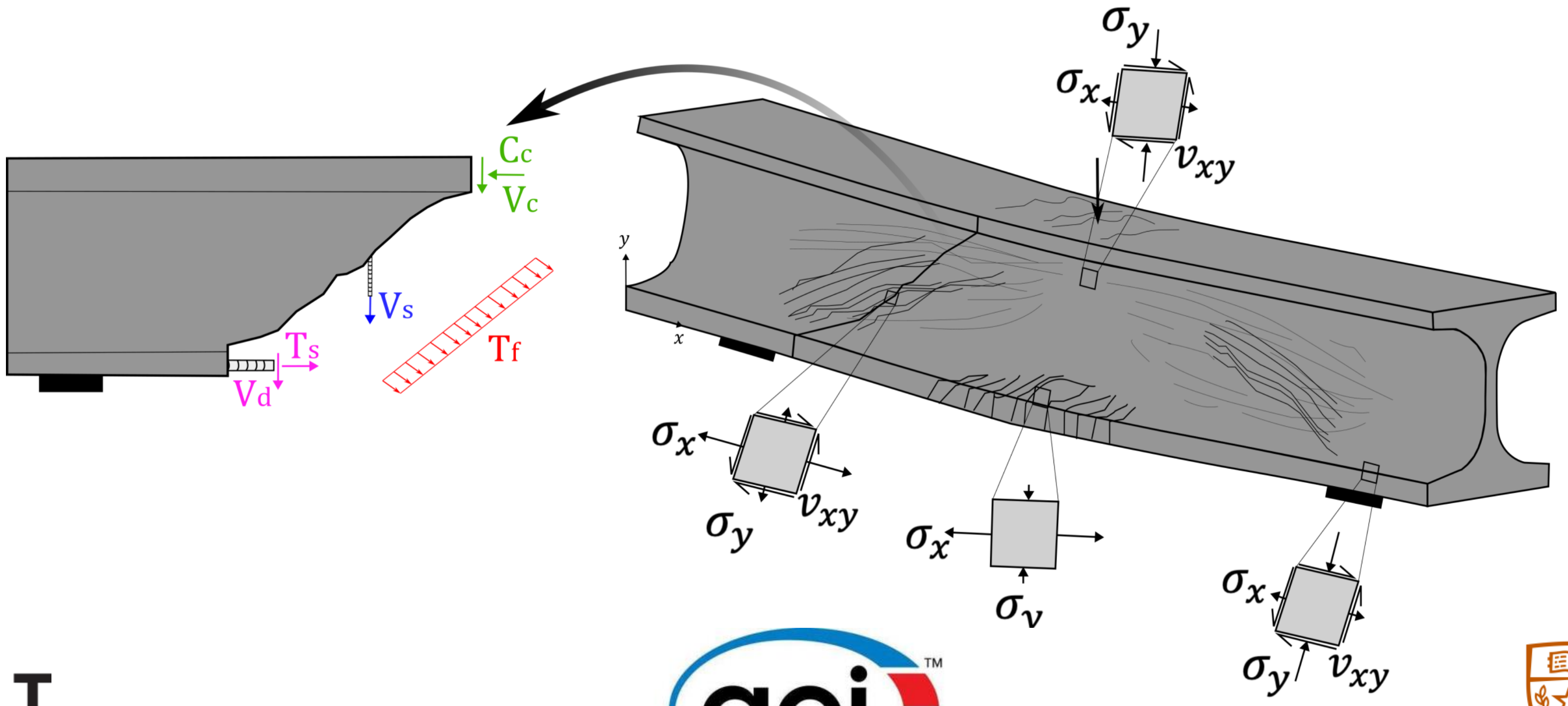
Influence of Fiber Orientation and Section Geometry on the Shear Strength of UHPC Members

AMJAD DIAB

ANCA FERCHE



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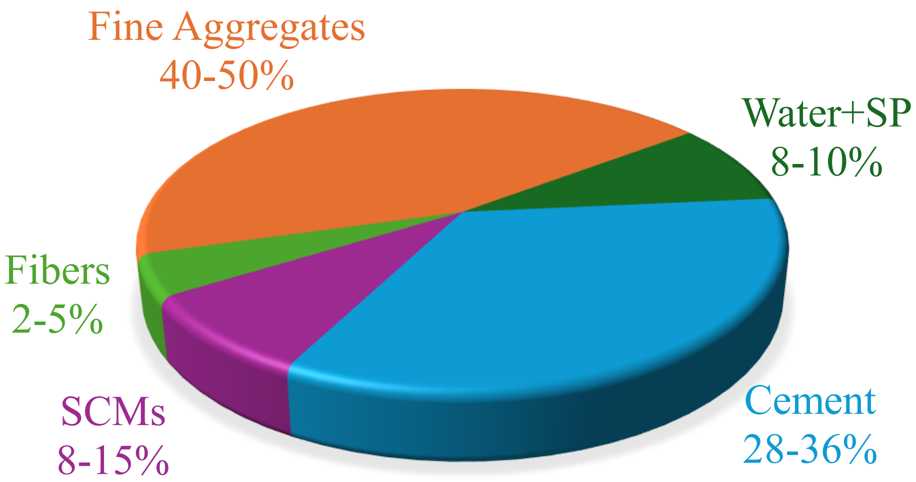
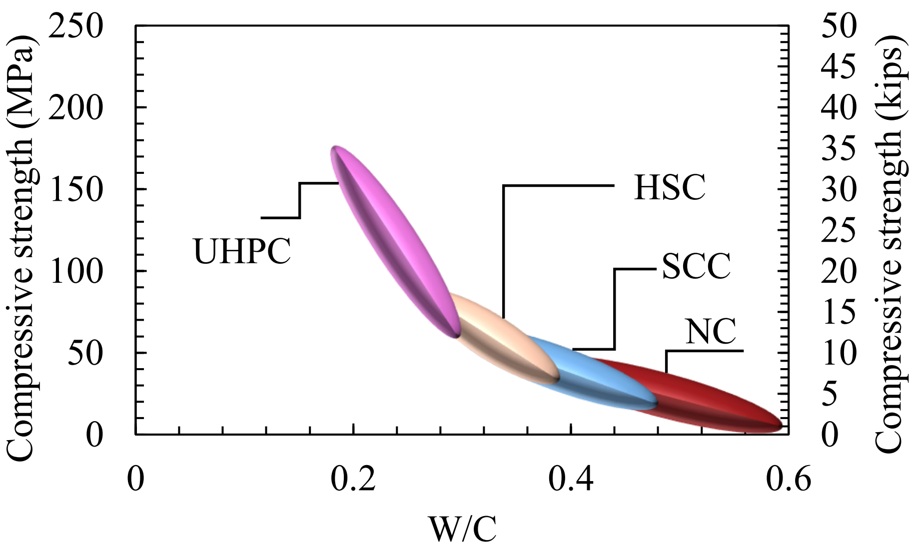
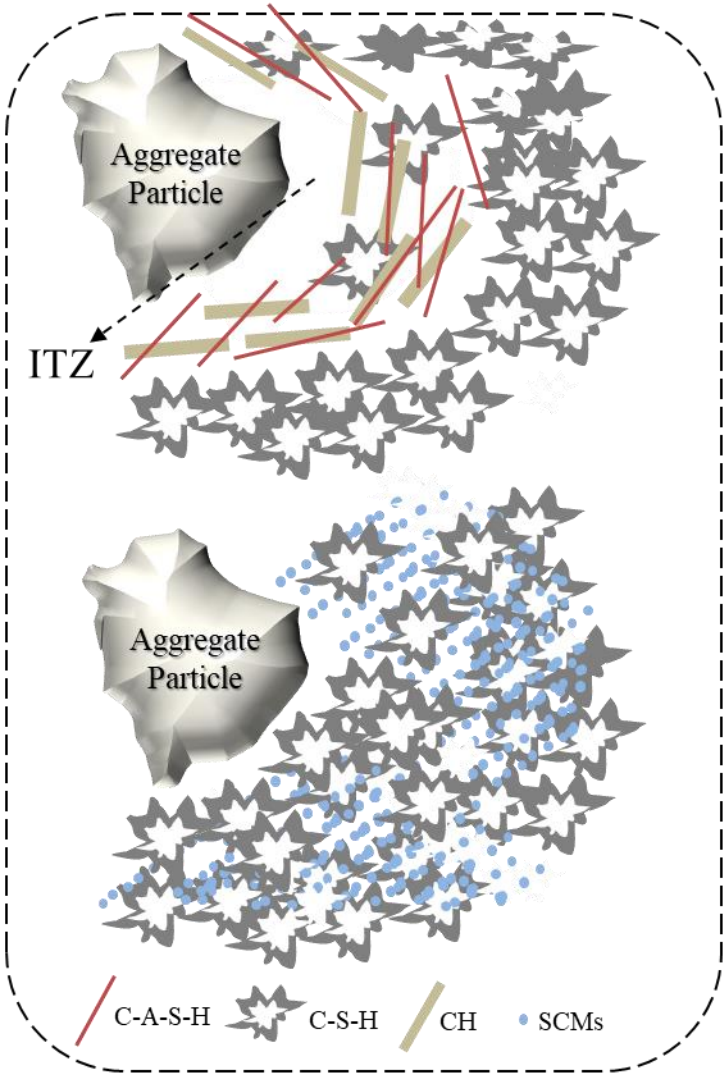
UHPC Overview



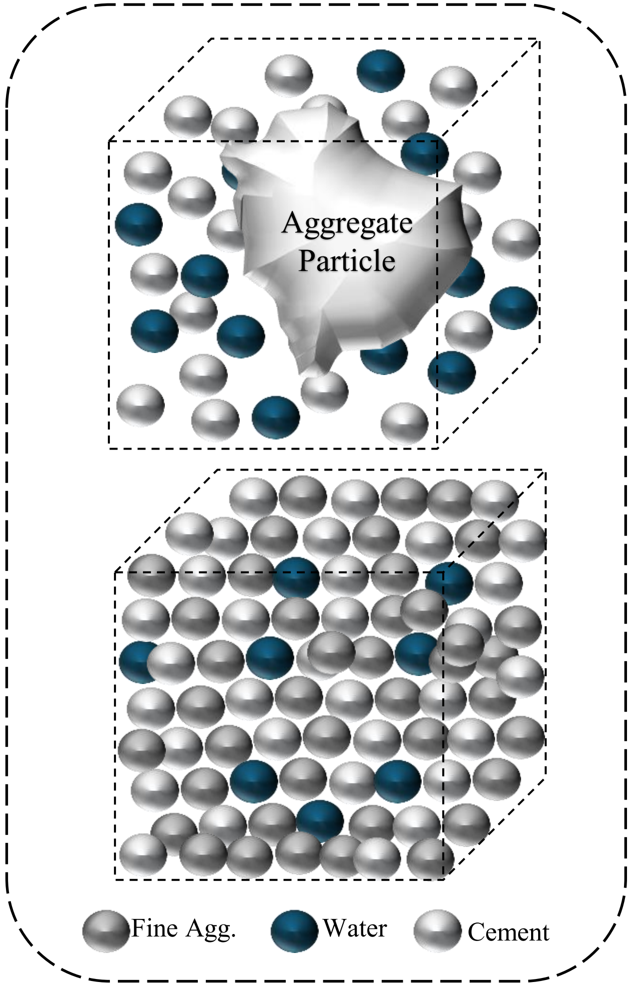
UHPC material composition



Compressive strength vs W/C ratio

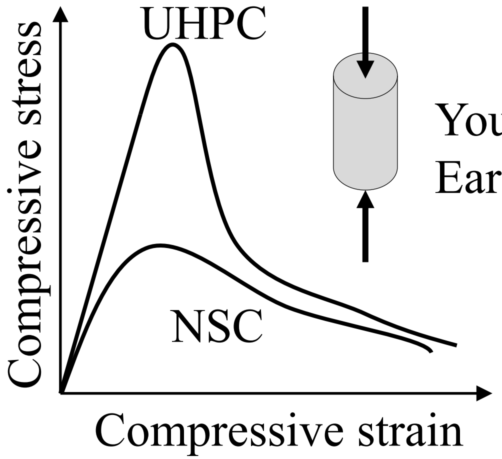


Interfacial transition zone comparison



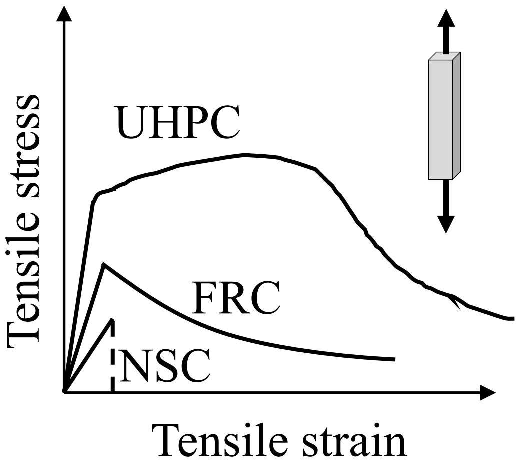
Particle packing comparison

UHPC Overview



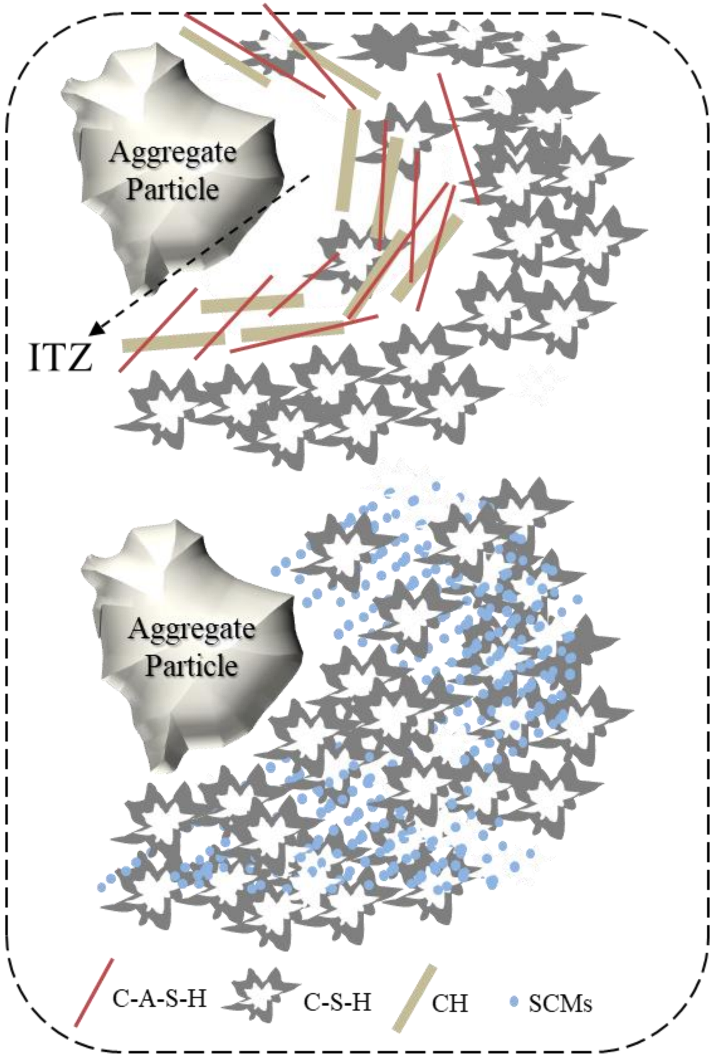
Young's modulus ⬆
Early-age compressive strength ⬆

Prestressing force ⬆

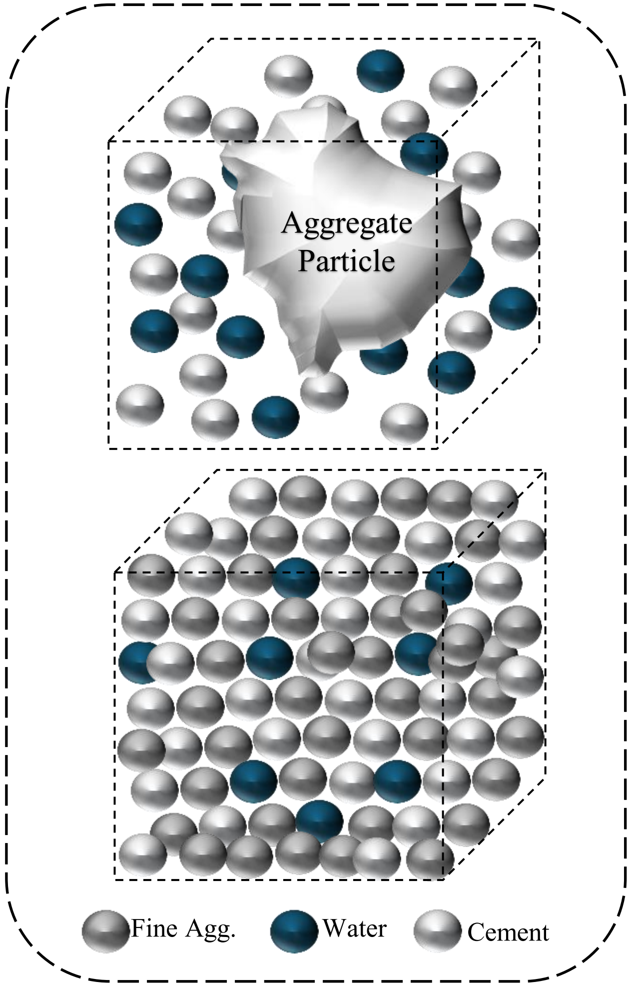


Tensile strength ⬆
Post-cracking ductility ⬆

Cracking at critical regions ⬇

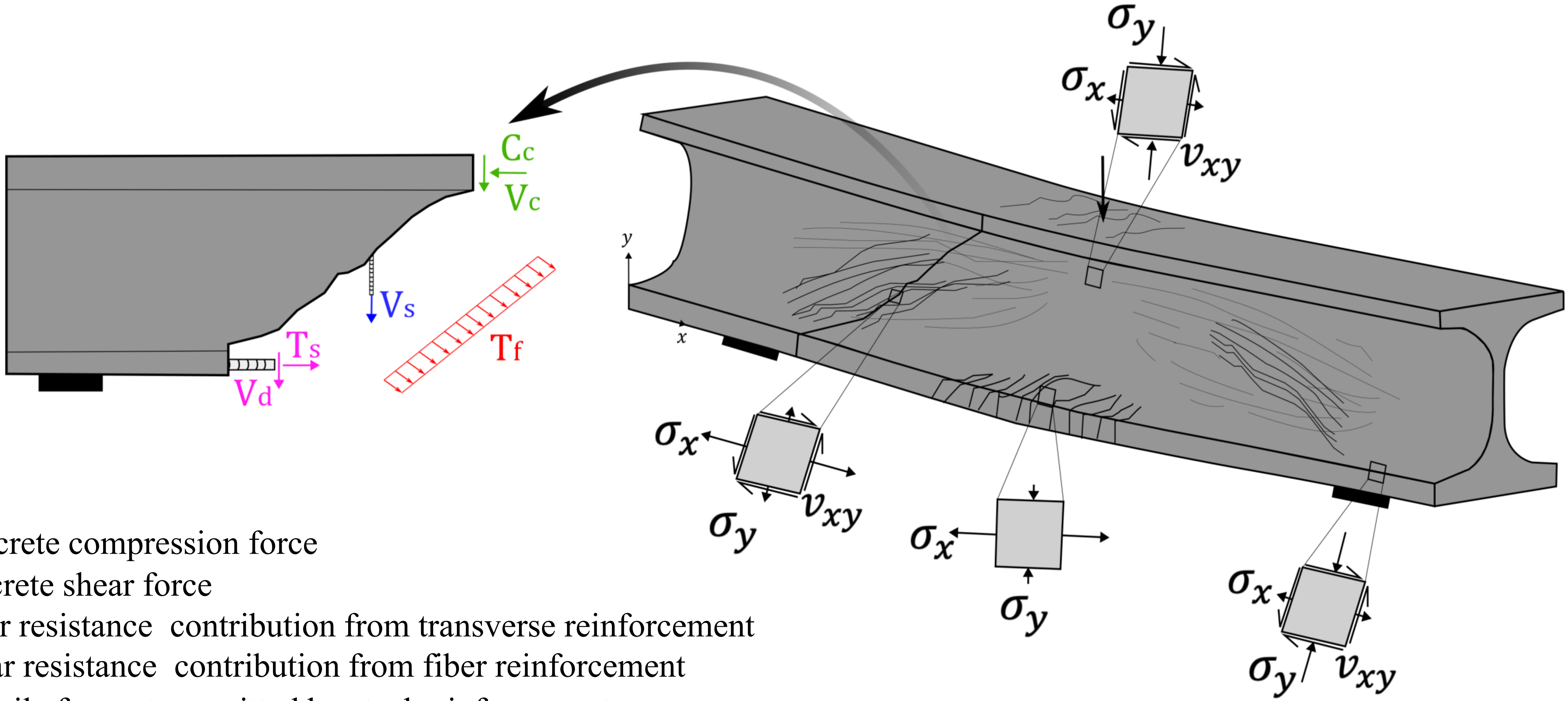


Interfacial transition zone comparison



Particle packing comparison

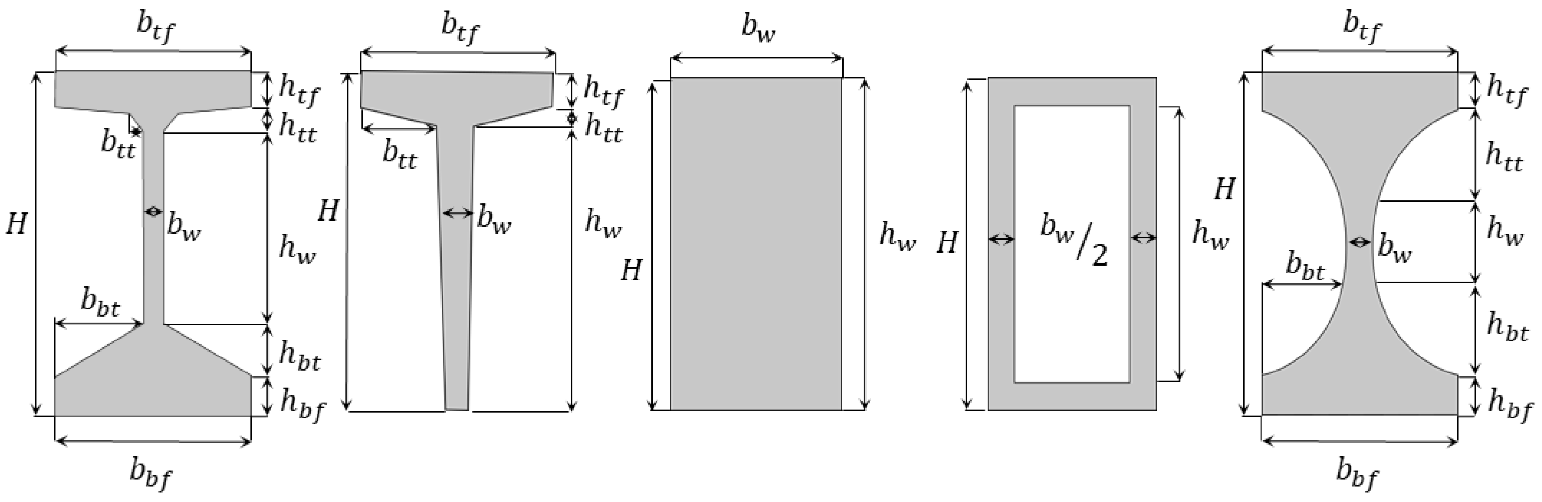
Shear resistance mechanisms in UHPC Beams

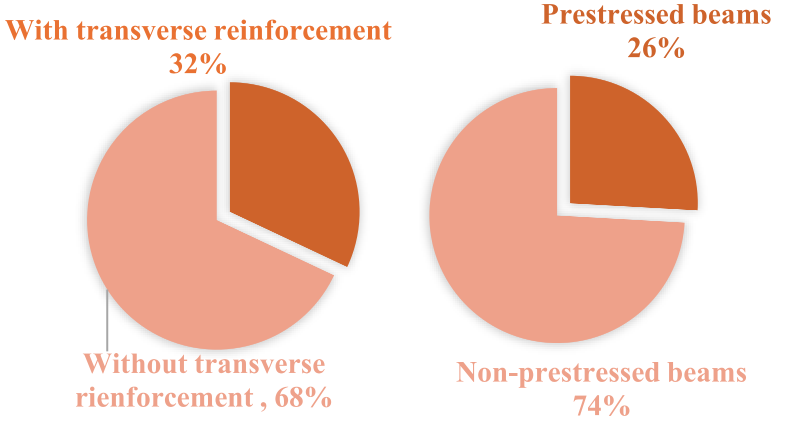


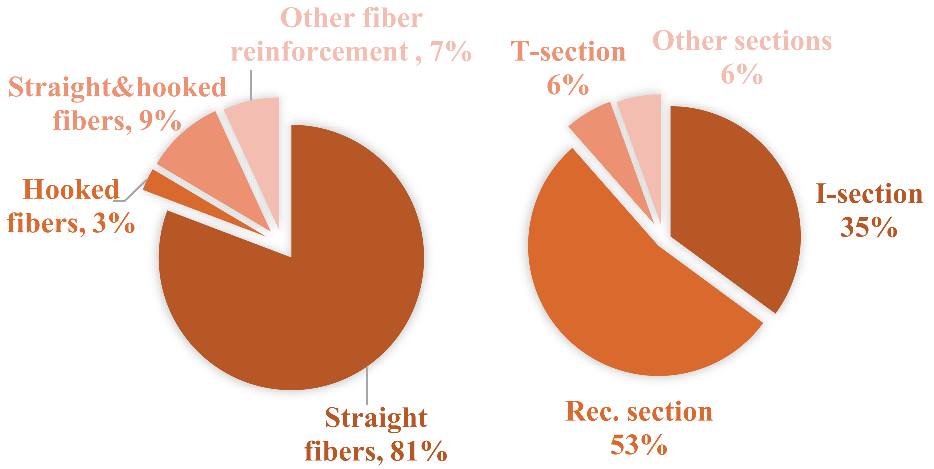
C_c: concrete compression force
V_c: concrete shear force
V_s: shear resistance contribution from transverse reinforcement
T_f: shear resistance contribution from fiber reinforcement
T_s : Tensile forces transmitted by steel reinforcement
V_d: Shear resistance contribution from dowel action

UHPC Shear-Critical Beams Database

- 534 experimentally-measured shear strengths of UHPC beams from 51 experimental studies.

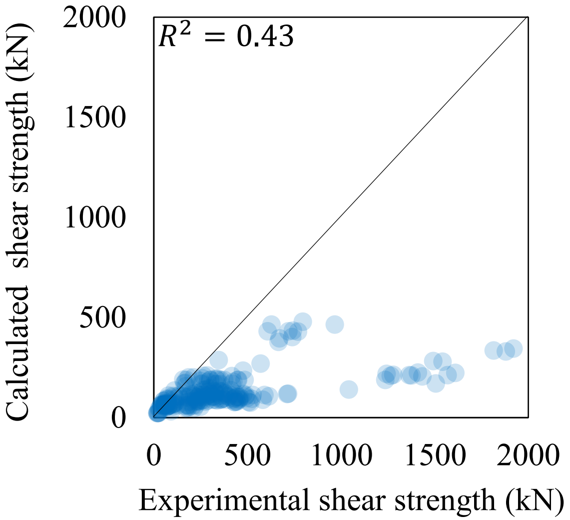






Author	Year	Specimen	Section type	Fiber type	a/d	Beam length (mm)	Beam height (mm)	Effective depth (mm)	Web height (mm)	Web width (mm)	Top transition height (mm)	Bottom transition height (mm)	Top transition width (mm)	Bottom transition width (mm)	Top flange height (mm)	Top flange width (mm)	Bottom flange height (mm)	Bottom flange width (mm)
Voo	2005	SB1	I	S	3	4000	650	600	400	50	25	25	350	200	100	400	100	750
		SB2	I	S	3	4000	650	600	400	50	25	25	350	200	100	400	100	750
		SB3	I	S	3	4000	650	600	400	50	25	25	350	200	100	400	100	750
		SB4	I	S	3	4000	650	600	400	50	25	25	350	200	100	400	100	750
		SB5	I	S&H	3	4000	650	600	400	50	25	25	350	200	100	400	100	750
		SB6	I	H	3	4000	650	600	400	50	25	25	350	200	100	400	100	750
		SB7	I	S	3	4000	650	600	400	50	25	25	350	200	100	400	100	750

Existing Shear Strength Models

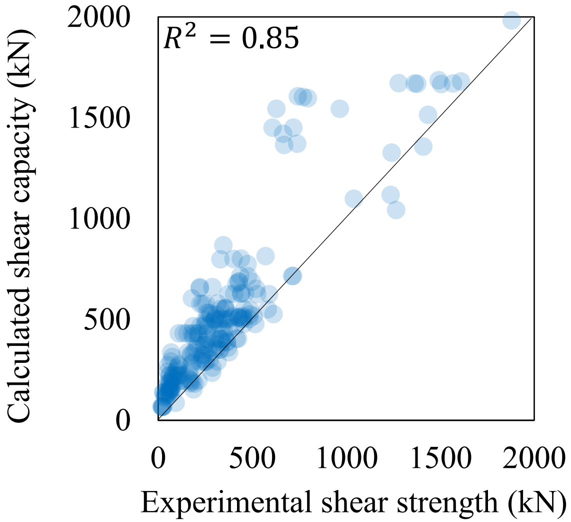


fib Model Code (2020)

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

Where:

$V_{Rd,F}$: Contribution of UHPC and fibers to the shear resistance in UHPC members.
γ_c : Safety factor for UHPC with no fibers (recommended to be taken as 1.5).
k : The size effect, taken as 1+200*d*
ρ_l : longitudinal reinforcement ratio.
f_{Ftuk} $= f_{R,3}/3$, where $f_{R,3}/3$ is the residual flexural tensile strengths corresponding to crack mouth opening displacement of 3.5 mm.
f_{ctk} $= 2.12\ln(1+0.1(f_{ck}+8))$, where **f_{ck}** is the cylindrical compressive strength.
σ_{cp} is the prestressing stress acting on the section
b_w is the minimum cross section web width
d is the effective depth of the section

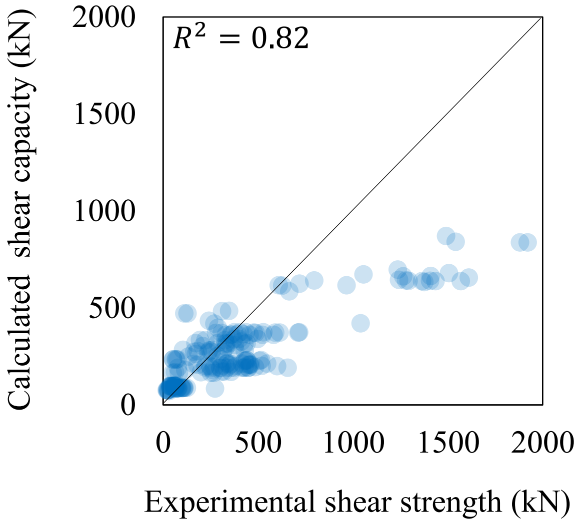


AFGC (2013)

$$V_{Rd,F} = V_{Rd,c} + V_{Rd,f}$$
$$V_{Rd,c} = \frac{0.24}{\gamma_{cf}\gamma_E} k f_{ck}^{0.5} b_w z$$
$$V_{Rd,f} = \frac{A_{fv}\sigma_{Rd,f}}{\tan(\theta)}$$

Where:

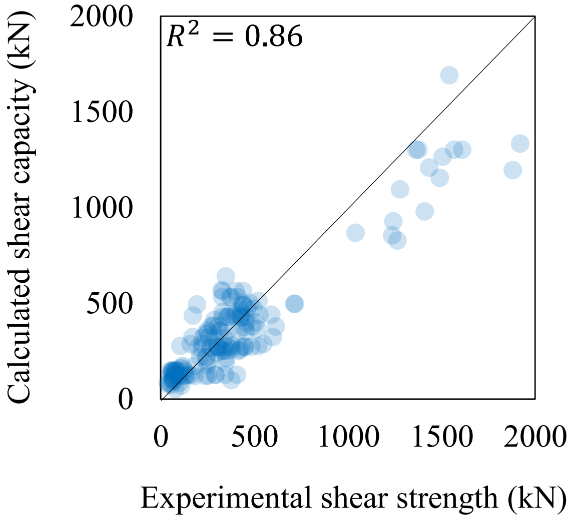
$V_{Rd,c}$: Concrete contribution to the shear resistance in UHPC members.
γ_{cf} : Factor for UHPC in tension and is recommended to be taken equal to 1.3.
γ_E : Factor to account for uncertainty in extrapolating the model developed for UHPC and is recommended to be taken equal to 1.15.
k $= 1 + \frac{3\sigma_{cp}}{f_{ck}}$, for $\sigma_{cp} \geq 0$.
z is taken equal to 0.9 d
$V_{Rd,f}$: The fiber contribution to the shear resistance in UHPC members.
A_{fv} : The effective fiber contribution area, taken equal to bwz
$\sigma_{Rd,f}$: The residual tensile strength of the fiber reinforced member.
θ: The angle between the principal compression stress and the beam's horizontal axis (taken as 30°).



PCI (2021)

$$V_{UHPC} = 1.33 \cdot f_{rr} b_v d_v \cot\theta$$

Where:
f_{rr} = 5.17 MPa (0.75 ksi) for UHPC meeting the minimum PCI-UHPC tensile requirements.
b_v : Minimum web width.
d_v : The effective shear depth.
θ $= 29 + 3500 \cdot \varepsilon_s$, where ε_s is the net longitudinal strain at the centroid of the tension reinforcement.



FHWA (2024)

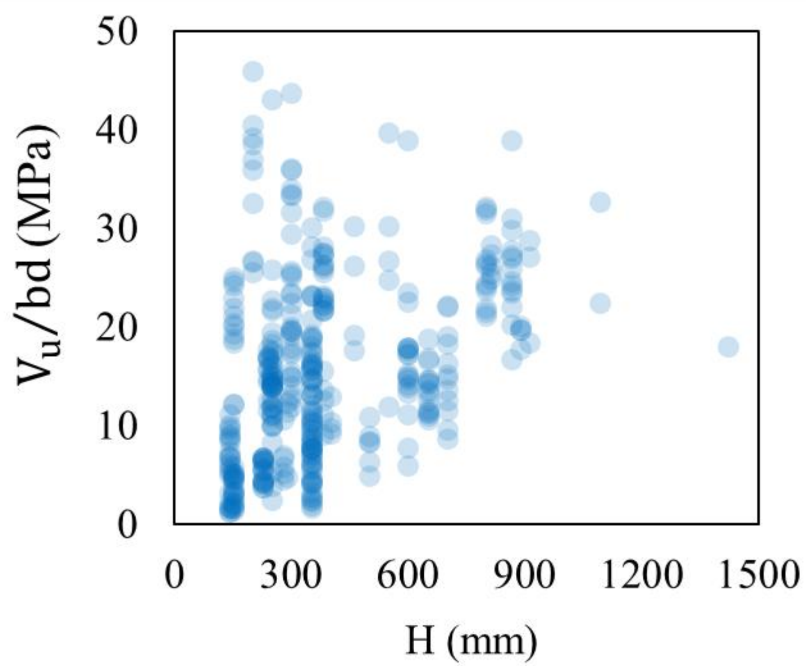
$$V_{UHPC} = \gamma_u f_{t,loc} b_v d_v \cot\theta$$

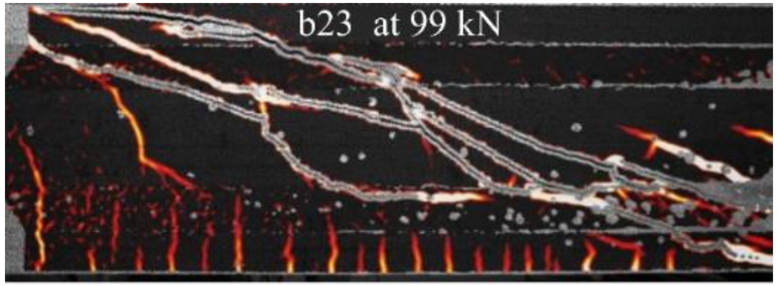
Where:
γ_u : Reduction factor to account for the variability in the UHPC tensile stress parameters.
$f_{t,loc}$: The localization tensile stress of the UHPC.

Fiber reinforcement effect on the behavior of shear-critical beams

- Enhancing the overall ductility
- Delaying crack initiation
- Reducing stress concentrations at crack locations
- Mitigating the size effect

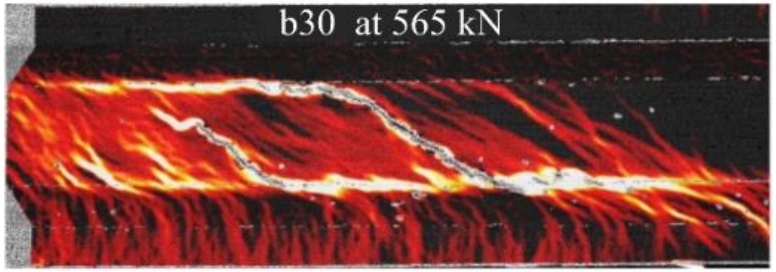
- Fiber reinforcement failure mode varies depending on their physical properties





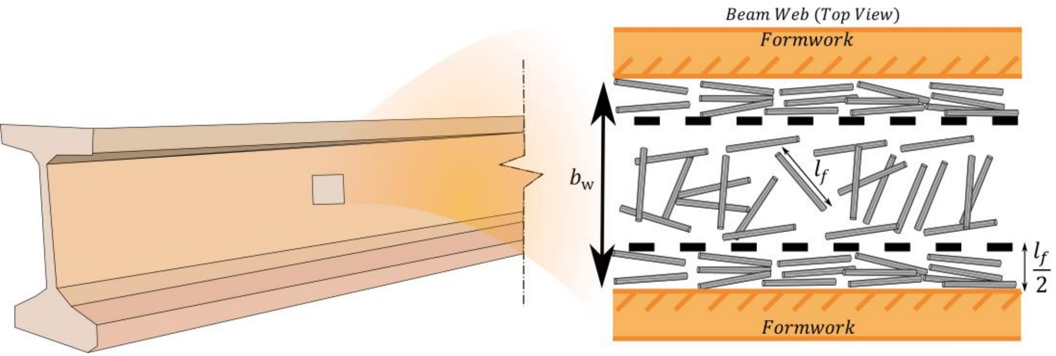
Without reinforcement

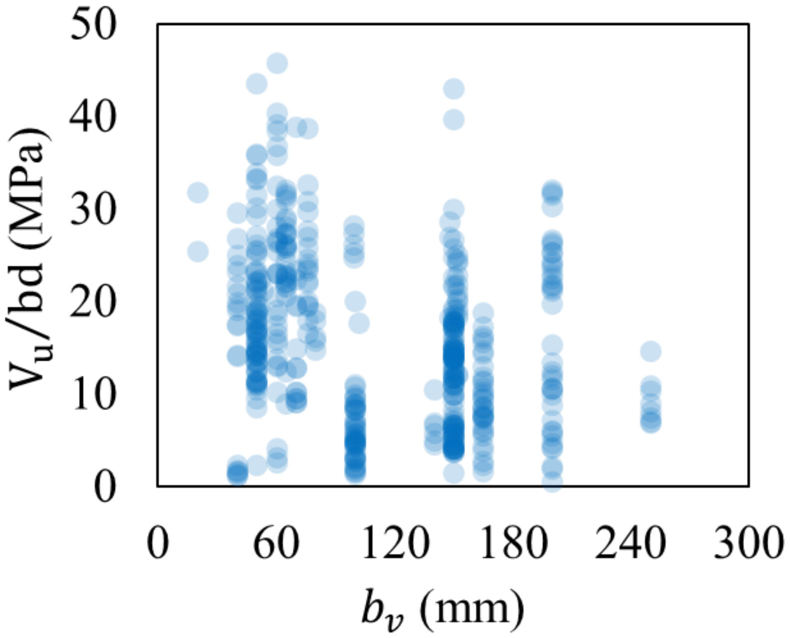
With transverse reinforcement

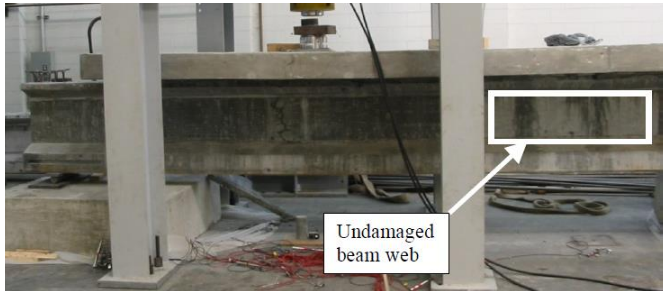


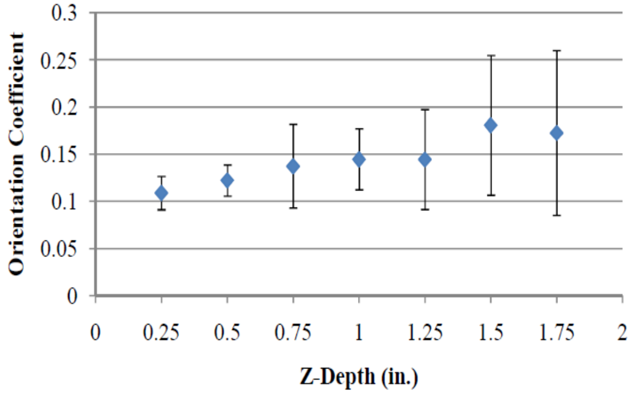
With fiber reinforcement

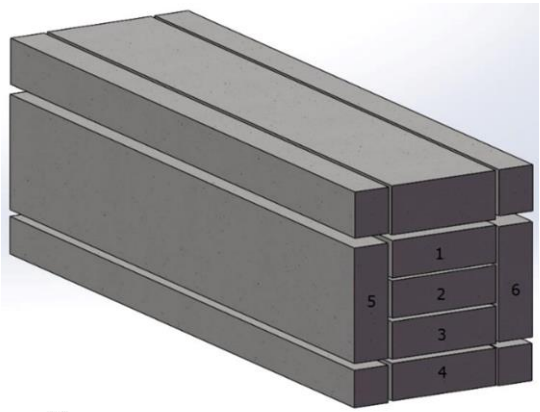
Fiber orientation effect

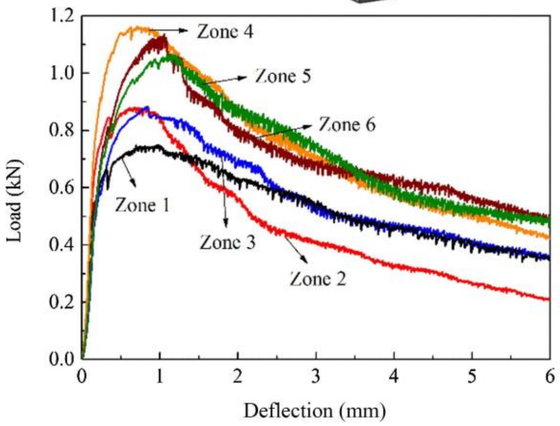






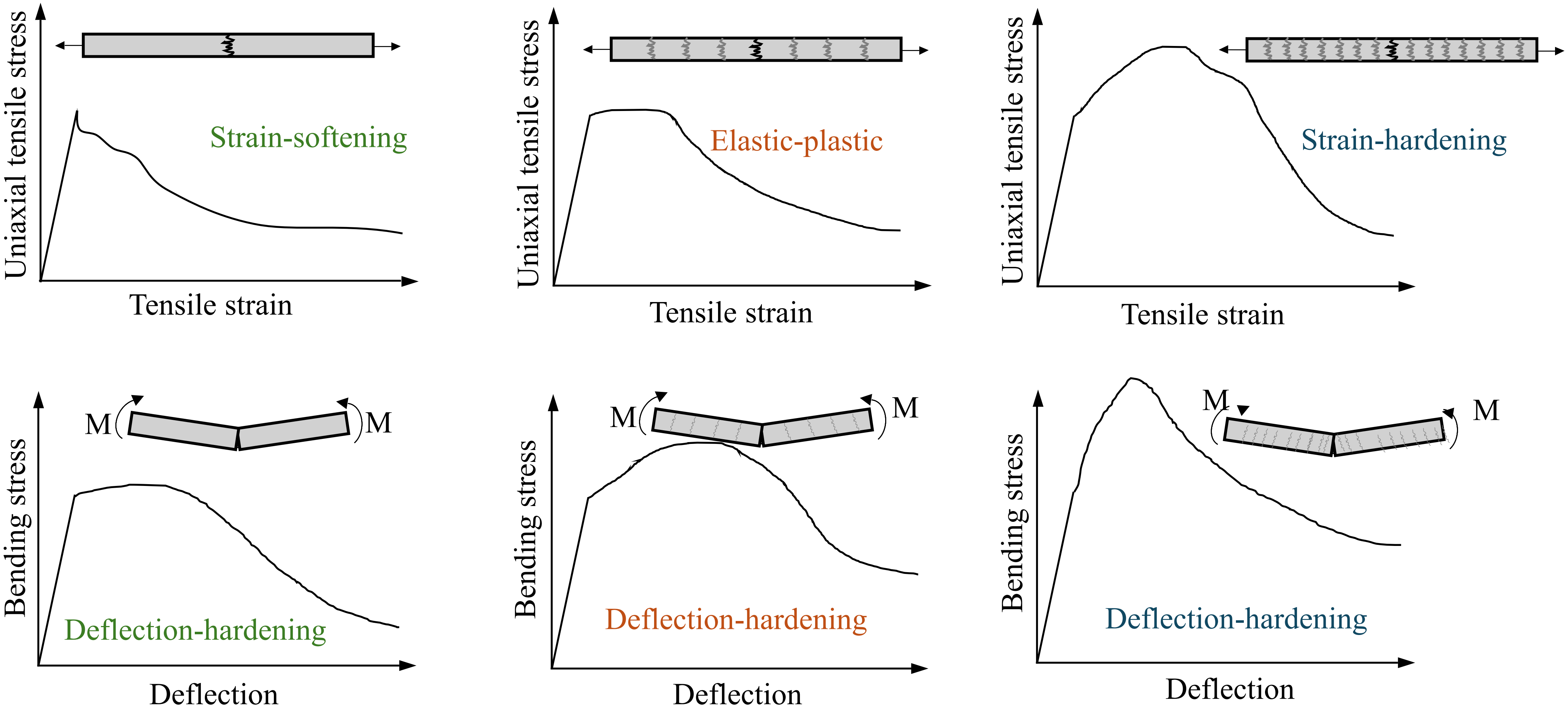






- Fiber orientation coefficient, $\eta_\theta = \frac{N_f A_f}{V_f}$
- η_θ ranges from 0 to 1, where the value 0 indicates that all fibers are parallel to the cut plane and 1 indicates that all fibers are perpendicular to the cut.

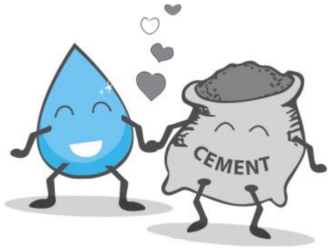
UHPC Tension Response

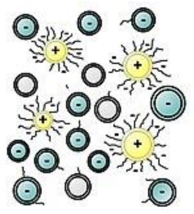


UHPC Direct Tension Database

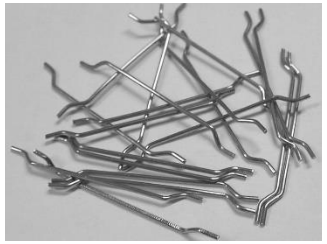
SCMs

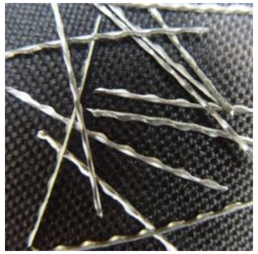
W/C & SP





Steel fibers



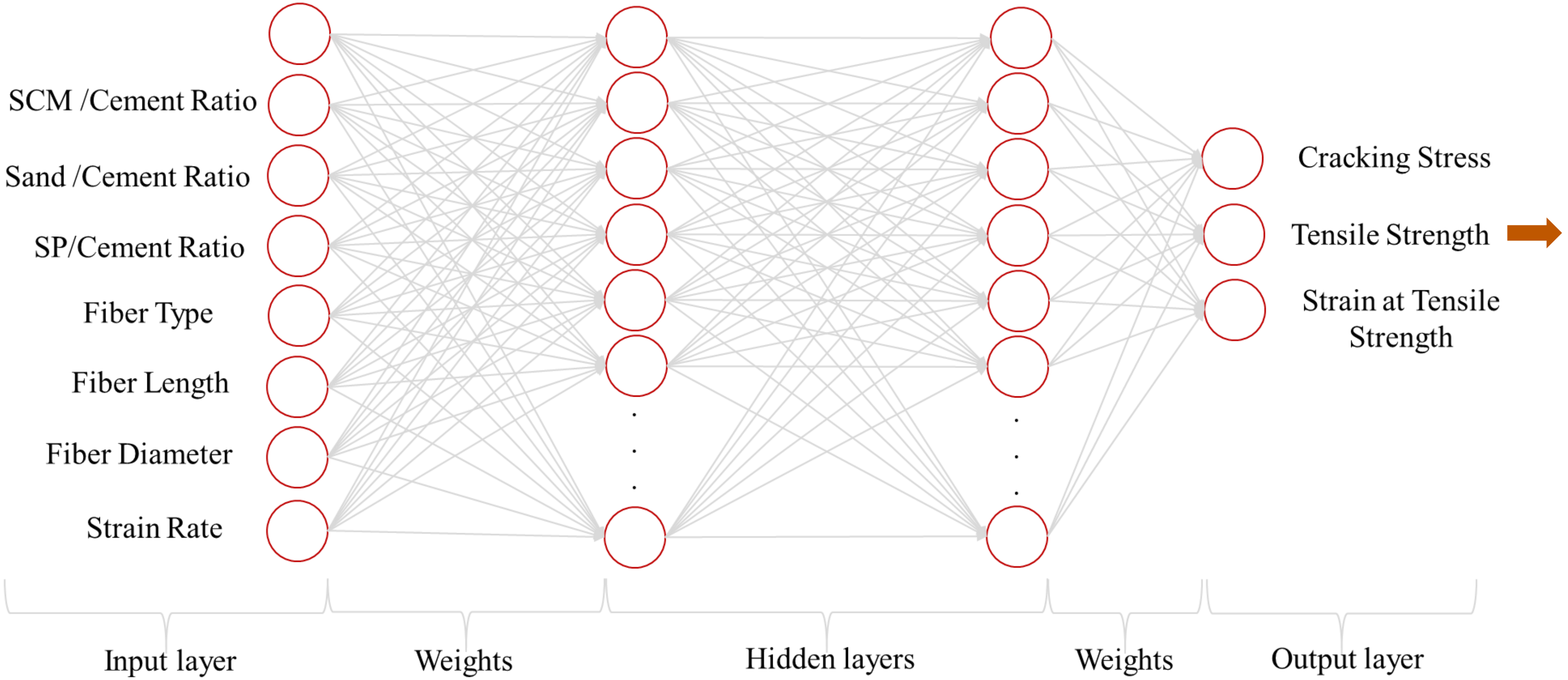


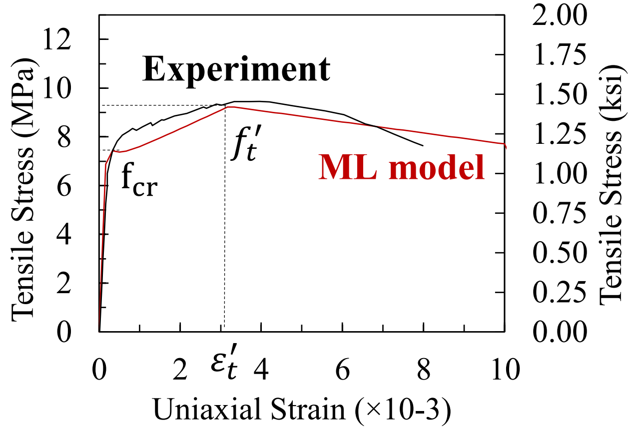
PE fibers

575 Datapoints

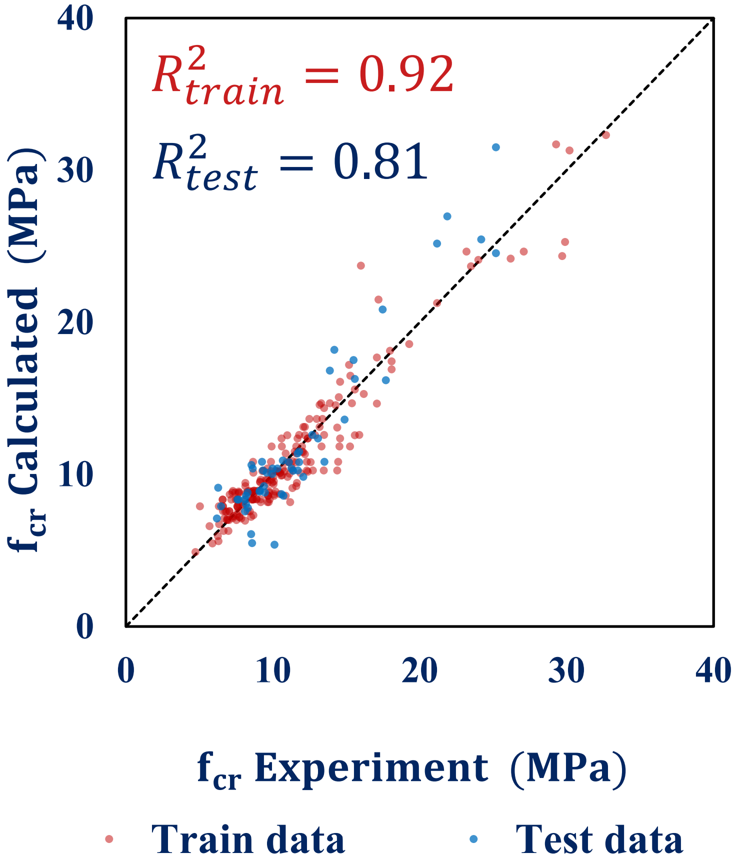
Train | Test

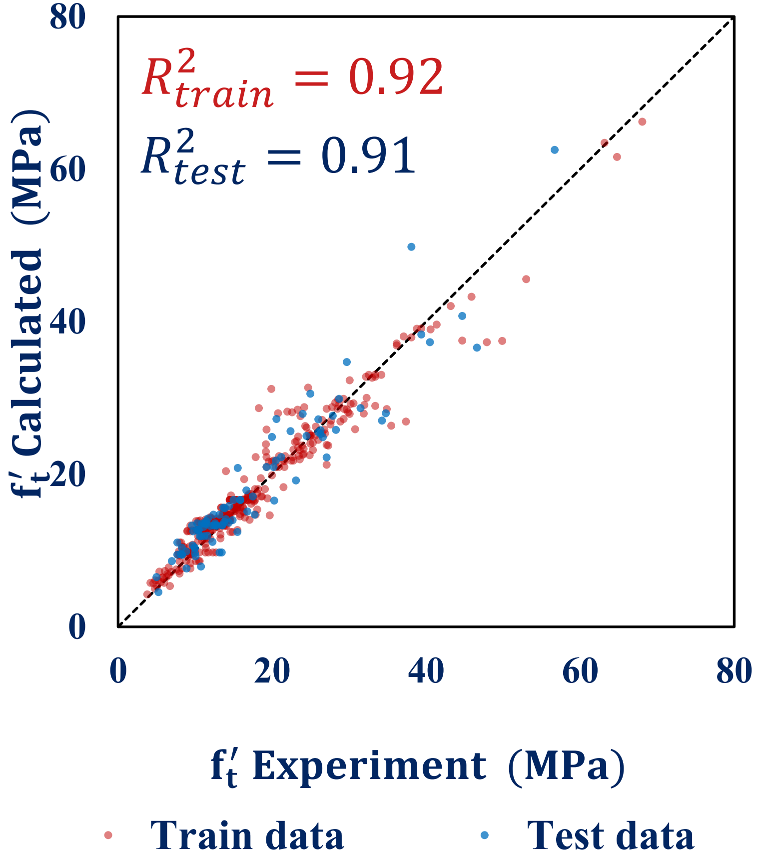
Artificial Neural Network

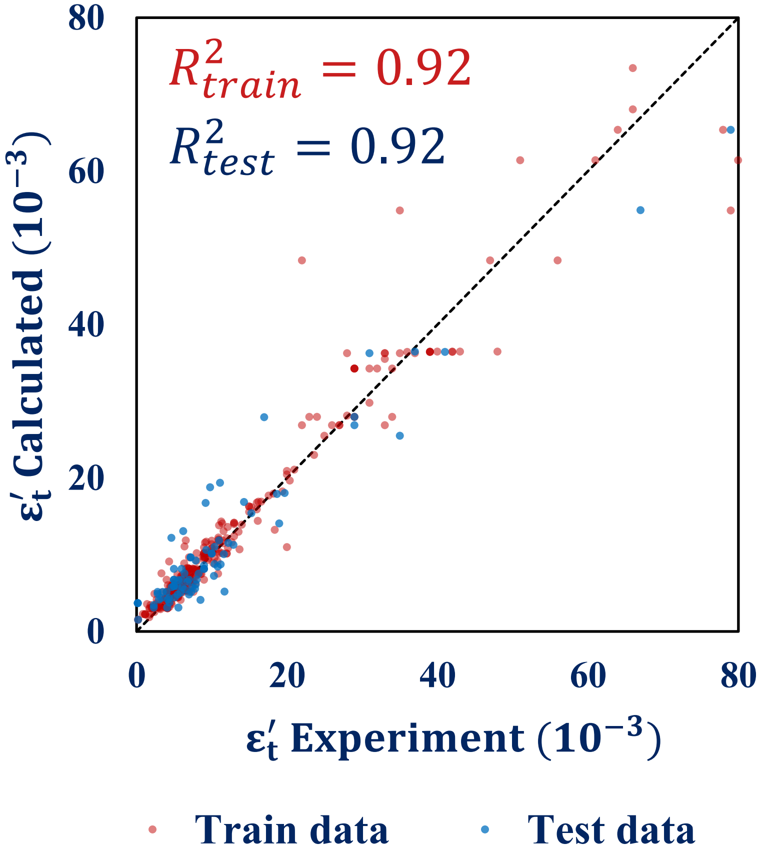




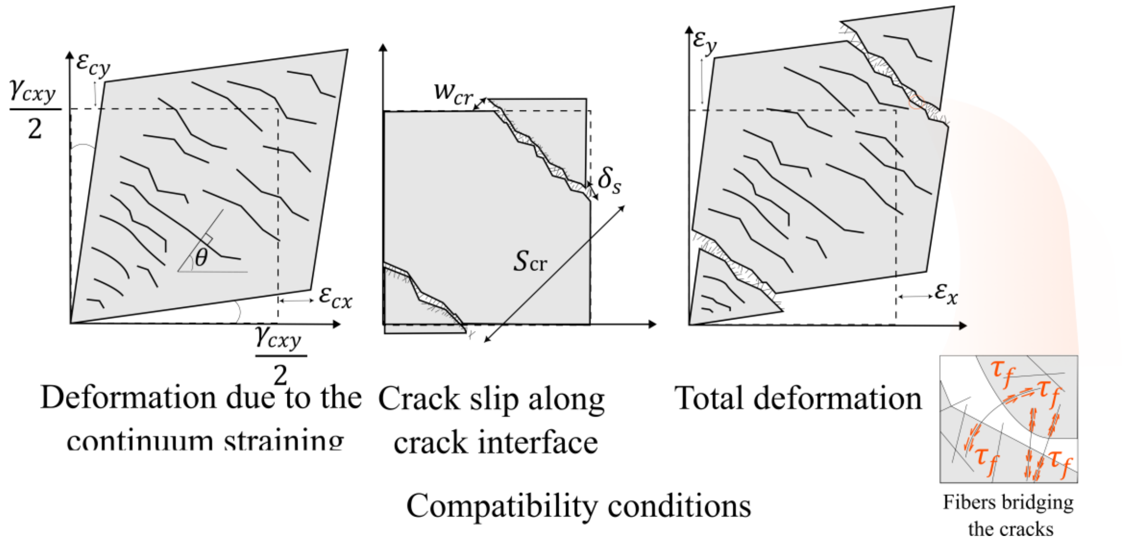
ANN Results


$R^2_{train} = 0.92$
$R^2_{test} = 0.81$
f_{cr} Calculated (MPa)
f_{cr} Experiment (MPa)
0
10
20
30
40
Train data
Test data

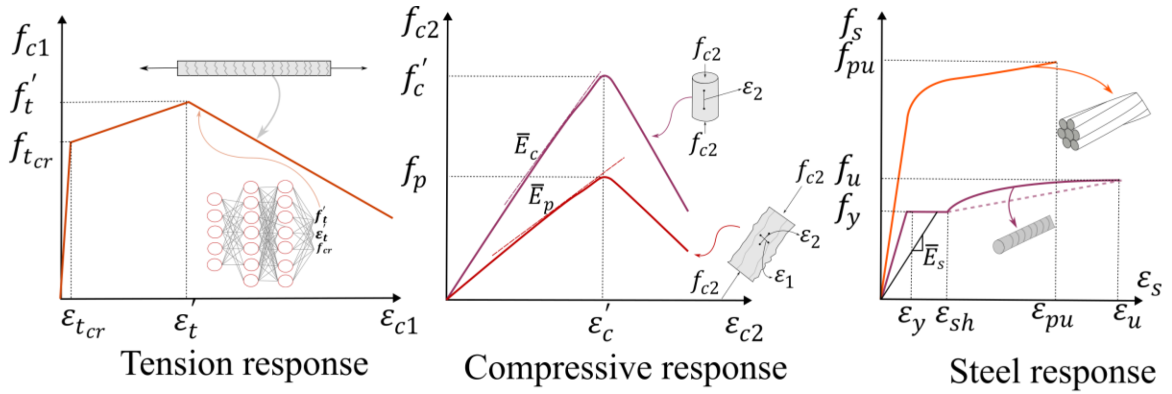

$R^2_{train} = 0.92$
$R^2_{test} = 0.91$
f'_t Calculated (MPa)
f'_t Experiment (MPa)
0
20
40
60
80
Train data
Test data


$R^2_{train} = 0.92$
$R^2_{test} = 0.92$
ε'_t Calculated (10^{-3})
ε'_t Experiment (10^{-3})
0
20
40
60
80
Train data
Test data

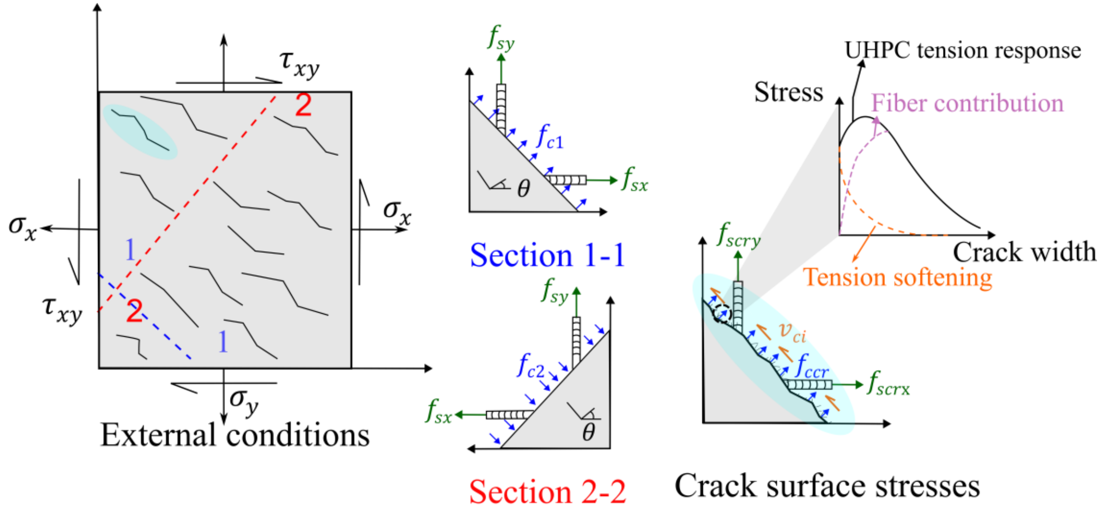
Modeling Approach



Compatibility conditions

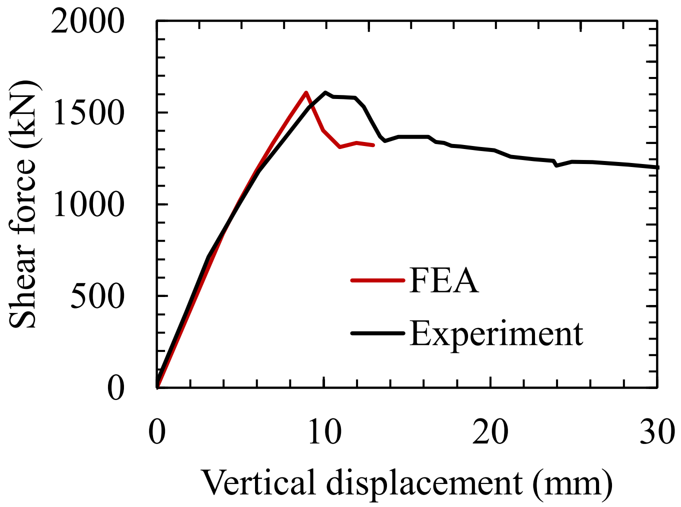


Constitutive relations



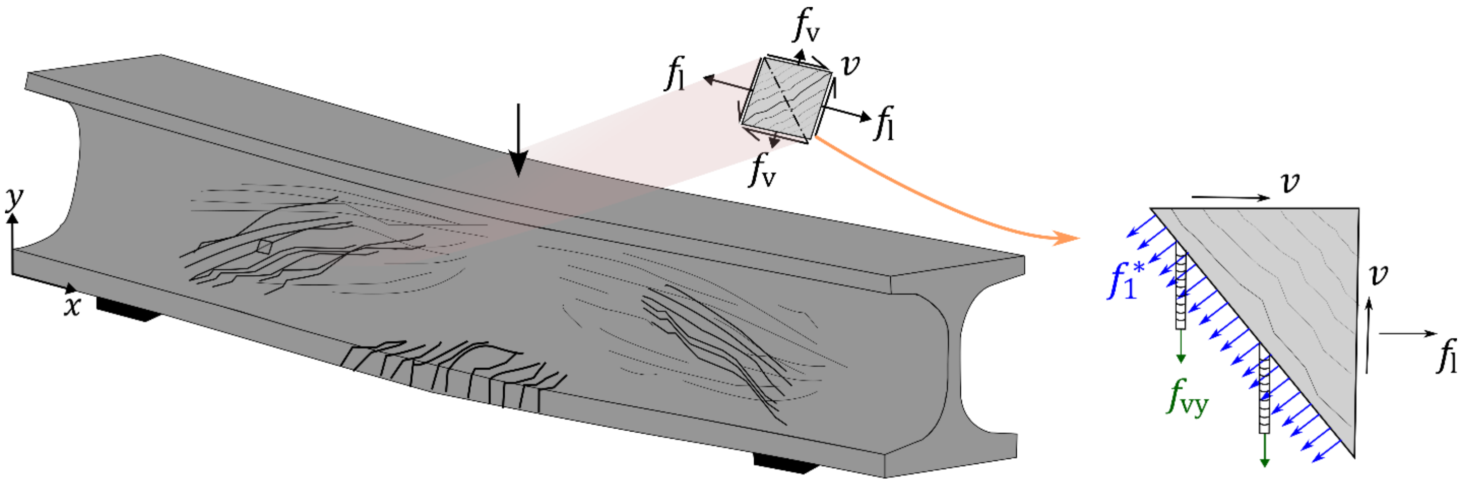
Internal stresses

Equilibrium conditions



Proposed shear strength model

- The model specifically addresses the behavior of an element located in a region of a shear-critical UHPC beam.
- With the fundamental assumption that the shear stresses are constant over the effective depth with conformity to the MCFT provisions.
- basic assumption in this model which conforms with the simplified MCFT is that the clamping stresses (f_y) in the beam's critical shear region are assumed to be negligibly small
- The proposed model also assumes that the transverse reinforcement yields at the ultimate shear strength in UHPC beams that are not limited by concrete crushing



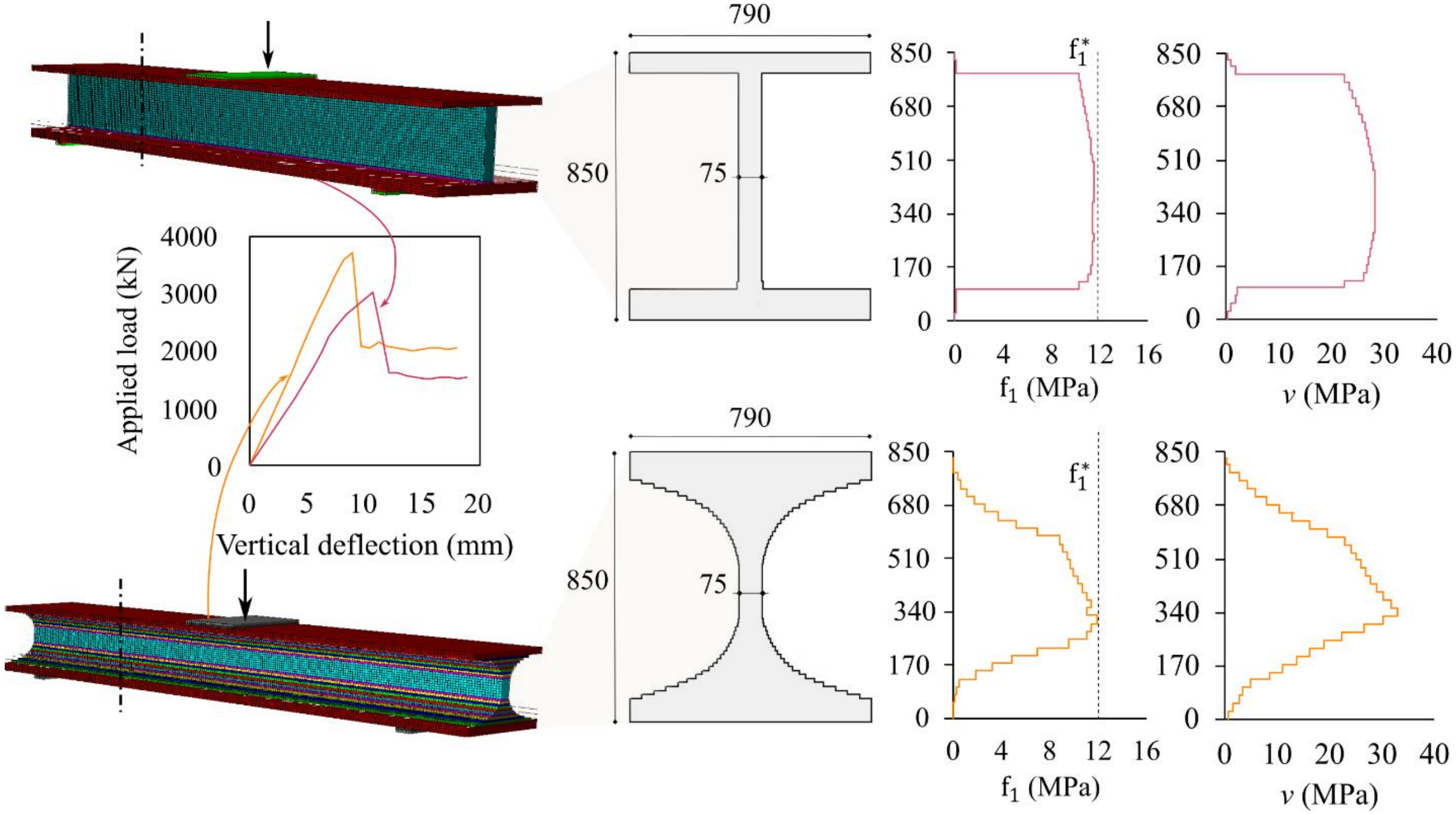
Shape effect analysis

- With the assumption of having negligible clamping stresses we get:

$$v(y) = f_1(y)\cot\theta + \rho_v f_{v_y}\cot\theta$$

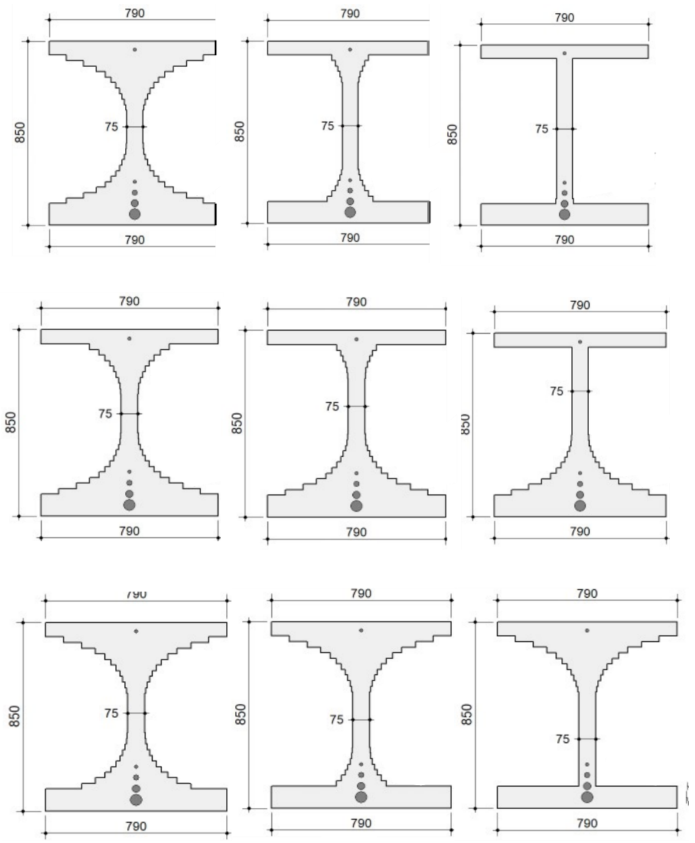
- Due to the difficulty in calculating the web width and the associated f_1 at each depth in the section. A parametric study was conducted to evaluate the shape effect on the behavior of shear critical beams using an analytical nonlinear finite element analysis (NLFEA) model previously developed by the authors

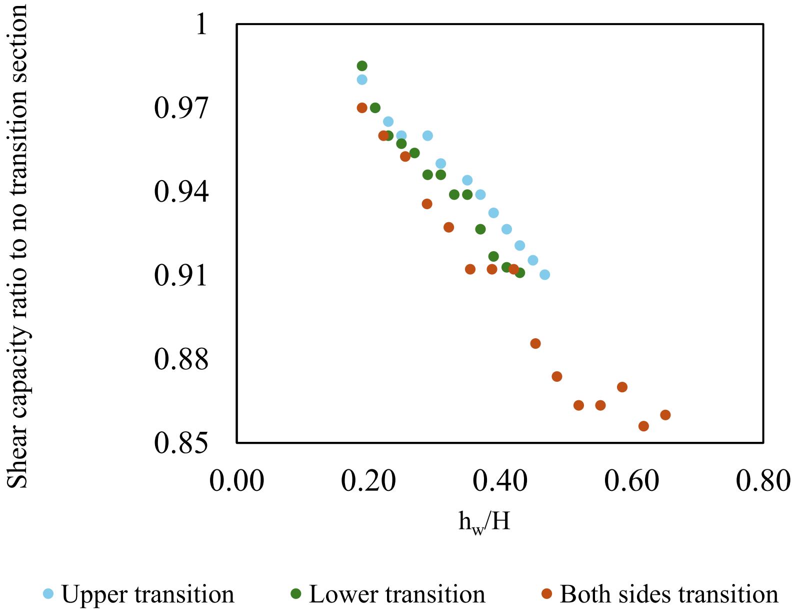
$$V_{UHPC} = f_1^* b_v d_v \cot\theta$$

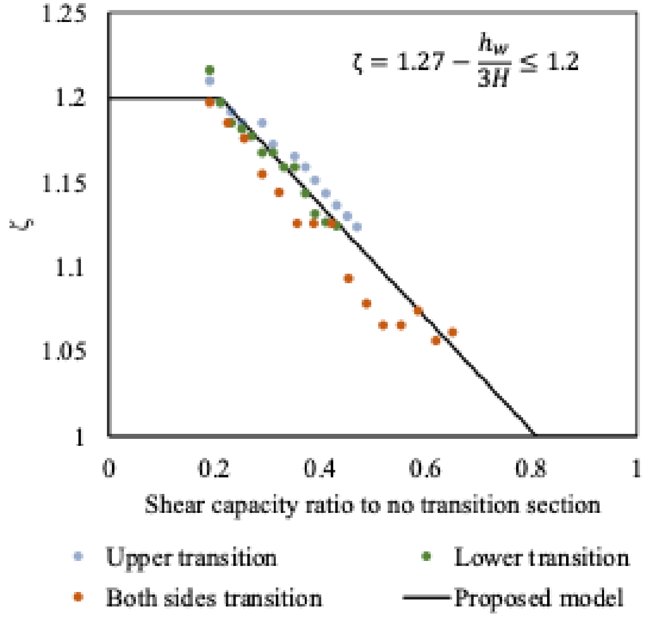


$$V_{UHPC} = d_v \cot\theta \int_{y_t}^{y_c} f_1(y) b_w(y).\, d_y$$

Shape effect analysis







Proposed shear strength model

$$V_n = V_{UHPC} + V_s + V_p \leq V_{n_{max}} + V_p$$

$$V_{UHPC} = \zeta\varphi\psi f_t' b_v d_v \cot\theta$$

$$V_S = \frac{A_v f_{vy}}{s} d_v \cot\theta$$

$$V_{n_{max}} = 0.25 f_c' b_v d_v$$

$$\psi = \frac{1300}{1300 + d_v}$$

$$\varphi = \left(1 - 0.2\frac{H}{1000}\right)\left(1 - 2\frac{b_v/l_f}{1000}\right)$$

V_{UHPC}: Nominal shear contribution of UHPC.

V_s: Shear resistance provided by the transverse reinforcement.

V_p: The component of prestressing force in the direction of the shear force.

$V_{n_{max}}$: The maximum nominal shear resistance governed by UHPC crushing.

d_v: The effective shear depth taken as the distance between the resultants of the tension and compression forces due to flexure, as a simplification, d_v is taken as the maximum between 0.9d and 0.72H, where d is the effective depth from extreme compression fiber to the centroid of the tension force in the tension reinforcement.

b_v: The effective web width taken as the minimum web width within d_v.

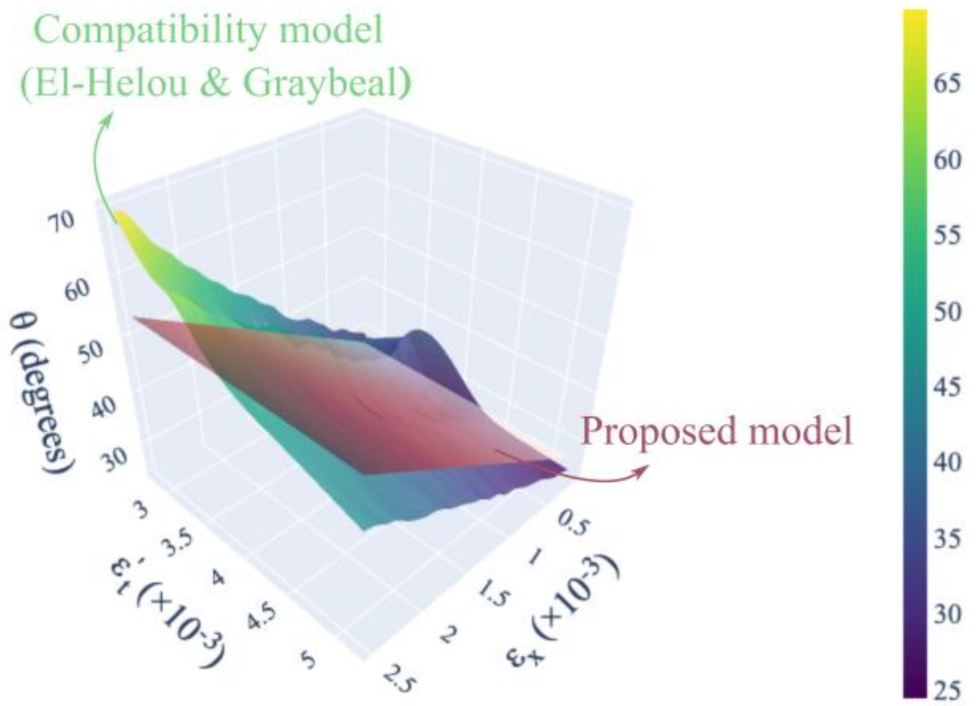
θ: The angle of inclination of diagonal compressive stresses.

A_v: the area of transverse reinforcement within the spacing s.

diagonal compressive stresses inclination angle

- f_{s_y} is assumed equal to f_{y_y} in this study
- the value of α was set equal to 1 in the equation.
- The equation was used to estimate θ for the beams tested by El-Helou & Graybeal (2022) .
- presents a 3D contour plot illustrating the relationship between the beams' mechanical properties and θ to different values of ε_x and ε_t'.
- the plane surface represents the model provided by the authors which provides a simplified approach to calculate θ for practicality purposes.

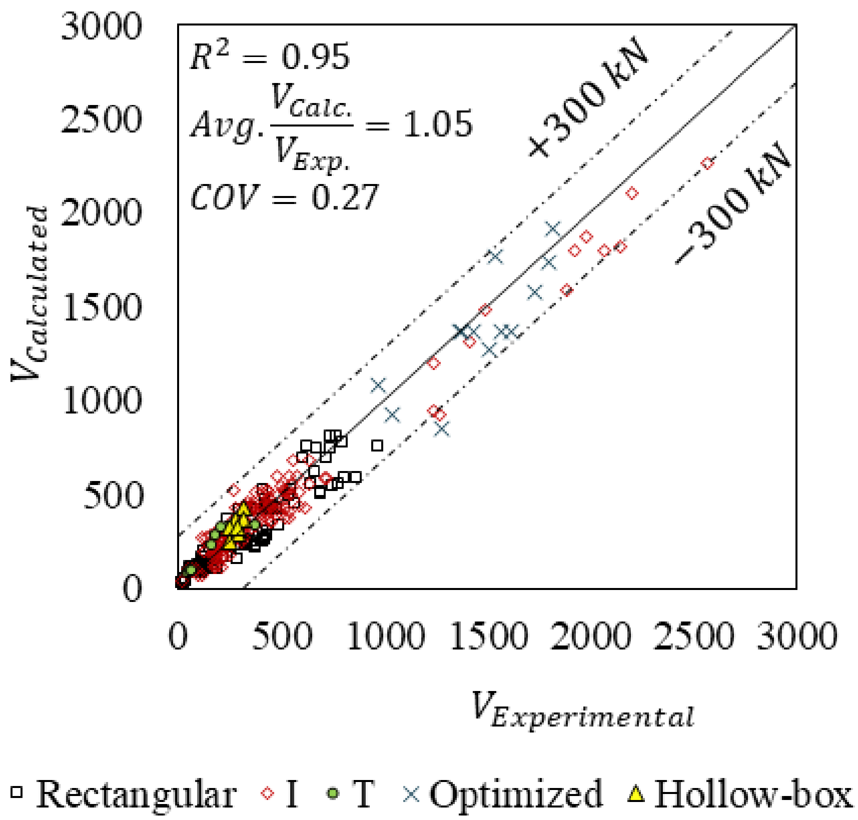
$$\varepsilon_t' = \varepsilon_x(1+\cot^2\theta) + \frac{f_t'}{\alpha E_c}\cot^4\theta + \frac{\rho_y f_{s_y}}{\alpha E_c}\cot^2\theta\,(1+\cot^2\theta)$$



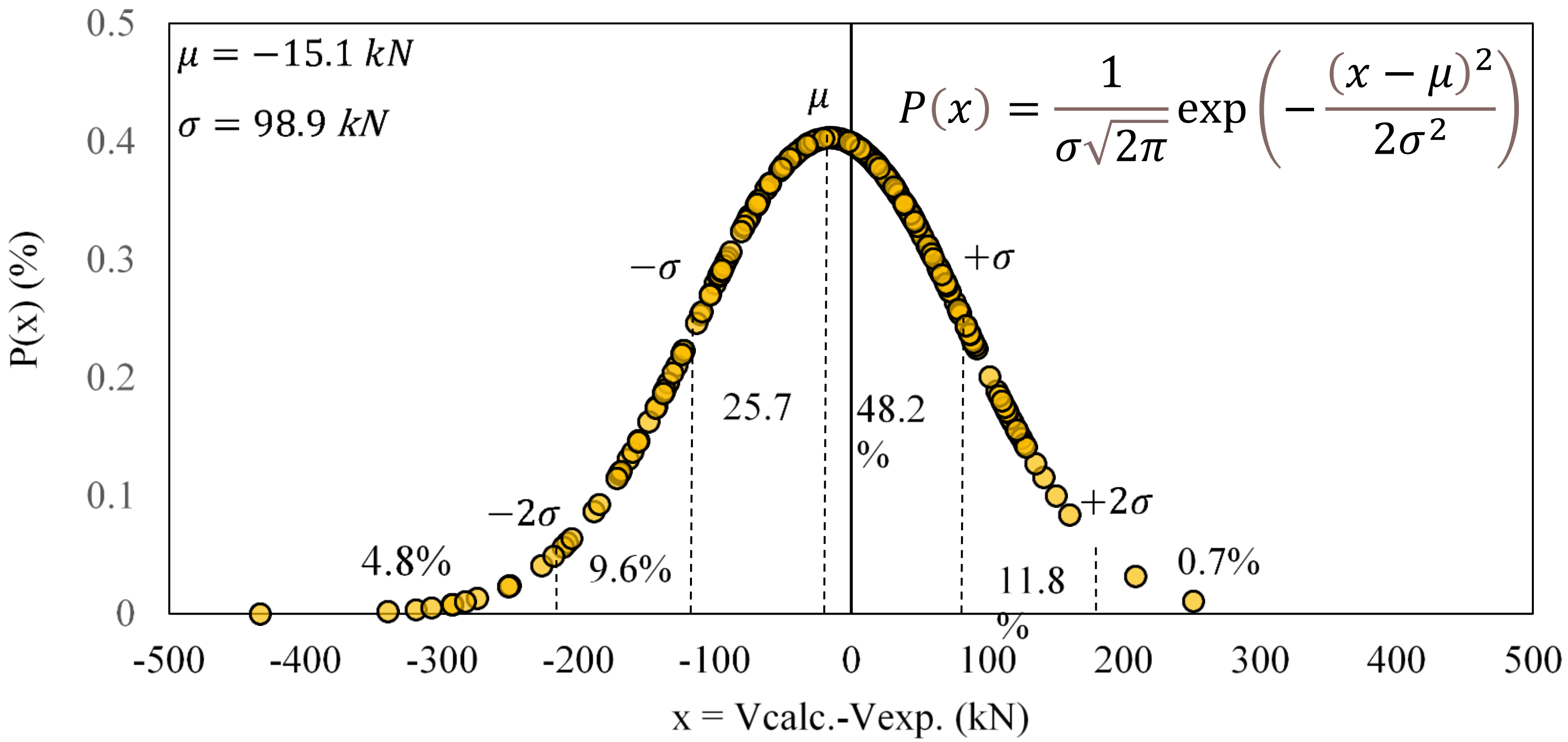
$$\theta = 26 + 11000\varepsilon_x$$

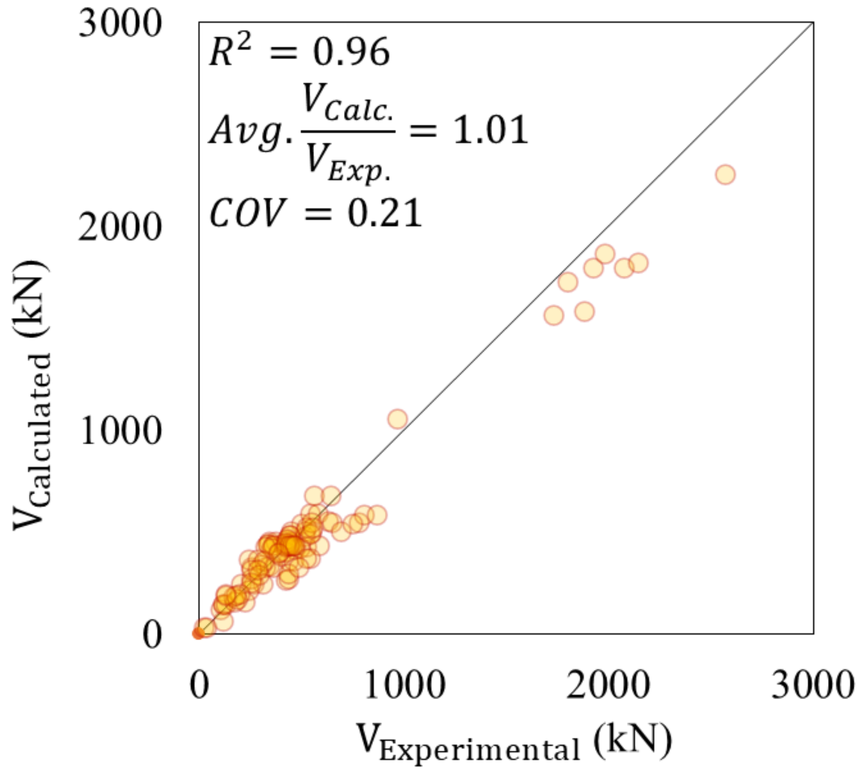
Model verification

Section	Avg. $\frac{V_{Calculated}}{V_{Experimental}}$	COV	R^2
Rectangular	1.04	0.29	0.87
I	1.09	0.28	0.96
T	1.40	0.16	0.83
Optimized	0.99	0.12	0.71
Hollow box	1.22	0.12	0.54



Model verification





Conclusions

- The MCFT formulation is a valid platform for developing a shear strength model suited for UHPC members. The defining characteristic of the approach presented in this paper lies the integration of the MCFT theoretical formulations with elements derived from experimental observations and analytical studies to account for the implications of cross-sectional shape effect and the fiber orientation..
- Utilizing a previously developed ML model for characterizing the uniaxial direct tension behavior of UHPC was crucial for verifying the accuracy of the shear strength model proposed in this paper. This necessity arose because many experimental studies did not characterize the direct tension behavior of the UHPC mix used in the beams tested.
- The analysis of failure modes at different effective depths shows that the presence of fiber reinforcement in shear-critical UHPC beams minimizes the size effect.
- The model demonstrated reliable results in calculating the shear strength of shear-critical UHPC members with various cross-sectional shapes in addition to transversely reinforced shear-critical UHPC members.

Thank you!