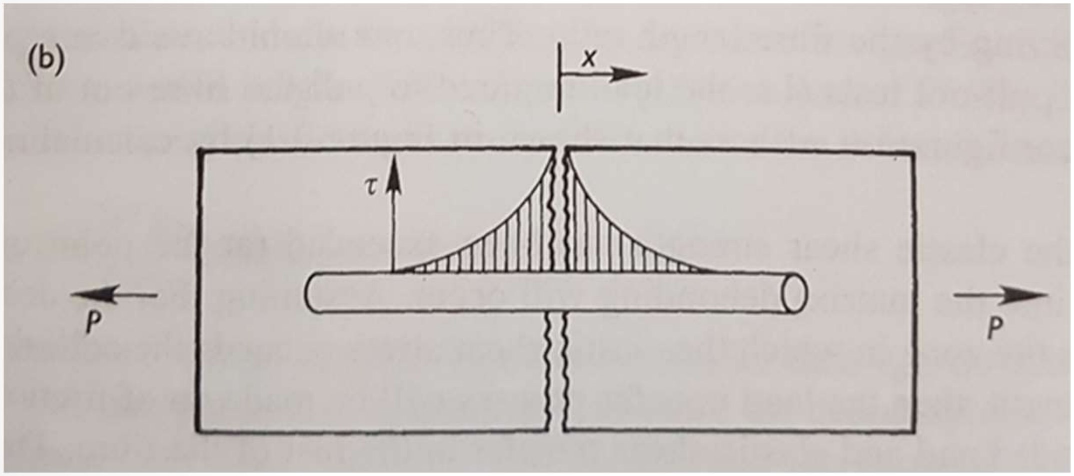
If debonding has occurred at this intersection; shear stress distribution will be combined mode with frictional shear adjacent to crack, and decreasing elastic shear stresses.



Debonding preceded cracking

Fiber – matrix interaction – Theory
iii) Stress transfer in the cracked composite

If no debonding preceded cracking, the interfacial shear stress distribution at the fiber – crack intersection will initially be elastic in nature and at advanced stages of loading it will combine frictional shear and elastic shear.

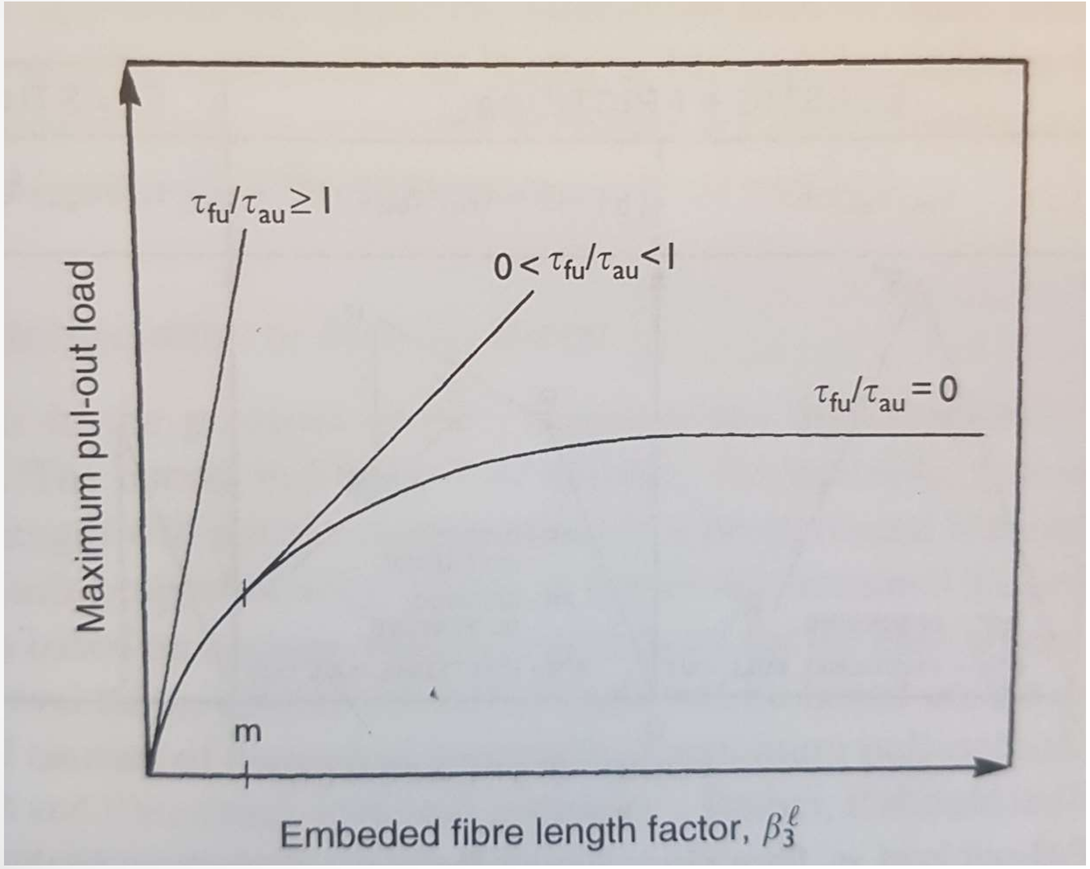


No debonding prior to cracking

Fiber – matrix interaction – Theory Analysis of pull – out behavior

- *The embedded length of the fiber, l*
- *The adhesional shear bond strength,* τ_{au}
- *The frictional shear bond strength,* τ_{fu}

Fiber – matrix interaction – Theory
Analysis of pull – out behavior



Fiber – matrix interaction – Theory
Analysis of pull – out behavior

- $\tau_{fu}/\tau_{au} \geq 1$; after τ_{au} is exceeded, debonding initiates and gradually develops along the fiber length – no catastrophic failure.

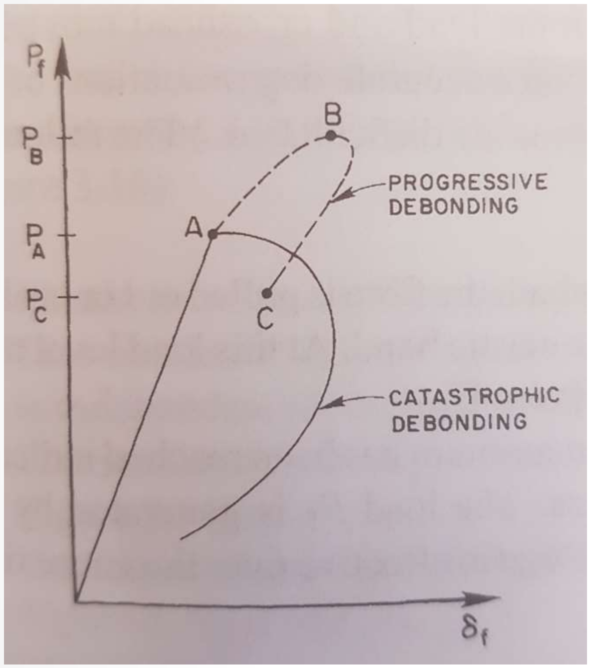
Fiber – matrix interaction – Theory
Analysis of pull – out behavior

- $0 < \tau_{fu}/\tau_{au} < 1$; after τ_{au} is exceeded , debonding initiates and may continue without any further increase in load
  - May result in catastrophic bond failure if embedded length of the fiber is less than a minimum value l_{min}. *When* $l < l_{min}$
  - *If* $l > l_{min}$ *catastrophic bond failure will not occur, fiber will be gradually extracted from the matrix.*

Fiber – matrix interaction – Theory
Analysis of pull – out behavior

- $\tau_{fu}/\tau_{au} = 0$; only mechanism of stress transfer is elastic stress transfer (τ_{fu} much smaller than τ_{au} - embedded fiber lengths are very small)

Fiber – matrix interaction – Theory
Interpretation of pull-out curves



Early stages (until point A); no debonding, elastic stress transfer mechanism is active, the curves is linear

Point A: debonding initiates (τ_{au} is exceeded)

i) Progressive debonding
ii) Catastrophic debonding

Note: An increased load required to overcome frictional resistance for progressive debonding

Theoretical pull out load vs. fiber extension/displacement curves

Fiber – matrix interaction – Theory
Interpretation of pull-out curves

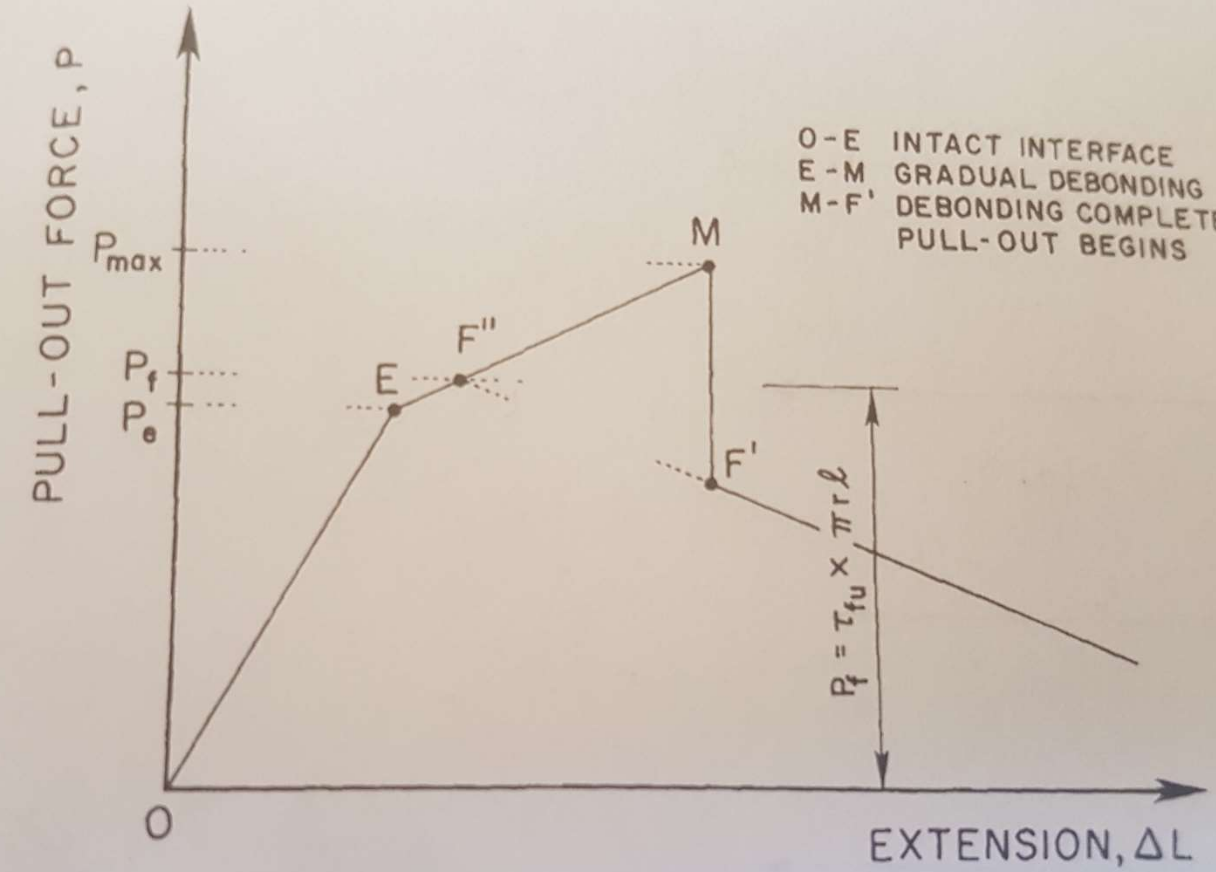
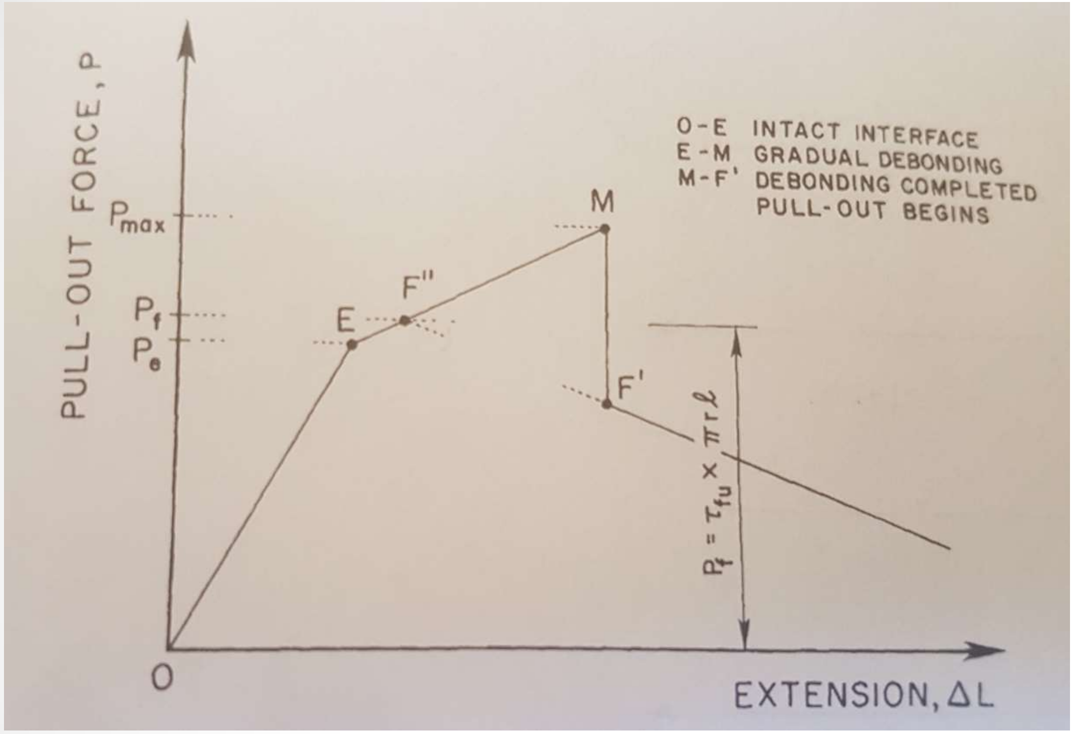


Figure 3.15 A simplified pull-out force–displacement diagram (after Bartos [1]).

Fiber – matrix interaction – Theory
Interpretation of pull-out curves



Pmax : maximum pull out force at which the fiber is pulled out or broken
Pe : required to start breaking the elastic bond (slope of the diagram changes)
Pf : frictional resistance to slip which at this stage over the entire fiber length

MF' can be eliminated if $\tau_{fu} > \tau_{au}$

Fiber – matrix interaction – Theory
Characteristic pull – out stress values

Table 3.4 Effect of several variables on bond strength values of macrofibres [34]

Diameter (mm)	*Matrix*	τ_{ave} *(MPa)*	τ_a *(MPa)*	τ_f *(MPa)*	*Reference*
Effect of age					
0.2	OPC 14 days	1.5	—	0.84	[37]
	OPC 28 days	2.0	—	1.2	
	OPC 14 days	—	1.12	1.05	[44]
	OPC 28 days	—	2.74	1.97	
Effect of silica fume					
0.19	OPC	2.0	—	1.20	[37]
	OPC+10%SF	2.5	—	1.68	
	OPC+20%SF	2.8	—	2.57	
	OPC	1.9	—	—	[39]
	DSP	4.4	—	—	
Effect of polymeric additive					
0.40–0.76	OPC	1.5	—	—	[38]
	OPC+ PVA	2.5–2.8	—	—	
0.5	OPC	—	1.49	1.49	[12]
	OPC +Latex	—	9.80	1.82	
Effect of processing					
0.6	no processing	0.7	—	—	[45]
	20 min processing	1.0	—	—	
	40 min processing	1.3	—	—	

Fiber – matrix interaction – Theory
The effect of matrix composition

Curing; continuous curing results in densification of the ITZ (important increase in shear stress from 14 days to 28 days

Modification of the cementitious binder with silica fume; enhanced interfacial bond

Modification of the cementitious binder with polymers; enhanced interfacial bond

Surface treatment of the fibers; chemical treatments or surface roughening highly increases bond strength.

Fiber – matrix interaction – Theory
Characteristic pull – out stress values

Table 3.3 Bond strength values of fibres of different moduli of elasticity [34]

Fibre	Fibre modulus (GPa)	Fibre diameter (mm)	τ_{ave} (MPa)	τ_a (MPa)	τ_f (MPa)	Reference
Steel	210	0.1–1.0	—	7.4–94.7	1.2–4.9	[34][a]
Steel	210	0.1–1.0	0.95–4.2	—	—	[35][a]
Steel	210		2	—	1.2	[37]
Steel	210	0.40,0.76	1.5	—	—	[36]
Steel	210	0.19	1.9	—	—	[38]
Steel	210		—	1.49	1.49	[39]
Steel	210	0.20	—	0.78–1.12	0.43–1.05	[40]
Poly-propylene	0.40	0.51	0.45	—	—	[25]
Poly-ethylene	0.89	0.25	0.11	—	—	[41]
Nylon	6	0.027	0.16	—	—	[42]
Kevlar 49		0.012	4.5	—	—	[42]
Poly-ethylene spectra	120	0.038	1.02	—	—	[42]
		0.042	0.40–0.63	—	—	[43]
Carbon	240	0.010	0.52–0.66	—	—	[43]

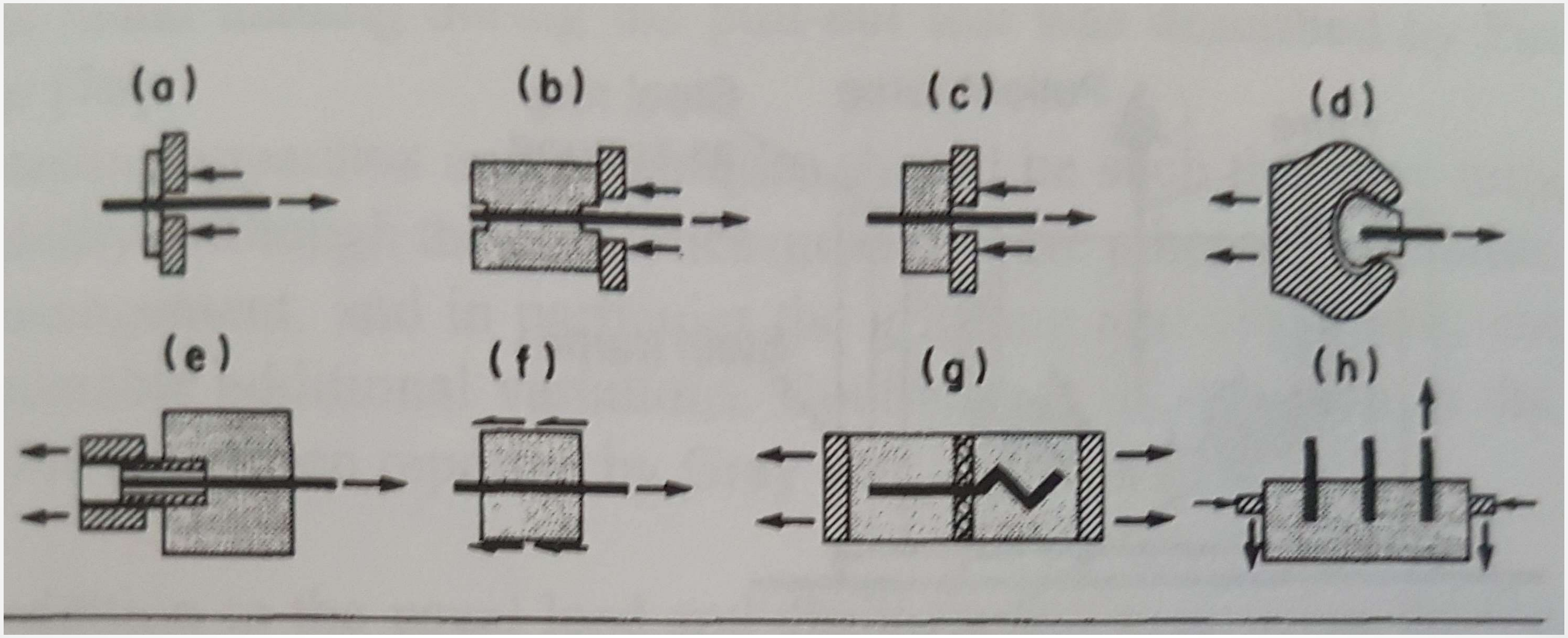
Note
a Review of data in literature.

Fiber – matrix interaction – Theory Experimental methods for determinationof pull-out resistance

Indirect methods; composite is tested in tension or bending and the fiber contribution is evaluated by doing extensive calculations to separate the resistance provided by the fiber from the matrix resistance. The results highly dependent on the selected mathematical models.

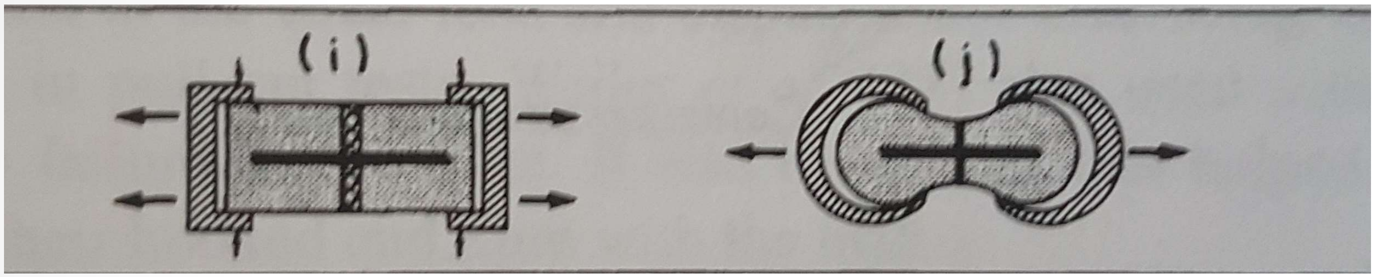
Direct methods; either a single fiber or an array of parallel fibers are pulled out from the matrix

Fiber – matrix interaction – Theory Experimental methods for determining pull-out resistance



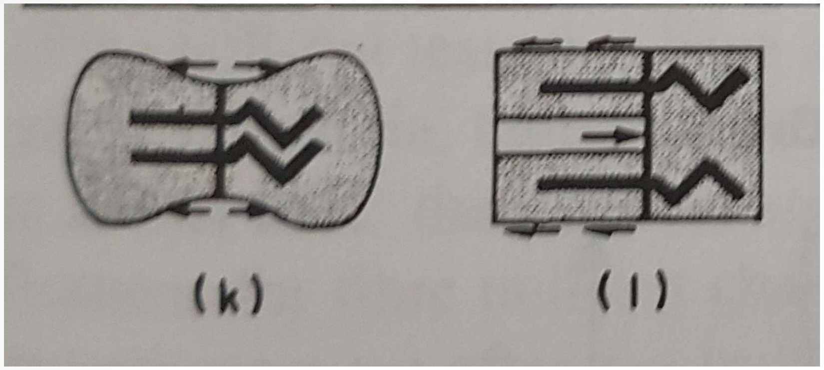
Single fiber single sided

Fiber – matrix interaction – Theory Experimental methods for determining pull-out resistance

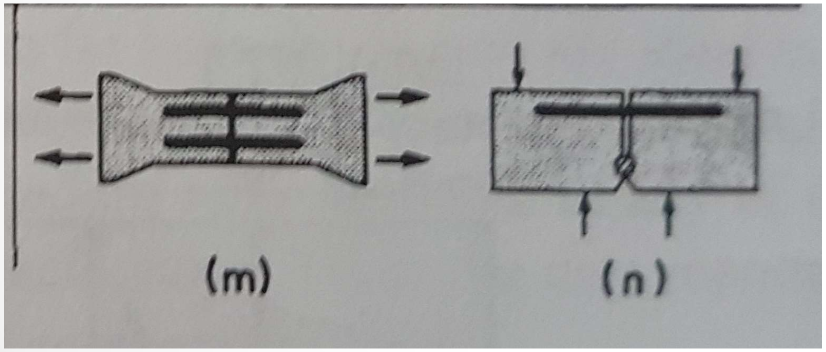


Single fiber double sided

Fiber – matrix interaction – Theory Experimental methods for determining pull-out resistance



Multiple fiber, single sided



Multiple fiber, double sided

Fiber – matrix interaction – Theory
The effect of fiber orientation

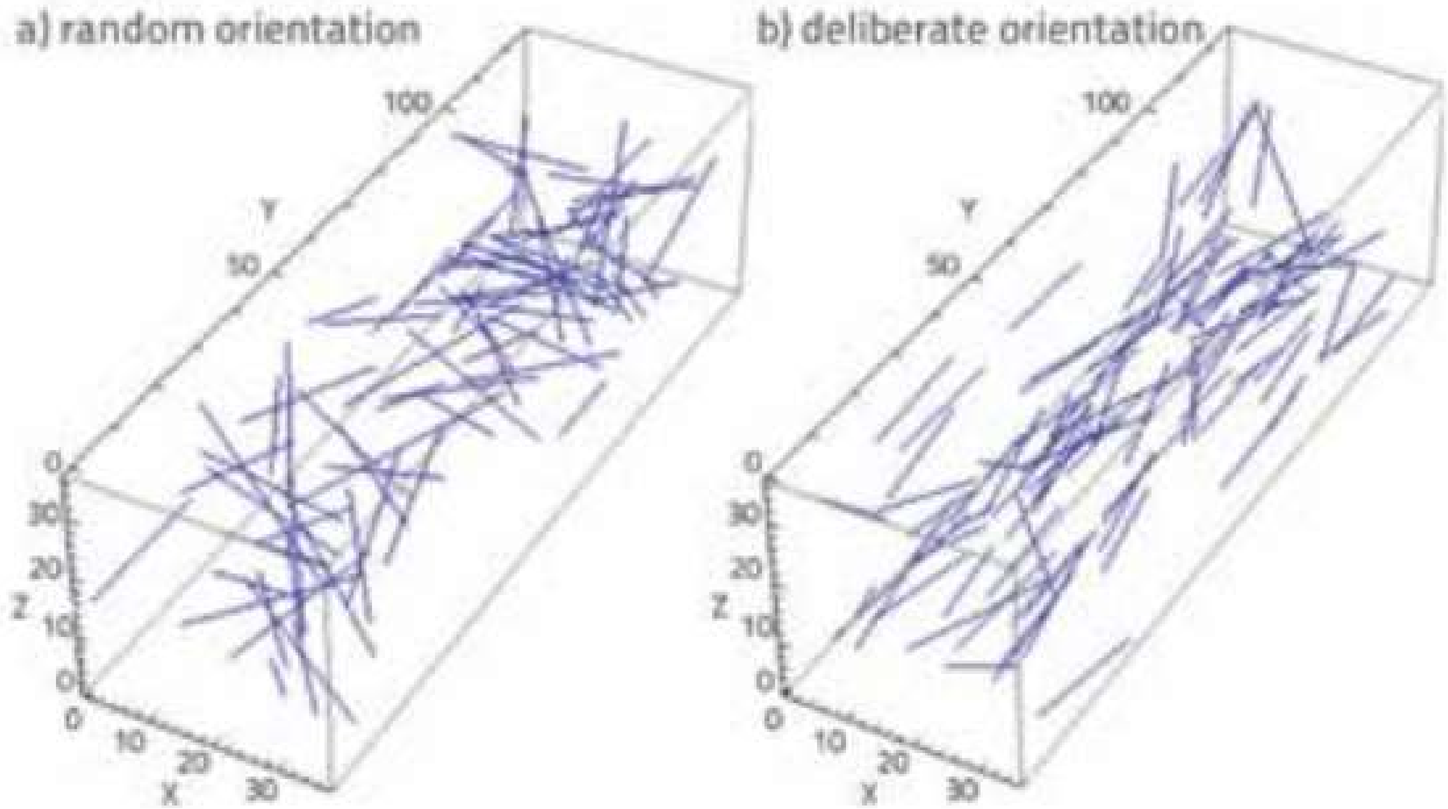
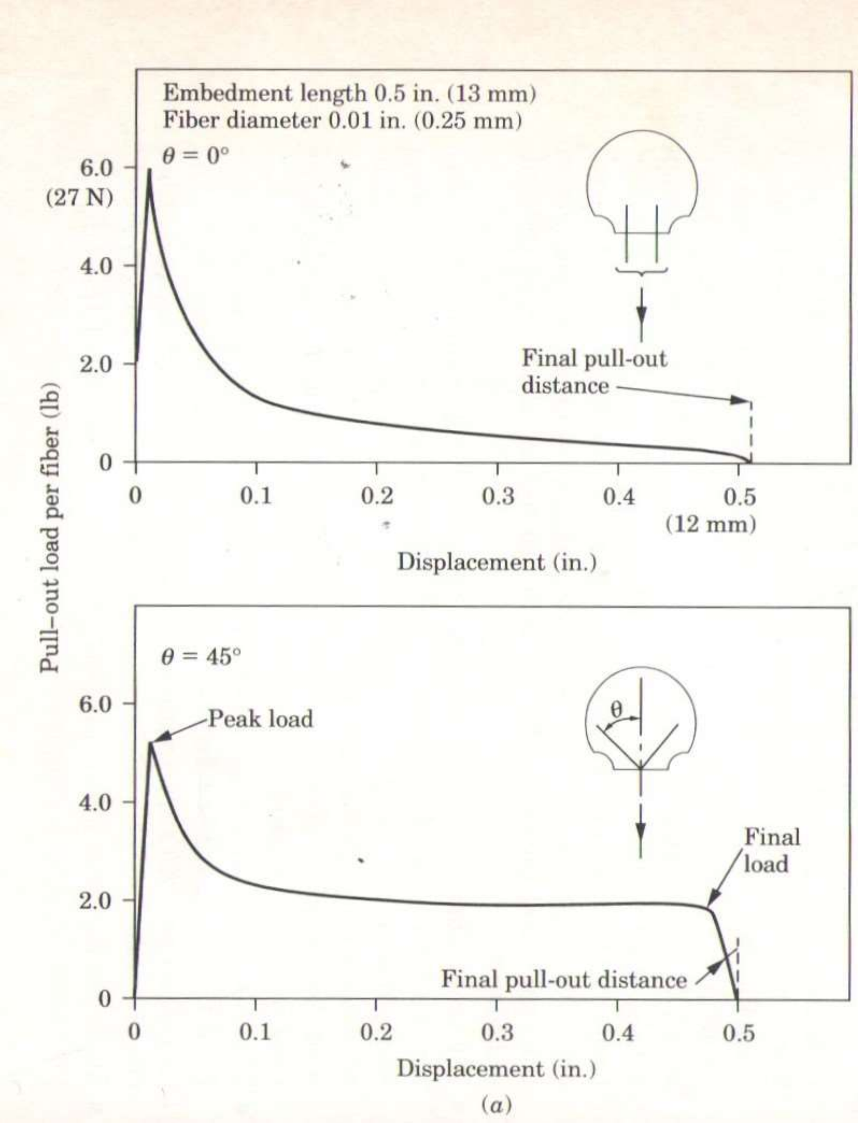


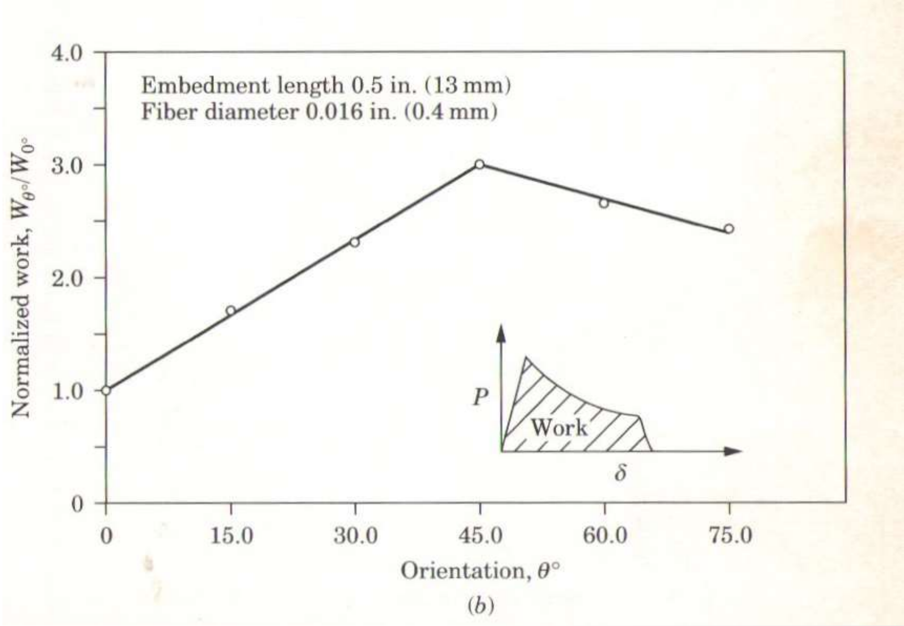
Figure 17. 3D-plot in Mathematica in case of mass content of 40 kg/m³: a) random and b) deliberate orientation

Michels, Gems; DOI: 10.14256/JCE.1356.2016

Fiber – matrix interaction – Theory
The effect of fiber orientation



(a)



(b)

Contents

4. Basic Concepts and Mechanical Properties: Tension

Behavior of the composites under direct tension

Parameters used for SLS and ULS such as 1st crack strength, tensile strength and tensile strain capacity are obtained by using direct tension tests.

Direct measure of tensile behavior

Testing cement based composites under direct tension may be cumbersome!

4. Basic Concepts and Mechanical Properties: Tension

Strong brittle fibers in a ductile matrix

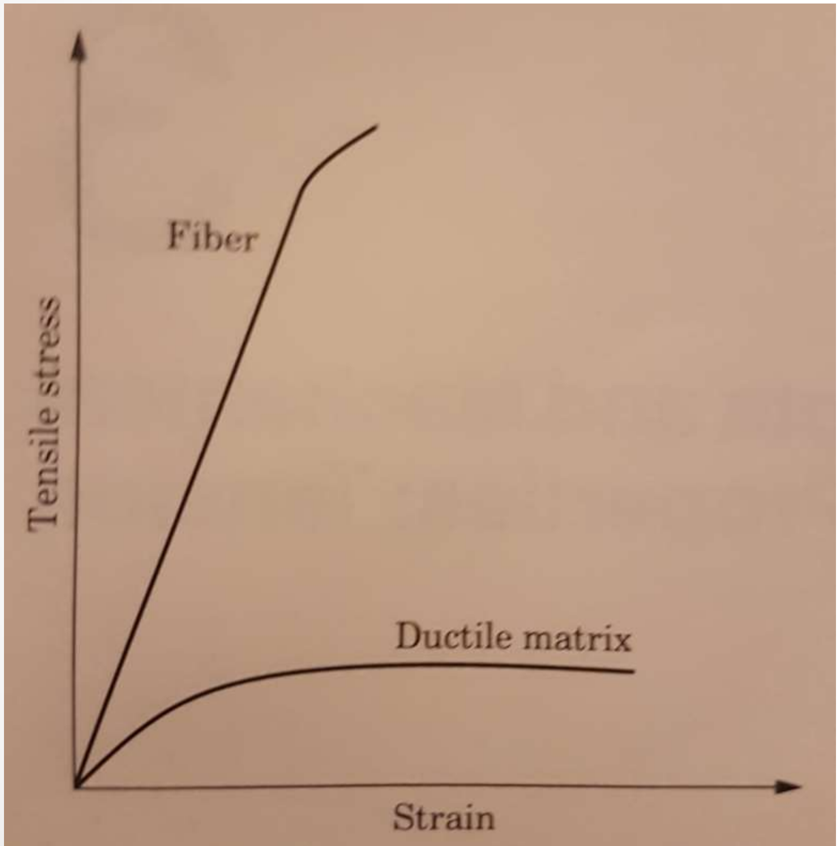


Figure 3-1 Tensile stress-strain curves for fibers with a ductile matrix.

Fiber volumes are high (up to 40 %), fibers are very strong, since surface area of the fibers is large it is possible to obtain perfect bond.

i.e. fiberglass, carbon fiber reinforced plastics

4. Basic Concepts and Mechanical Properties: Tension

Strong fibers in a brittle matrix

Main objective: to increase ductility
Fiber volume fractions; relatively low

Ultimate strain capacity of the matrix is relatively low than that of the fibers and matrix fails before the full potential capacity of the fibers achieved.

Fibers bridge the cracks, contribute to the energy absorption through debonding and pull – out.

4. Basic Concepts and Mechanical Properties: Tension

Strong fibers in a brittle matrix

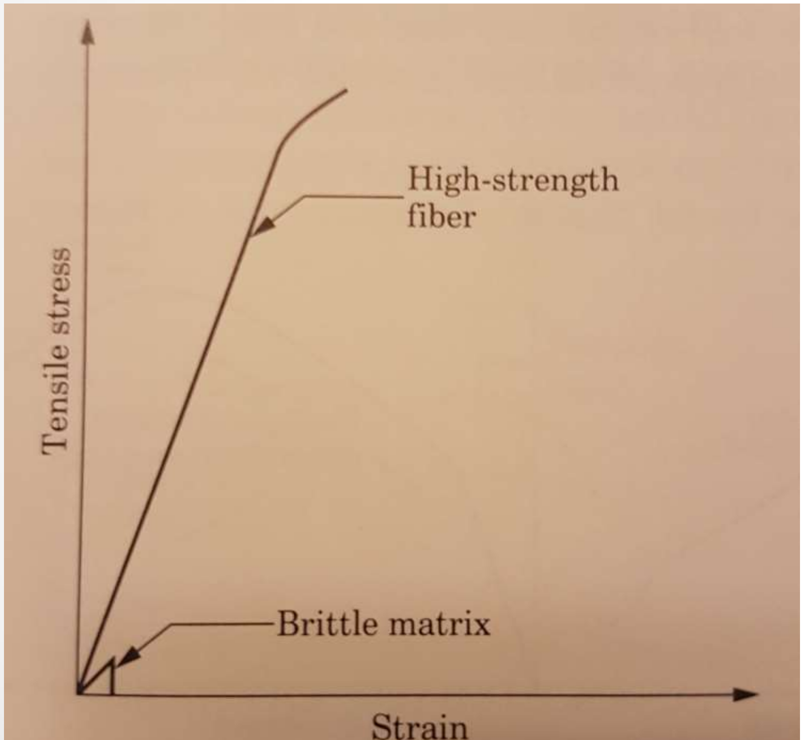


Figure 3-2 Tensile stress-strain curves for fibers with a brittle matrix.

4. Basic Concepts and Mechanical Properties: Tension

Strong fibers in a brittle matrix

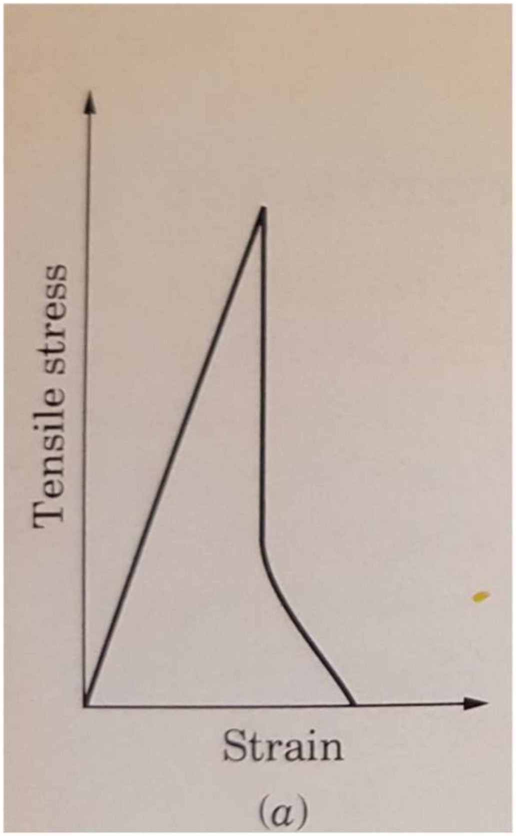
Once the matrix cracks further behavior could be one of the following;

1) Composites fractures immediately after the fracture of the matrix (very low fiber volume fraction)

2) Following the cracking of matrix, load carrying capacity decreases but the composite could continue to resist loads that are lower than the peak load.

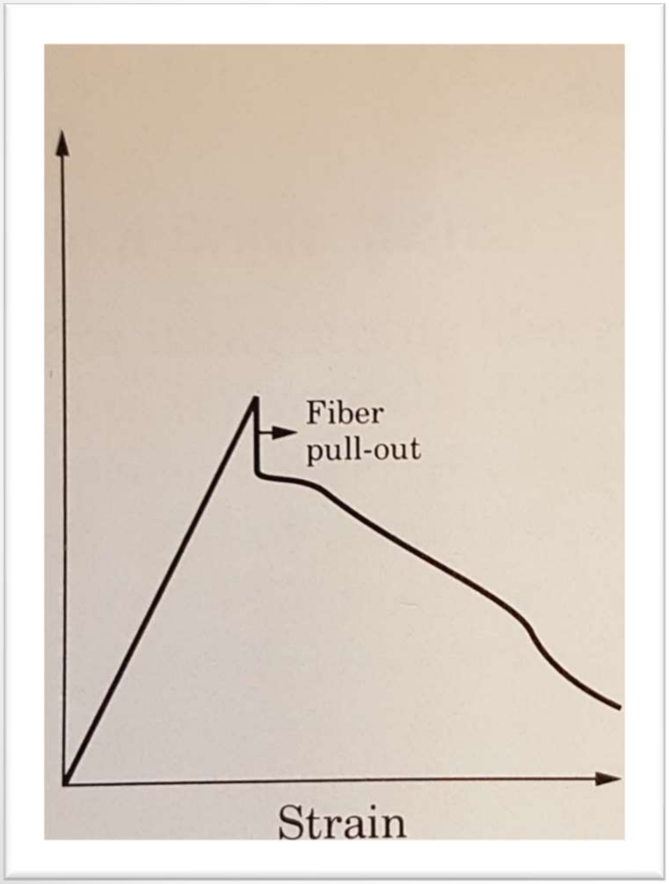
3) If the volume fraction of fibers is large enough, after the matrix cracks, the fibers will start carrying the increased loads.

4. Basic Concepts and Mechanical Properties: Tension



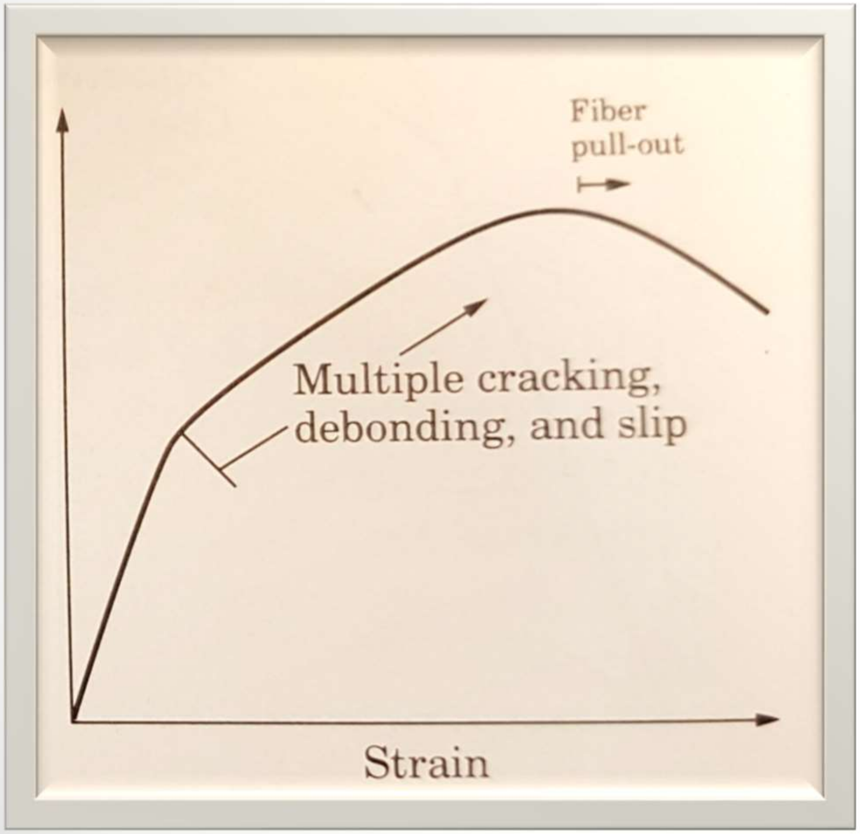
1st case – very low fiber volume, limited strain

4. Basic Concepts and Mechanical Properties: Tension



2nd case – strain softening behavior; Following the cracking of matrix, load carrying capacity decreases but the composite could continue to resist loads that are lower than the peak load.

4. Basic Concepts and Mechanical Properties: Tension



3rd case – strain hardening behavior; if the volume fraction of fibers is large enough, after the matrix cracks, the fibers will start carrying the increased loads.

Stiffness decreases in the hardening branch due to loss of matrix contribution.

4. Basic Concepts and Mechanical Properties: Tension

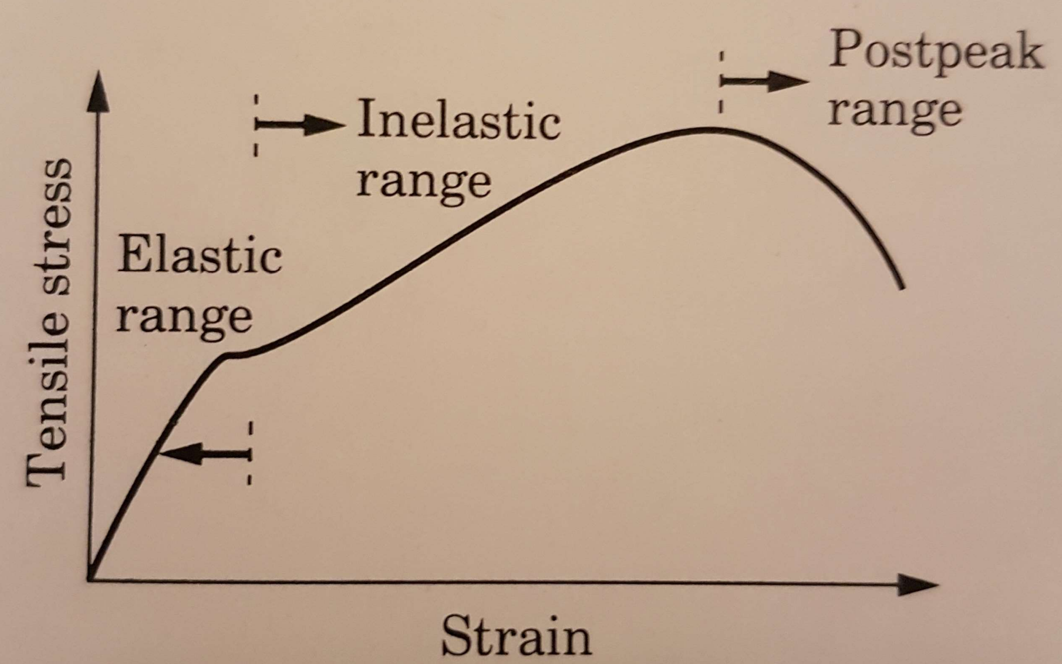


Figure 3-4 The three ranges of tensile stress-strain behavior for high fiber volume composites.

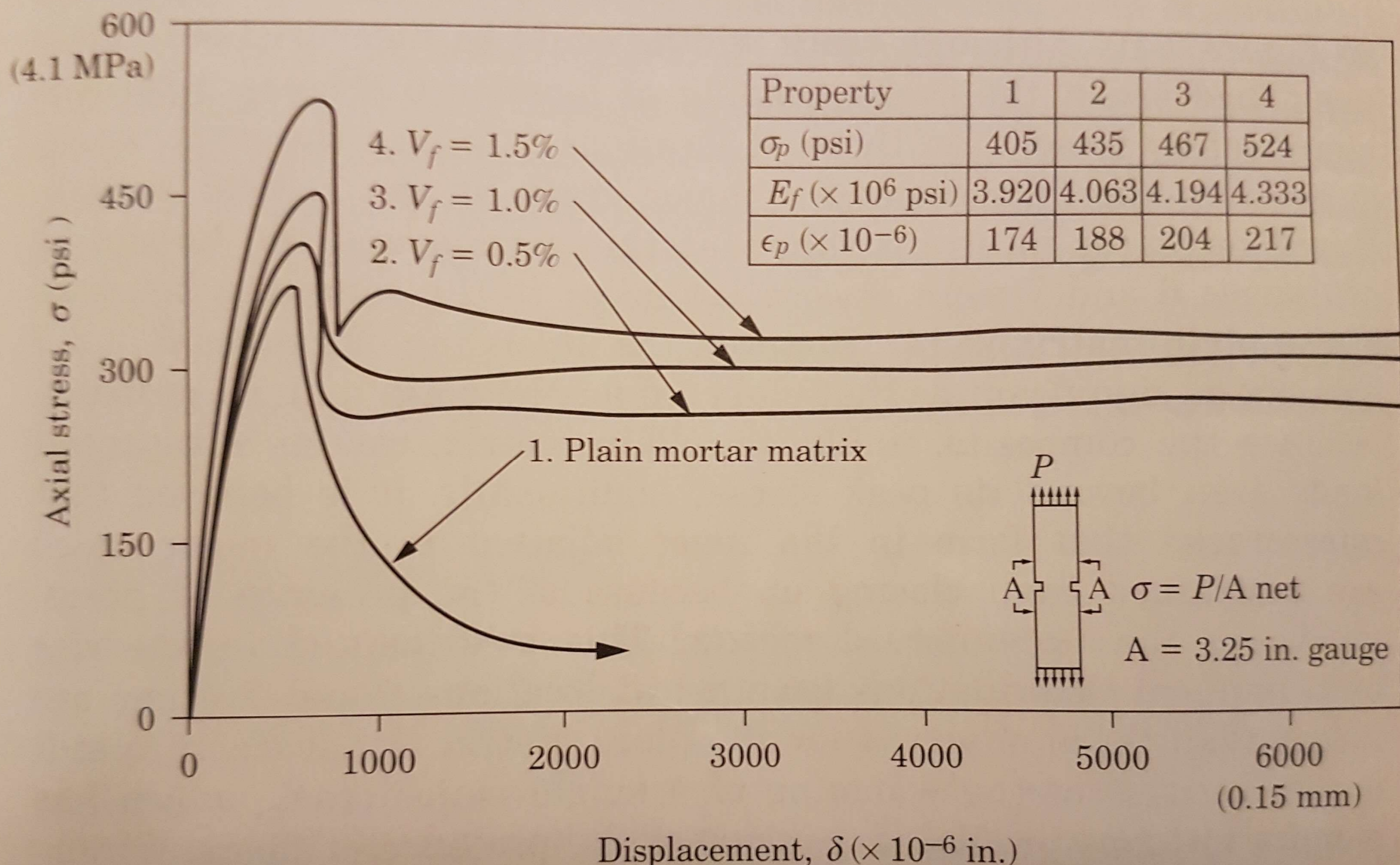
Linear elastic range is present for all composites and gives modulus of elasticity.

4. Basic Concepts and Mechanical Properties: Tension – Experimental evaluation

- Stress – strain response can be evaluated in 3 segments (for composites with less than 2 % fiber volume content)
  - 1st segment - Precracked (elastic) region represented by the modulus of elasticity of the matrix.
  - 2nd segment - Zone of non linear deformation between the 1st cracking of the matrix and the ultimate tensile strength of the composite (most of the time relatively small)
  - 3rd segment – post peak response

4. Basic Concepts and Mechanical Properties:

Tension – Tensile stress – displacement response



Property	1	2	3	4
σ_p (psi)	405	435	467	524
E_f ($\times 10^6$ psi)	3.920	4.063	4.194	4.333
ϵ_p ($\times 10^{-6}$)	174	188	204	217

Figure 3-9 Tensile stress-strain response: Comparison of plain and fiber-reinforced concrete (1 psi = 6.895 × 10^{-3} MPa) [3.14].

4. Basic Concepts and Mechanical Properties:

Tension – Tensile stress – displacement response

- SFRC behavior represented in the prev. slide;
  - Linear elastic almost up to 80% of matrix tensile strength – non linear deformations beyond the linear elastic limit
  - After composite peak stress, the load carrying capacity abruptly drops to post cracking strength. One single crack becomes visible at the critical section.
  - With an increase in displacement, the load carrying capacity further drops

Contents

4. Basic Concepts and Mechanical Properties: BENDING

- Tensile test is the most direct method to obtain *material parameters* (ε_{cc} - ε_{pc} - σ_{cc} - σ_{pc}) experimentally.
- However, application of direct tensile test is cumbersome!!!
- Bending test is one of the most preferred methods that is used to obtain *material parameters*

Why do we need material parameters? How do we make use of them?

4. Basic Concepts and Mechanical Properties: Bending

Mechanism of fiber contribution to bending

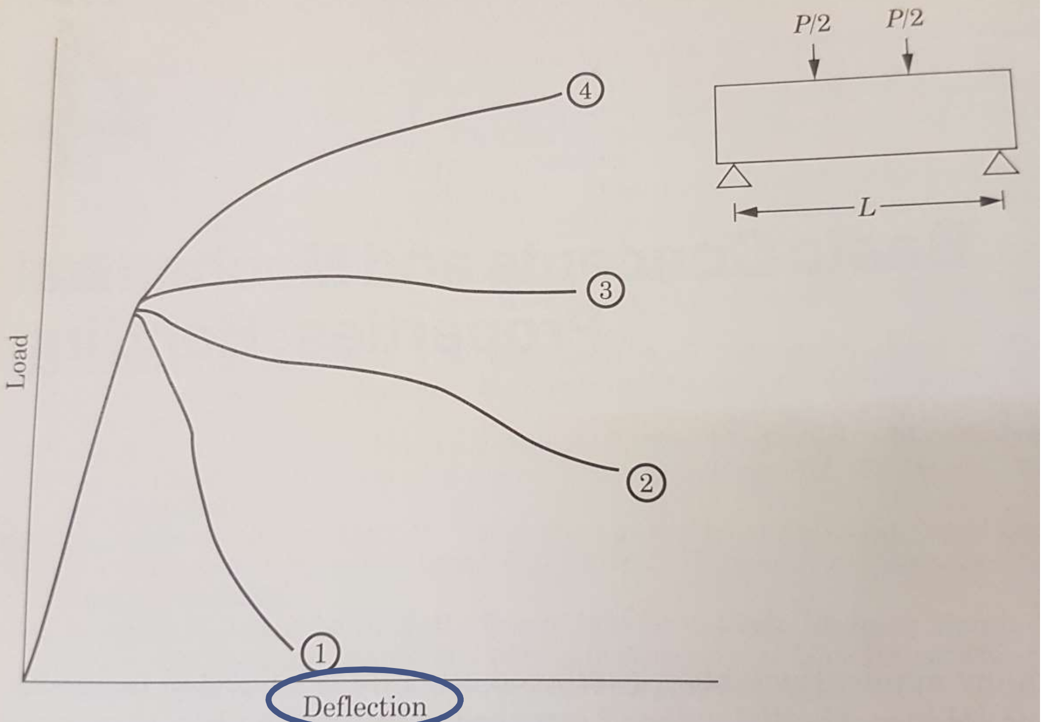
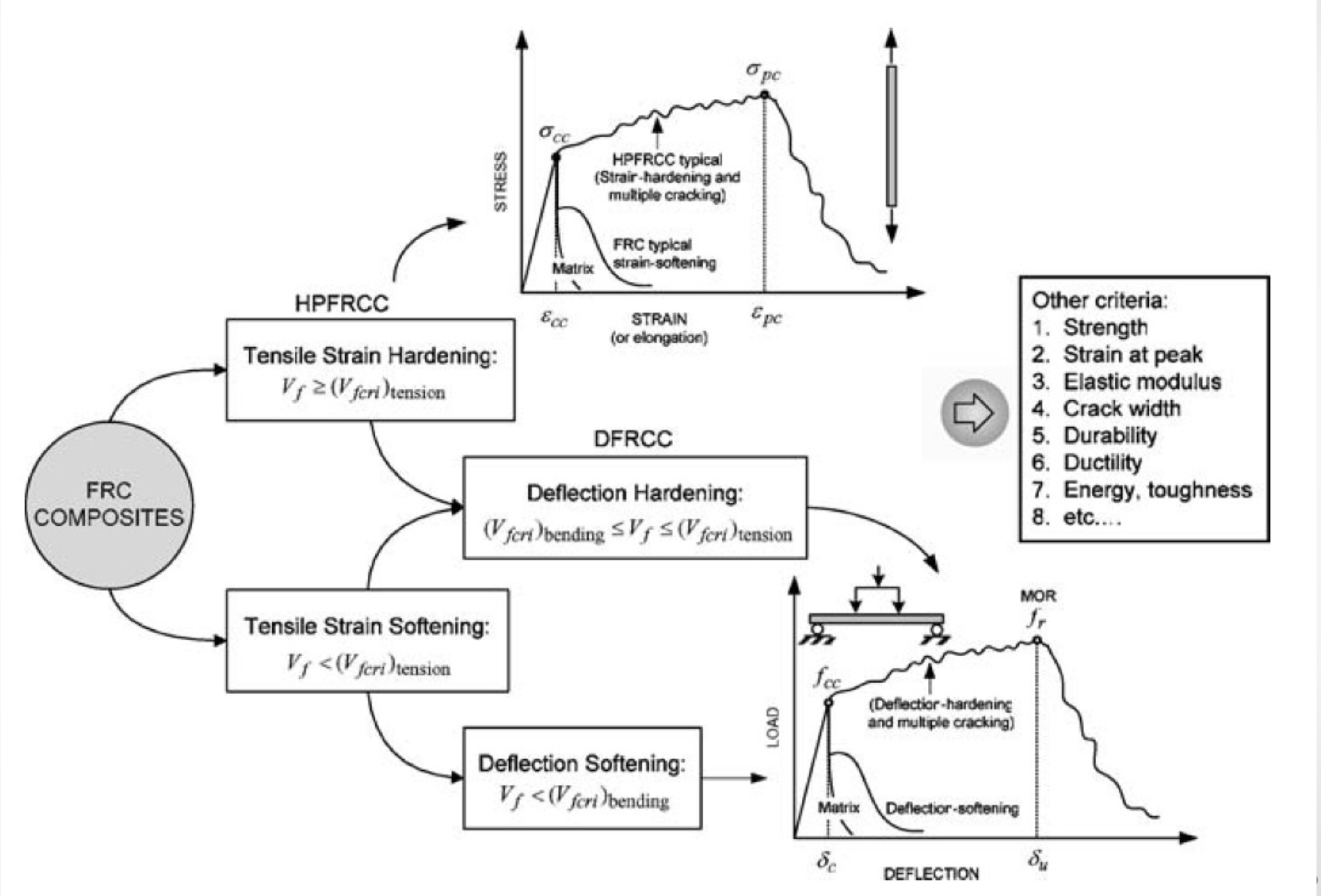


Figure 4-1 Typical load-deflection curve for fiber composites.

Common initial linear portion but dissimilar post crack branches.

4. Basic Concepts and Mechanical Properties: Classification – Tension + Bending



4. Basic Concepts and Mechanical Properties:
Bending
Flexural Toughness

Flexural toughness represents energy absorption capacity of the material and evaluated by determining the area under the stress – strain curve or by the load deformation behavior.

Increased toughness means improved performance under fatigue, impact and impulse loading.

4. Basic Concepts and Mechanical Properties:

Bending

Techniques for measuring material parameters

- 3 – point bending with a pre-made notch
- 4 point bending on unnotched specimens (or 3rd point bending)

4. Basic Concepts and Mechanical Properties:
Bending
Techniques for measuring material parameters

- Commonly used standards
  - EN 14651
  - ASTM C 1609

4. Basic Concepts and Mechanical Properties:
Bending
Measuring equipment

- **LVDT** : Linear variable displacement transducer

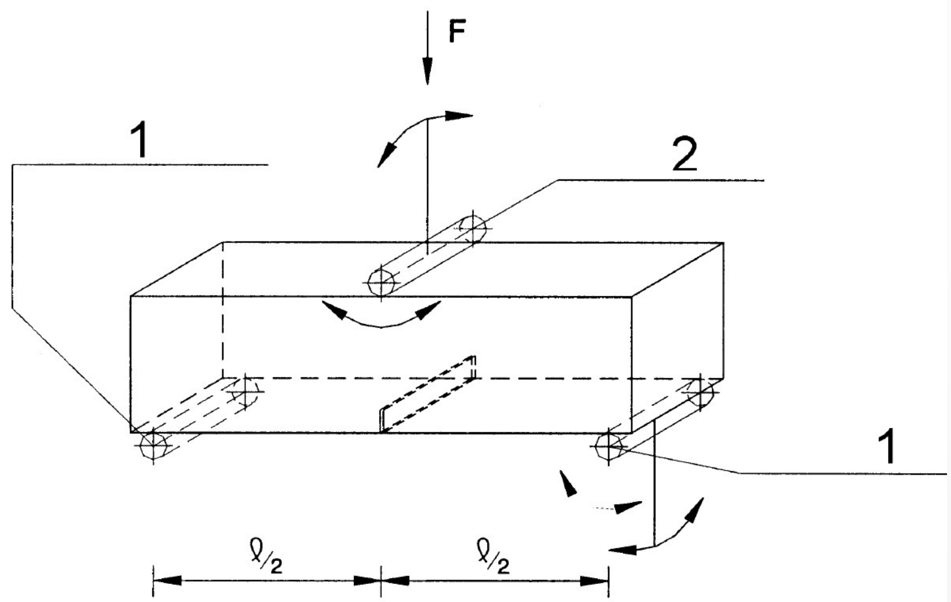
- **CMOD gauge** : Crack mouth opening displacement gauge

4. Basic Concepts and Mechanical Properties:

Bending

Techniques for measuring material parameters

- EN 14651
- Load – CMOD or Load deflection can be measured

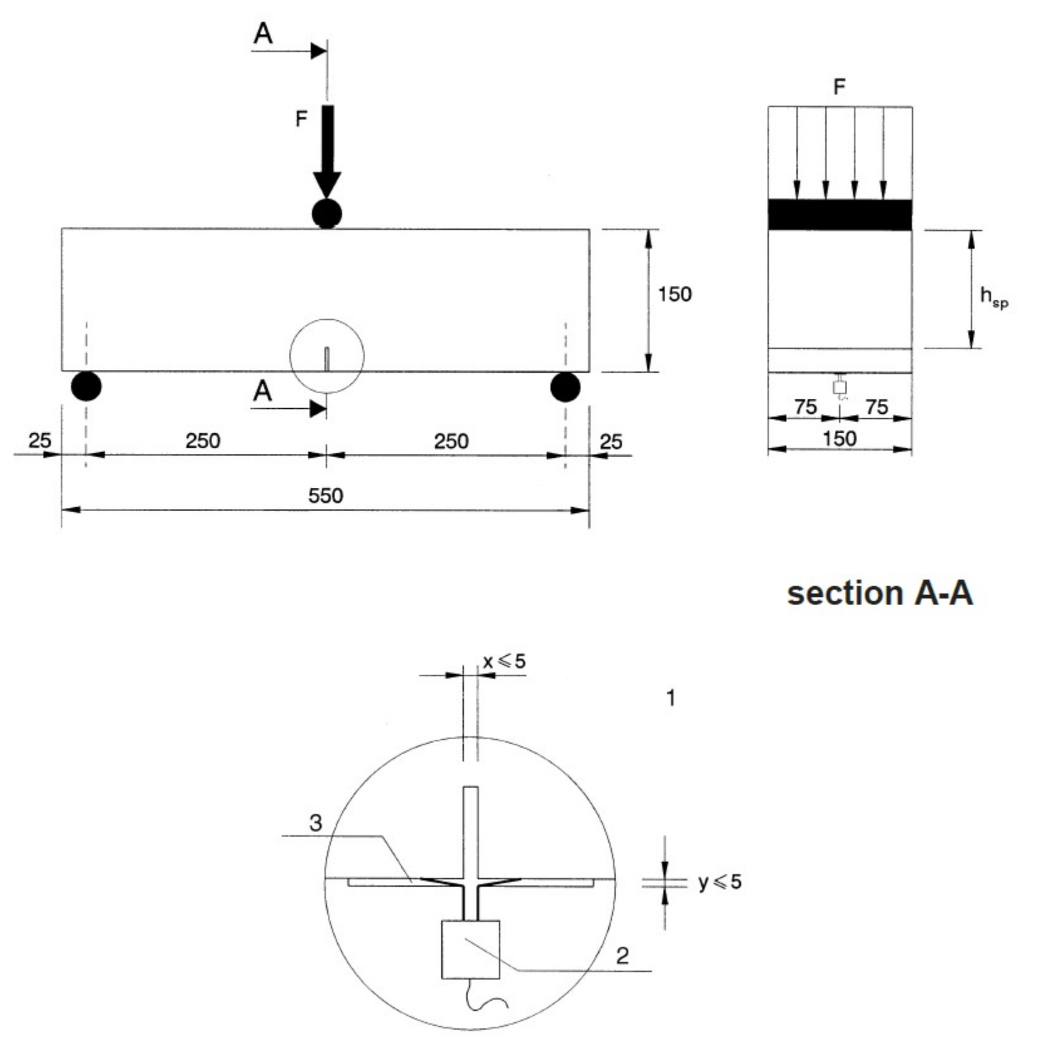


Key
1 Supporting roller
2 Loading roller

4. Basic Concepts and Mechanical Properties:
Bending
Techniques for measuring material parameters

- EN 14651

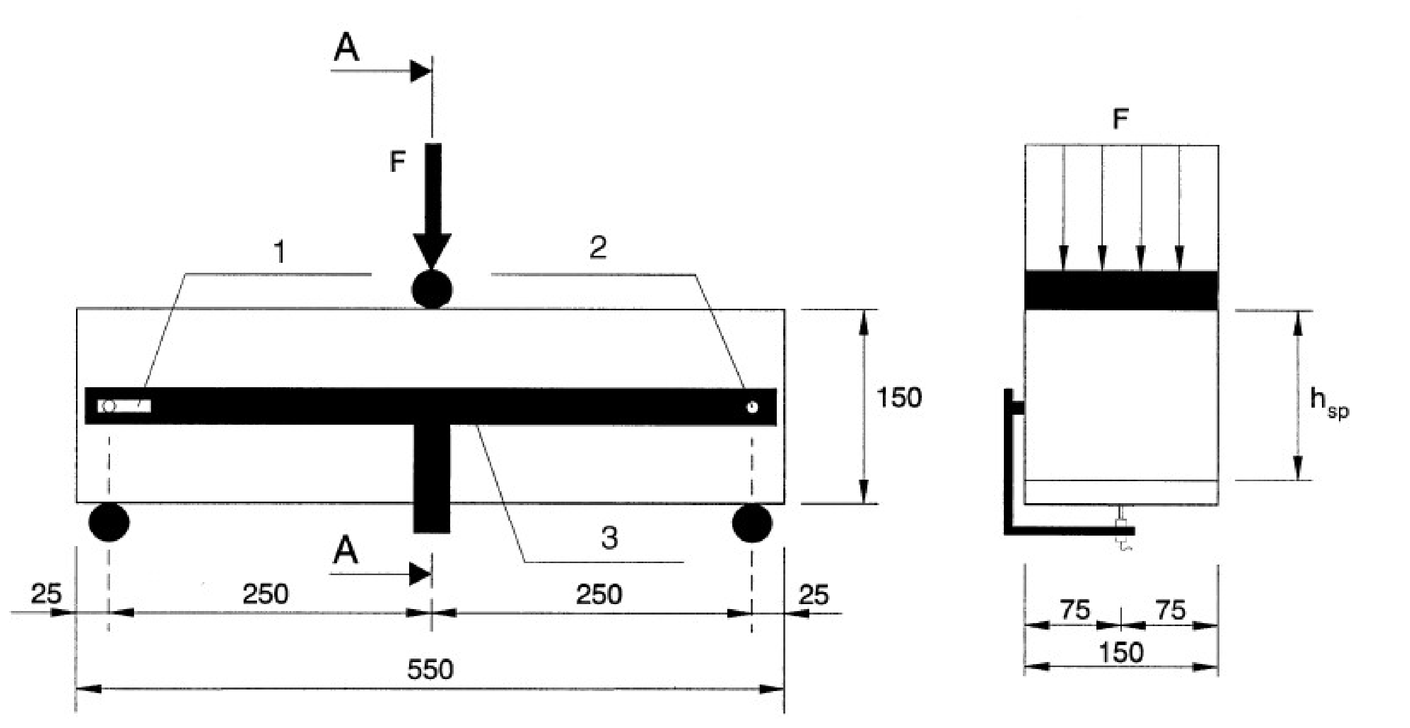
For measuring load vs. CMOD



Key
1 Detail (notch)
2 Transducer (clip gauge)
3 Knife edge

4. Basic Concepts and Mechanical Properties: Bending
Techniques for measuring material parameters

- EN 14651 – For measuring load vs. deflection

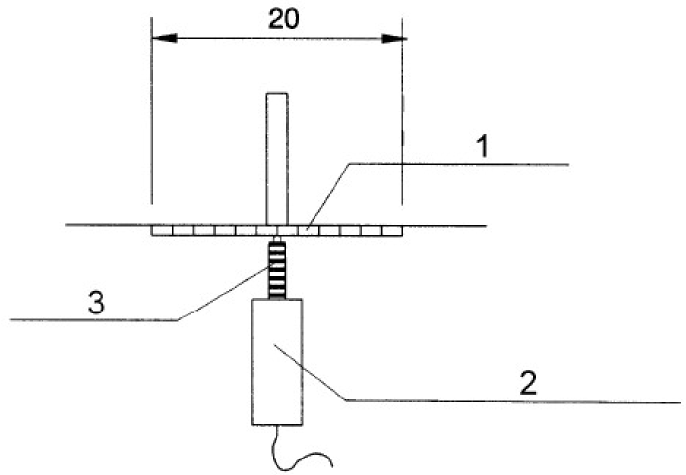


Key
1 Sliding fixture
2 Rotating fixture
3 Rigid frame

4. Basic Concepts and Mechanical Properties: Bending

Techniques for measuring material parameters

- EN 14651 – For measuring load vs. deflection



Key

1 1 mm thick aluminium plate
2 Transducer (linear variable differential transformer)
3 Spring shaft

4. Basic Concepts and Mechanical Properties: Bending

Techniques for measuring material parameters

EN 14651 – Limit of proportionality

9.2 Limit of proportionality

The *LOP* is given by the expression (see Annex A):

$$f_{ct,L}^{f} = \frac{3F_L l}{2bh_{sp}^2}$$

where

$f_{ct,L}^{f}$ is the *LOP*, in Newton per square millimetre;

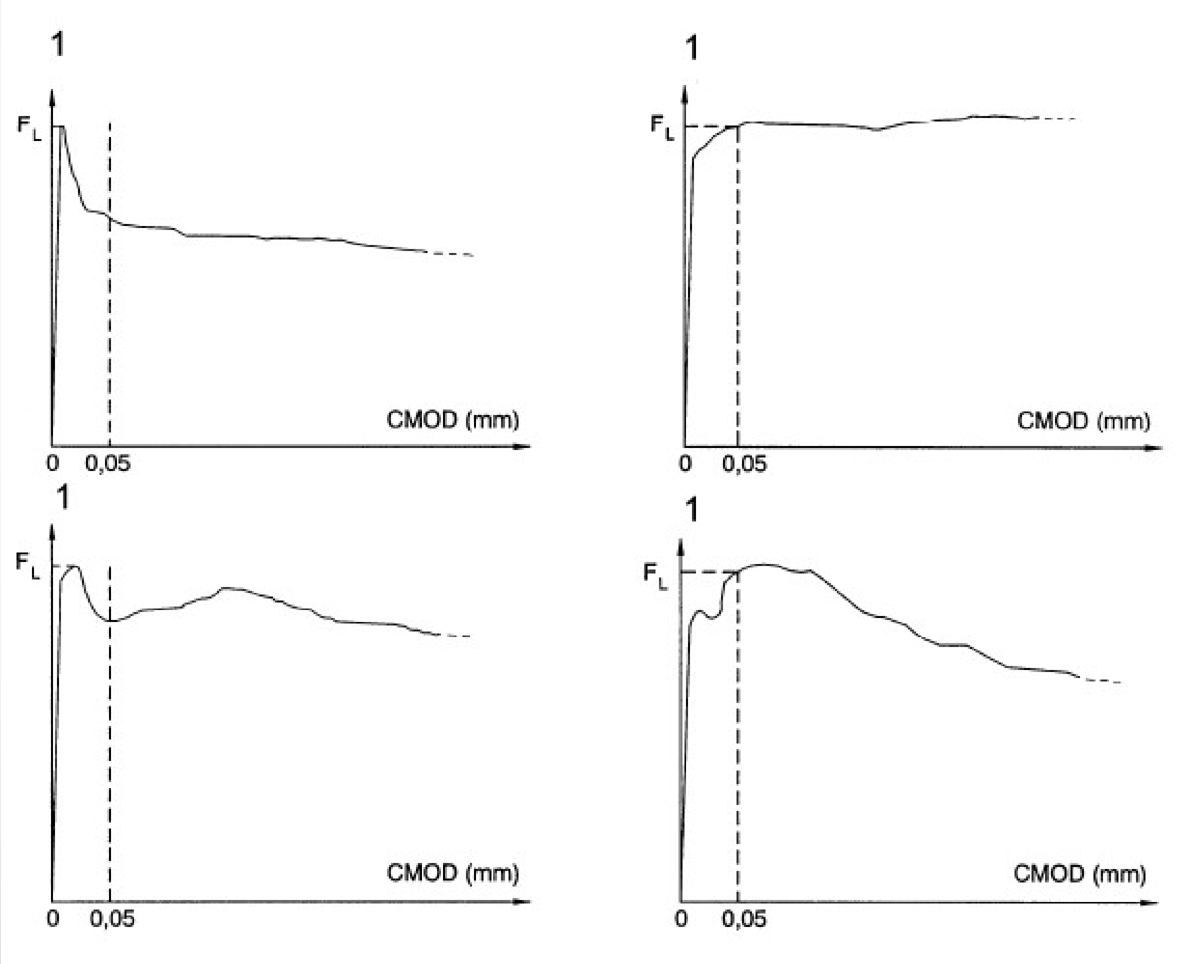
F_L is the load corresponding to the *LOP*, in Newton (see Figure 6);

l is the span length, in millimetres;

b is the width of the specimen, in millimetres;

h_{sp} is the distance between the tip of the notch and the top of the specimen, in millimetres.

4. Basic Concepts and Mechanical Properties:
Bending
Techniques for measuring material parameters
EN 14651 – Limit of proportionality



The load value FL shall be determined by drawing a line at a distance of 0,05 mm and parallel to the load axis of the load – CMOD or load deflection diagram and taking as FL the highest load value in the interval of 0,05mm

4. Basic Concepts and Mechanical Properties: Bending

Techniques for measuring material parameters

EN 14651 – Residual flexural tensile strength

9.3 Residual flexural tensile strength

The residual flexural tensile strength $f_{R,j}$ is given by the expression (see Annex A):

$$f_{R,j} = \frac{3F_j l}{2bh_{sp}^2} \qquad (4)$$

where

$f_{R,j}$ is the residual flexural tensile strength corresponding with $CMOD = CMOD_j$ or $\delta = \delta_j$ (j = 1,2,3,4), in Newton per square millimetre;

F_j is the load corresponding with $CMOD = CMOD_j$ or $\delta = \delta_j$ (j = 1,2,3,4), in Newton (see Figure 7);

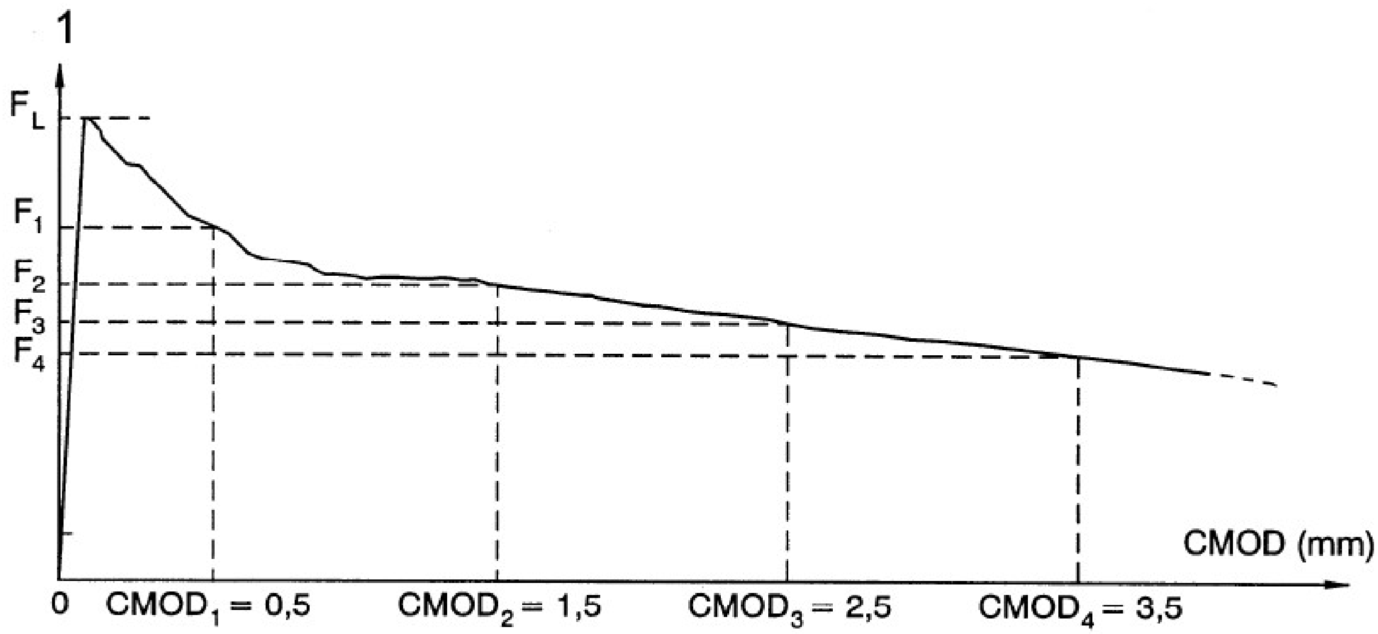
l is the span length, in millimetres;

b is the width of the specimen, in millimetres;

h_{sp} is the distance between the tip of the notch and the top of the specimen, in millimetres.

4. Basic Concepts and Mechanical Properties:
Bending
Techniques for measuring material parameters

EN 14651 – Residual flexural tensile strength



Key

1 Load F

4. Basic Concepts and Mechanical Properties:

Bending

Techniques for measuring material parameters

ASTM C 1609 - 4 point bending on unnotched specimen

FIG. 1 Arrangement to Obtain Net Deflection by Using Two Transducers Mounted on Rectangular Jig Clamped to Specimen Directly Above Supports

4. Basic Concepts and Mechanical Properties:
Bending
Techniques for measuring material parameters
ASTM C 1609

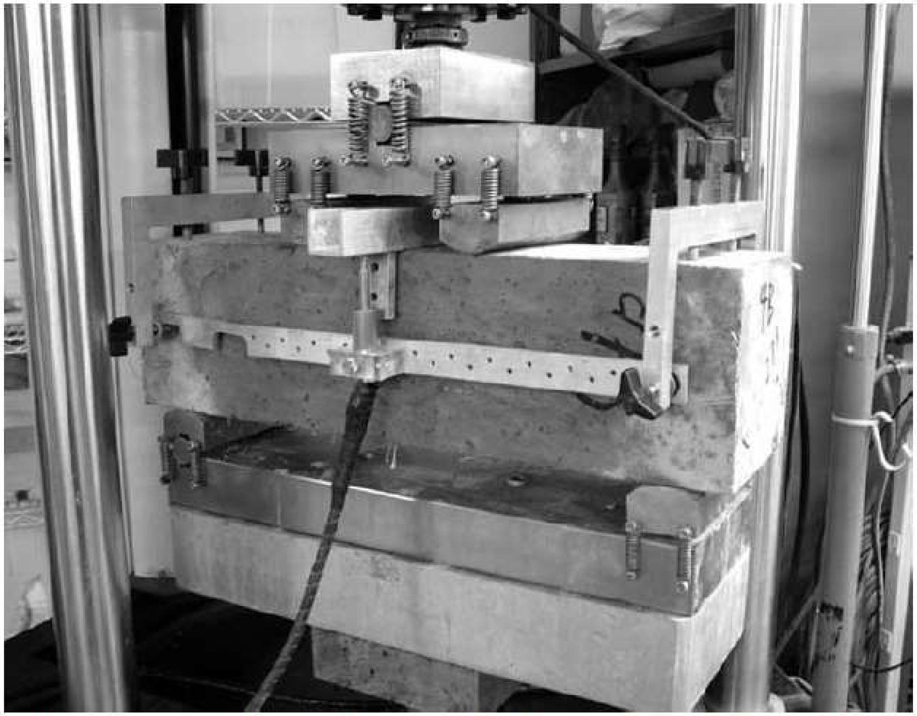


FIG. 2 Arrangement to Obtain Net Deflection by Using Two Transducers Mounted on Jig Secured to Specimen Directly Above Supports

4. Basic Concepts and Mechanical Properties:

Bending

Techniques for measuring material parameters

ASTM C 1609 - retrieved parameters

<u>1st peak load and residual load values</u>

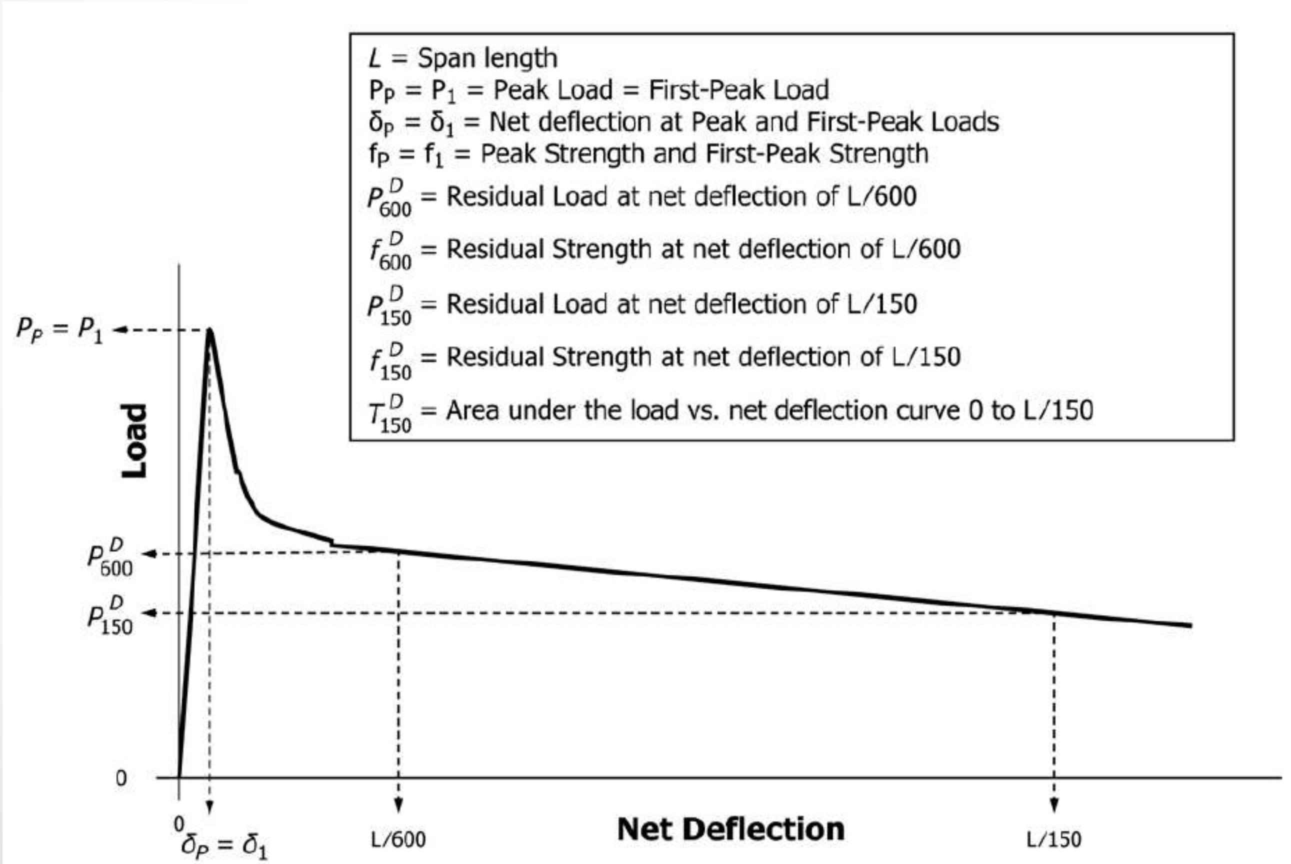


FIG. 3 Example of Parameter Calculations for First-Peak Load Equal to Peak Load (Not to Scale)

4. Basic Concepts and Mechanical Properties:

Bending

Techniques for measuring material parameters

ASTM C 1609 - retrieved parameters

1st peak strength and residual strength values

Calculate the 1st peak strength and residual strength values by using the below given formula

$$f = \frac{PL}{bd^2} \qquad (1)$$

where:

f = the strength, MPa [psi],
P = the load, N [lbf],
L = the span length, mm [in.],
b = the average width of the specimen at the fracture, as oriented for testing, mm [in.], and
d = the average depth of the specimen at the fracture, as oriented for testing, mm [in.].

4. Basic Concepts and Mechanical Properties:

Bending

Techniques for measuring material parameters

ASTM C 1609 - retrieved parameters

<u>1st peak strength and residual strength values</u>

Calculate the 1st peak strength and residual strength values by using the below given formula

$$f_1 = \frac{P_1 L}{bd^2}$$ → 1st peak strength

$$f^D_{150} = \frac{P^D_{150} \cdot L}{bd^2}$$ → Residual strength at net deflection of L/600

$$f^D_{600} = \frac{P^D_{600} \cdot L}{bd^2}$$ → Residual strength at net deflection of L/150

4. Basic Concepts and Mechanical Properties:
Bending
Techniques for measuring material parameters
ASTM C 1609 - retrieved parameters
1st peak deflection

NOTE 10—First-peak deflection for third-point loading is estimated assuming linear-elastic behavior up to first peak from the equation:

$$\delta_1 = \frac{23P_1L^3}{1296EI}\left[1+\frac{216d^2(1+\mu)}{115L^2}\right]$$

where:

δ_1 = the first peak deflection, mm [in.]
P_1 = the first-peak load, N [lbf]
L = the span length, mm [in.]
E = the estimated modulus of elasticity of the concrete, MPa [psi]
I = the cross-sectional moment of inertia, mm^4 [$in.^4$]
d = the average depth of specimen at the fracture, as oriented for testing, mm [in.] and
μ = Poisson's ratio

4. Basic Concepts and Mechanical Properties:

Bending

Techniques for measuring material parameters

ASTM C 1609 - retrieved parameters

Equivalent flexural strength ratio

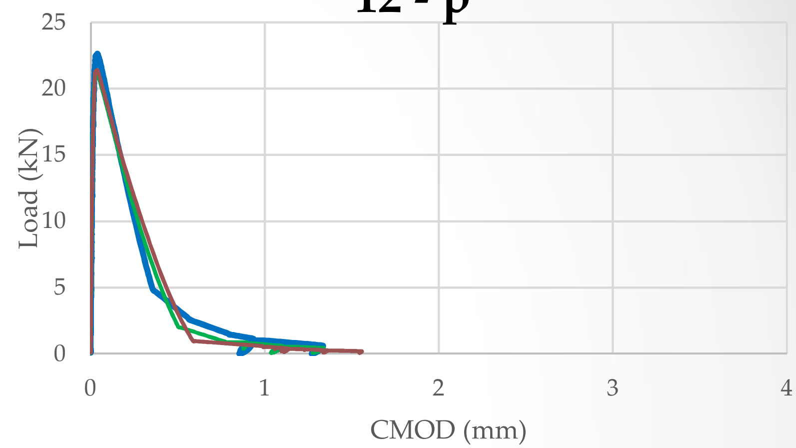
$$R_{T,\,150}^{D} = \frac{150 \cdot T_{150}^{D}}{f_1 \cdot b \cdot d^2} \cdot 100\ \%$$

Comparative results of a study carried out in BU Construction Materials Lab

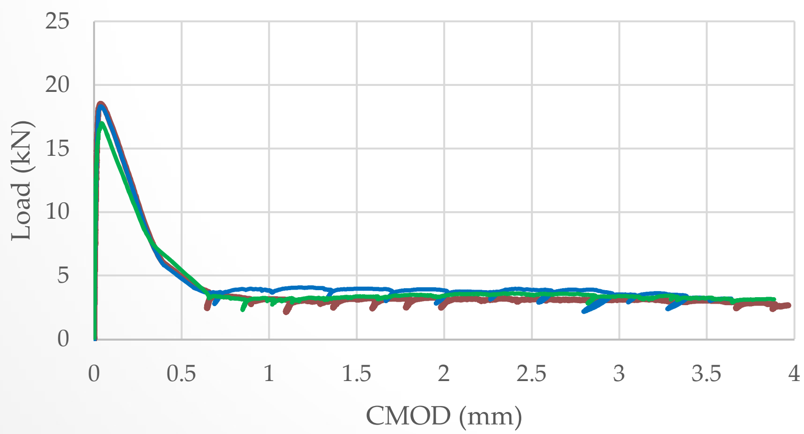
Objective; to compare the design results obtained by using the material parameters found by employing 2 different methods suggested by EN 14651 and ASTM C 1609.

Flexural Strength Test Results (EN 14651)

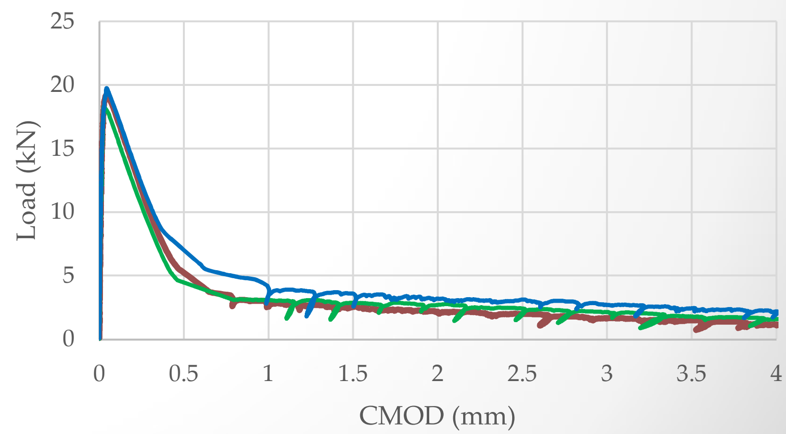
12 - p



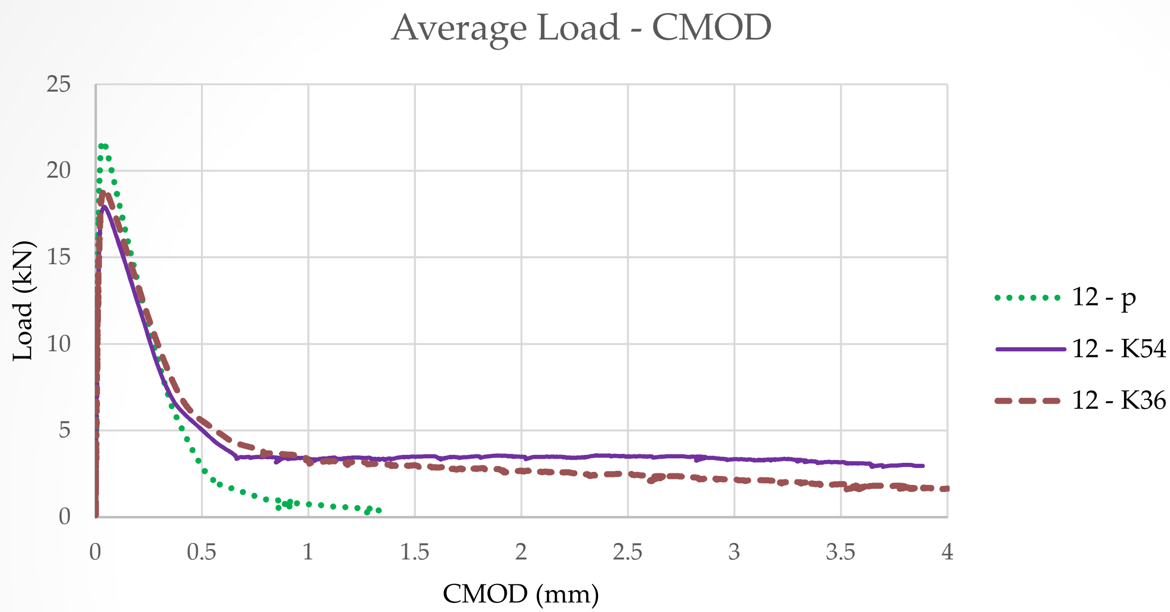
12 – K54



12 – K36



Flexural Strength Test Results (EN 14651)



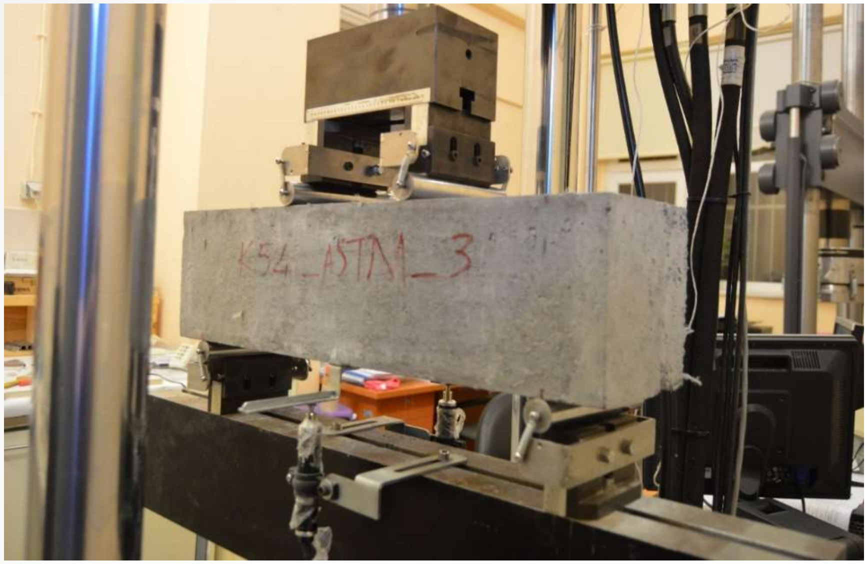
$$f_{ct,L}^{f} = \frac{3F_L l}{2bh_{sp}^2}$$

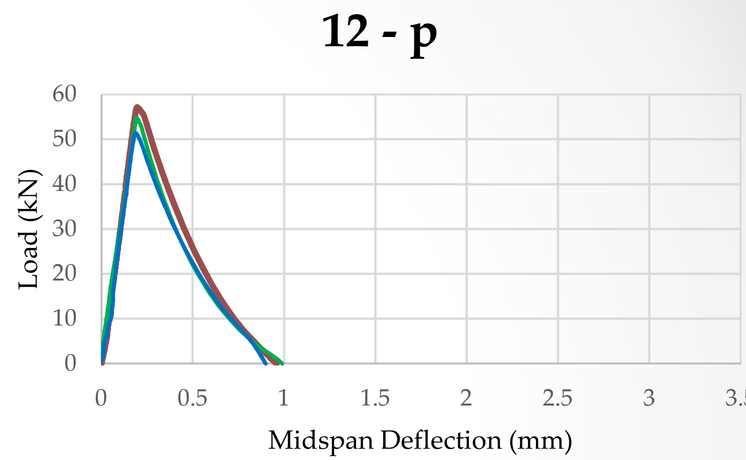
$$f_{R,j} = \frac{3 * F_j * l}{2 * b * h_{sp}^2}$$

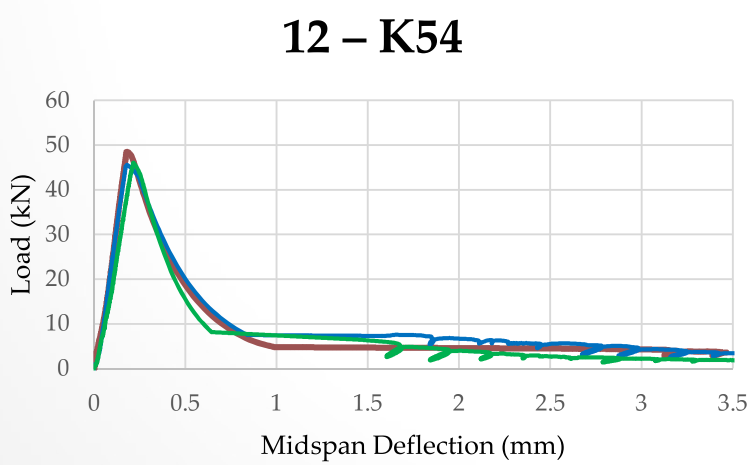
Average flexural and residual flexural strength values

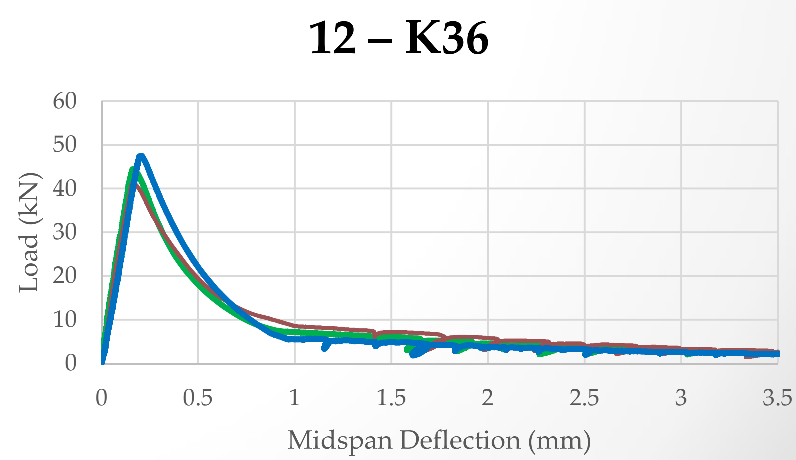
Mixture	F_L, average (kN)	$f_{ct,L}^{f}$, average (MPa)	$f_{R,j}$, average (MPa)	
			CMOD = 0.5 mm	CMOD = 3.5 mm
12 - p	21.76	6.96	-	-
12 - K54	17.95	5.74	1.61	1.02
12 - K36	19.08	6.11	1.76	0.61

Flexural Strength Test Results (ASTM C1609)

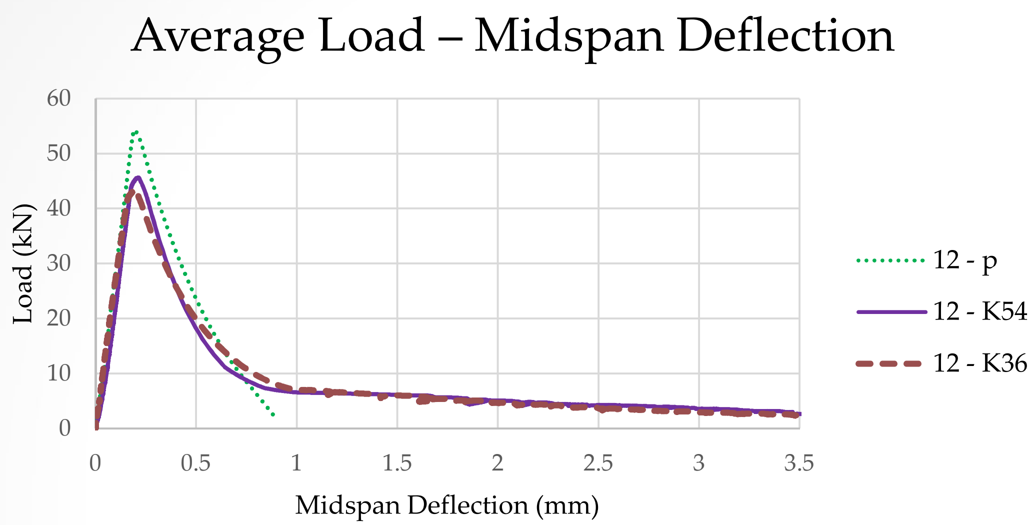








Flexural Strength Test Results (ASTM C1609)



$$f_1 = \frac{P * L}{b * d^2}$$

$$R^D_{T,150} = \frac{150 * T^D_{150}}{f_1 * b * d^2} * 100\%$$

$$f_{e,150} = R^D_{T,150} * f_1$$

Flexural strength, average toughness and equivalent flexural strength ratio values

Mixture	Specimen Number	P_1 (kN)	P_1, average (kN)	f_1 ,average (MPa)	T^D_{150} (kNmm)	$R^D_{T,150}$	$f_{e,150}$ (MPa)
12 - p	1	57.14	54.43	7.26	-	-	-
	2	54.80					
	3	51.35					
12 - K54	1	48.51	46.73	6.23	29.38	0.21	1.31
	2	45.59					
	3	46.08					
12 - K36	1	44.46	44.51	5.93	29.87	0.22	1.33
	2	41.54					
	3	47.53					

Thickness Design for a Sample Pavement IRC SP 46 (2013)

Material properties used in thickness design

		12 - K54	12 - K36
ASTM C1609	$f_{1,average}$	6.23	5.93
	f_{e150}	1.31	1.33
EN 14651	$f_{L,average}$	5.74	6.11
	$f_{1,average}$	1.61	1.76
	$f_{4,average}$	1.02	0.61
modulus of elasticity average		36.7	33.0
unit weight average		2485	2472
poisson's ratio (assumed)		0.15	0.15

Thickness requirements for ultimate moment resistance and fatigue damage analysis

	Ultimate Moment Resistance (TR 34 - third edition) (cm)	Ultimate Moment Resistance (TR 34 - fourth edition) (cm)	Fatigue Resistance (cm)
Plain 1	17.3	18.9	27.0
12 - K54	16.6	18.4	25.0
Plain 2	17.7	18.3	31.0
12 - K36	17	17.9	27.0