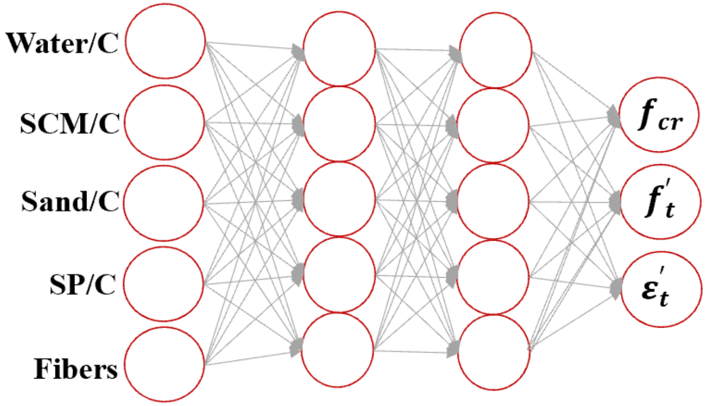
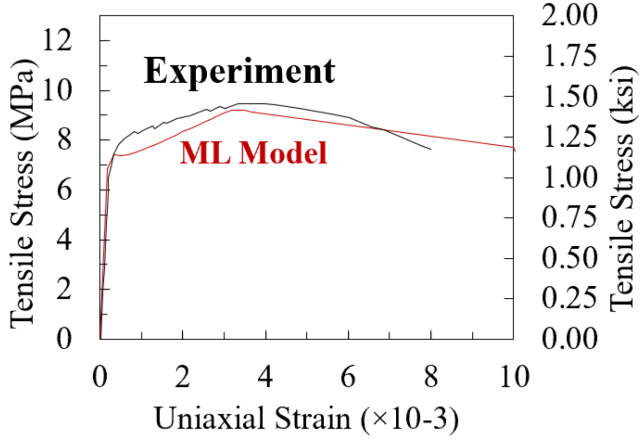
Synergizing machine learning and nonlinear finite element analysis to simulate the behavior of UHPC members

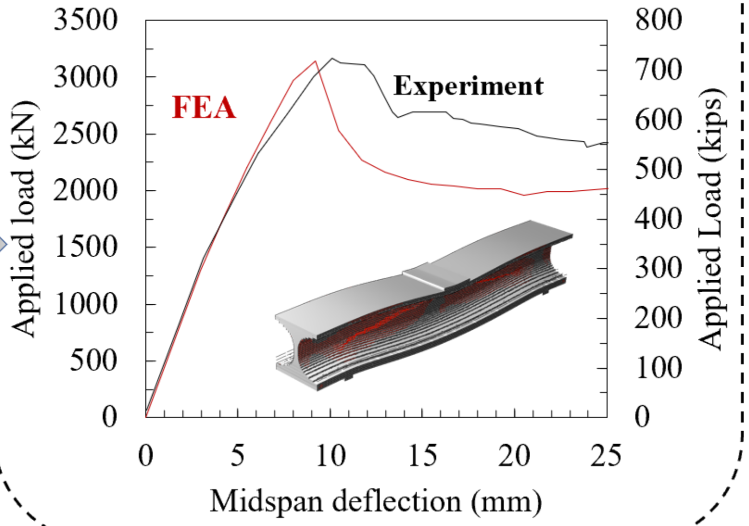
ML model used for the prediction of the UHPC tensile properties



ML-based UHPC tensile model versus experimental results comparison



FEA versus experimental results



Amjad Diab
Anca Ferche

Outline

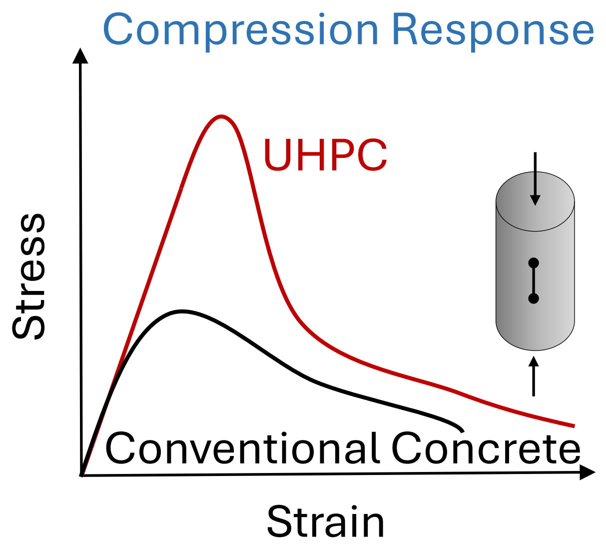
- UHPC Overview
- Modeling Approach
- Modeling Validation
- Conclusions

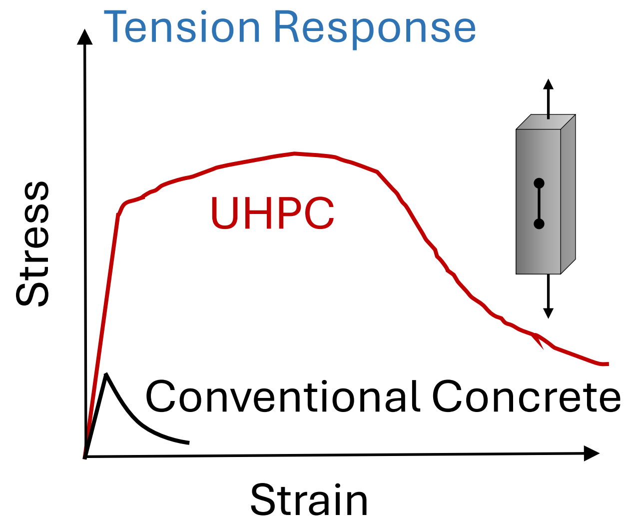
Introduction

Ultra-High Performance Concrete (UHPC) is a cementitious composite with a discontinuous pore structure, incorporating steel fiber reinforcement.

UHPC characteristics:

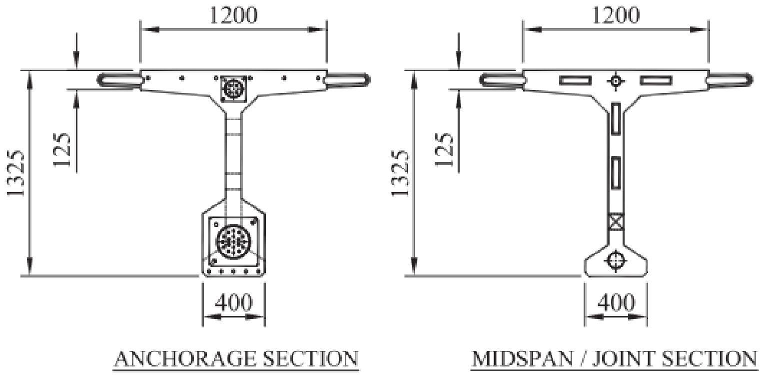
- high compressive strengths (~120-250 MPa),
- high tensile strengths (~6-16 MPa),
- superior post-cracking ductility compared to other cementitious composites,
- excellent crack control,
- self-consolidating workability,
- superior durability.



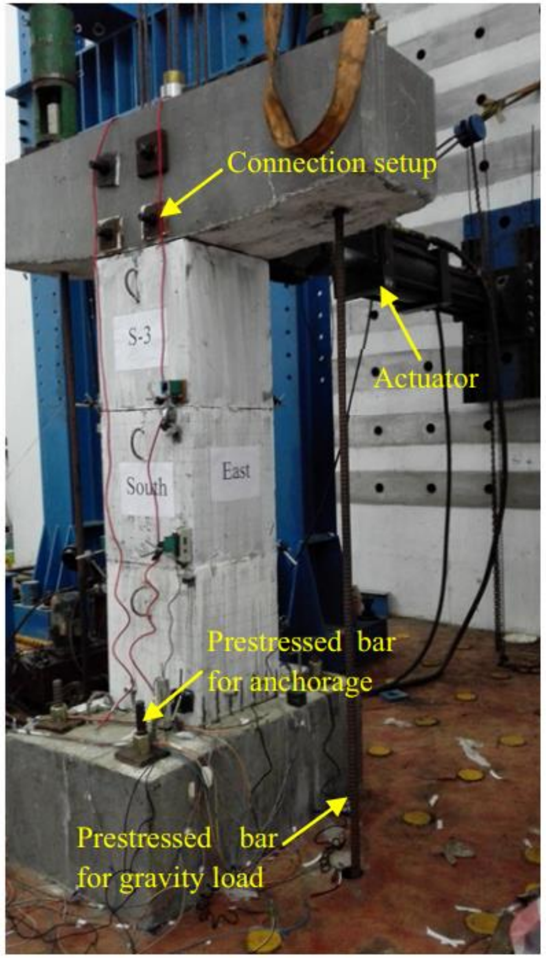


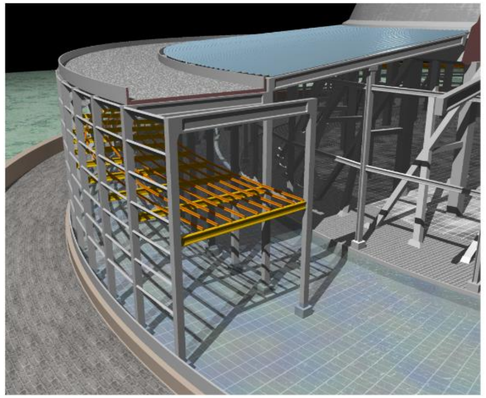
UHPC Applications

Pi section bridge girder



Sungai Nerok segmental bridge girder





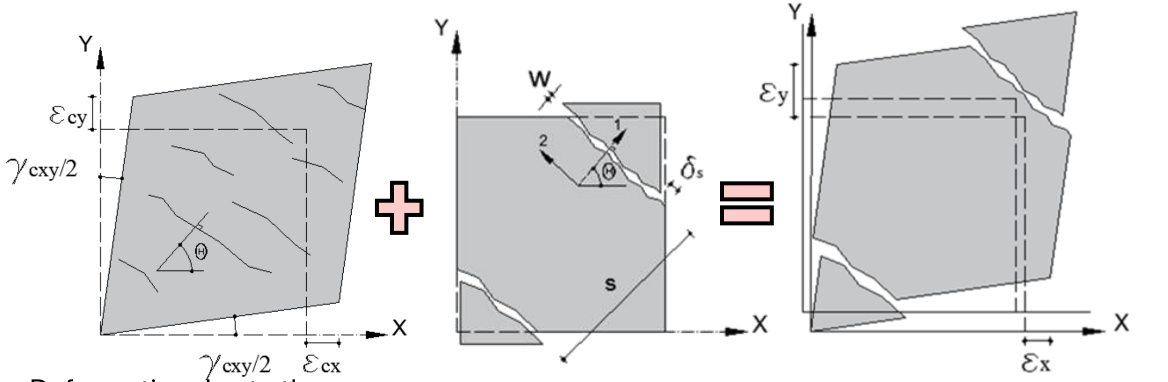
Cattenom power plant

Offshore wind turbine foundations

Segmental bridge columns

Modeling Approach

Compatibility requirements

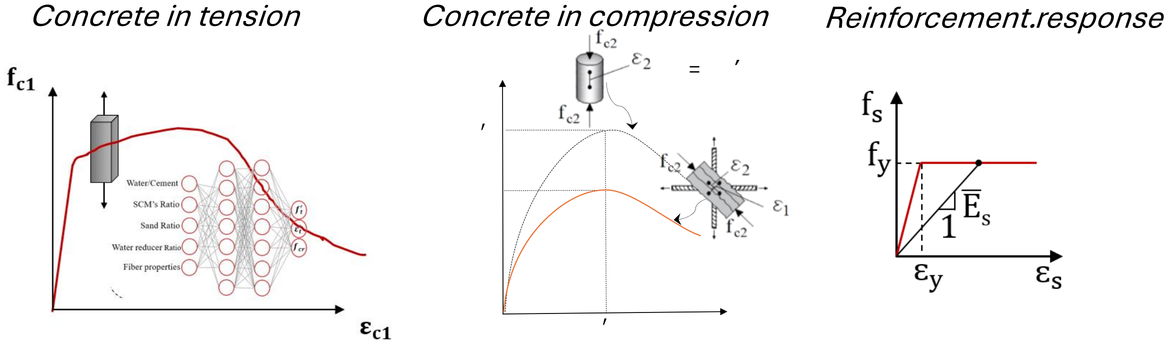


Deformation due to the average constitutive response

Crack shear slip deformation

Total deformation

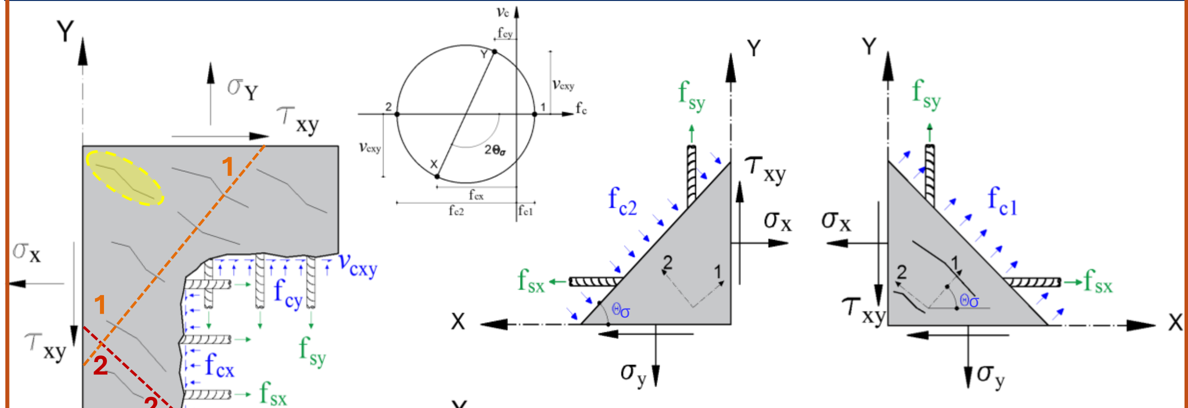
Constitutive relationships



Tension stiffening

Compression softening

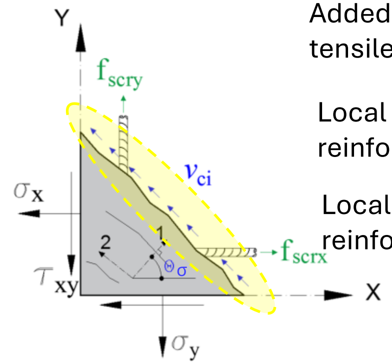
Equilibrium in terms of average stresses



Section 1-1

Section 2-2

Equilibrium in terms of local stresses at a crack



Added local strain in the principal tensile direction: $\varepsilon_{1cr} = \varepsilon_1 + \Delta\varepsilon_{1cr}$

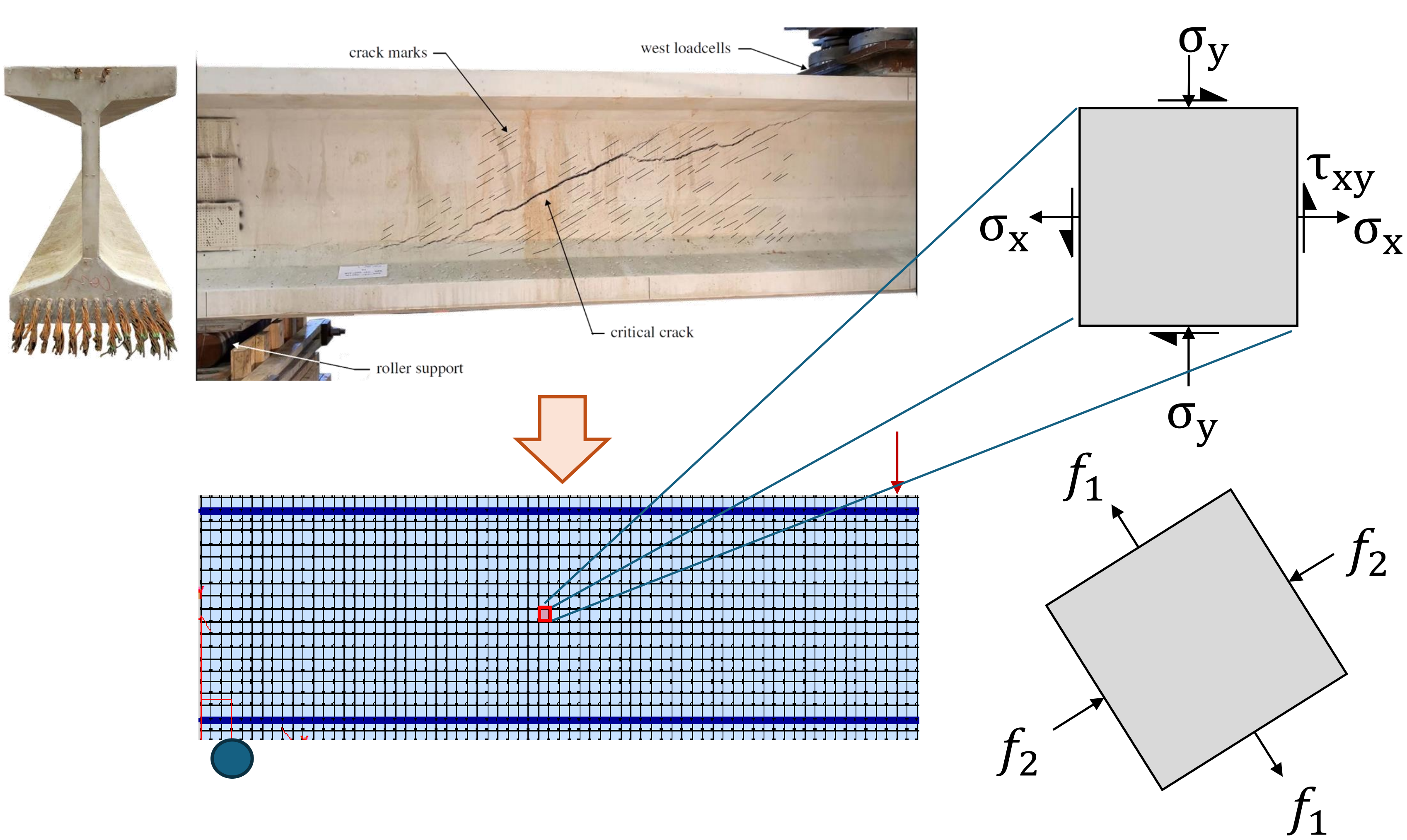
Local strain in the reinforcement: $\varepsilon_{scr.i} = \varepsilon_{s.i} + \Delta\varepsilon_{1cr} \cdot \cos^2\theta_{n.i}$

Local stress in the reinforcement: $f_{scr.i} = E_s \cdot \varepsilon_{scr.i} < f_{y.i}$

Concrete stress in the principal tensile direction:

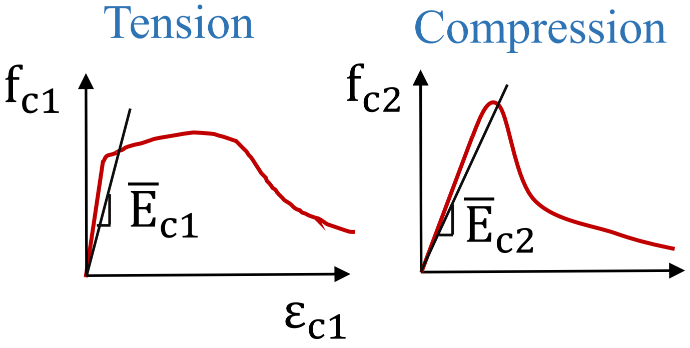
$$f_{c1} = \sum_{i=1}^{n} \rho_i (f_{scr.i} - f_{s.i}) \cdot \cos^2\theta_{n.i}$$

Modeling Approach



$$[D_c]' = \begin{bmatrix} \overline{E}_{c1} & 0 & 0 \\ 0 & \overline{E}_{c2} & 0 \\ 0 & 0 & \overline{G}_c \end{bmatrix}$$

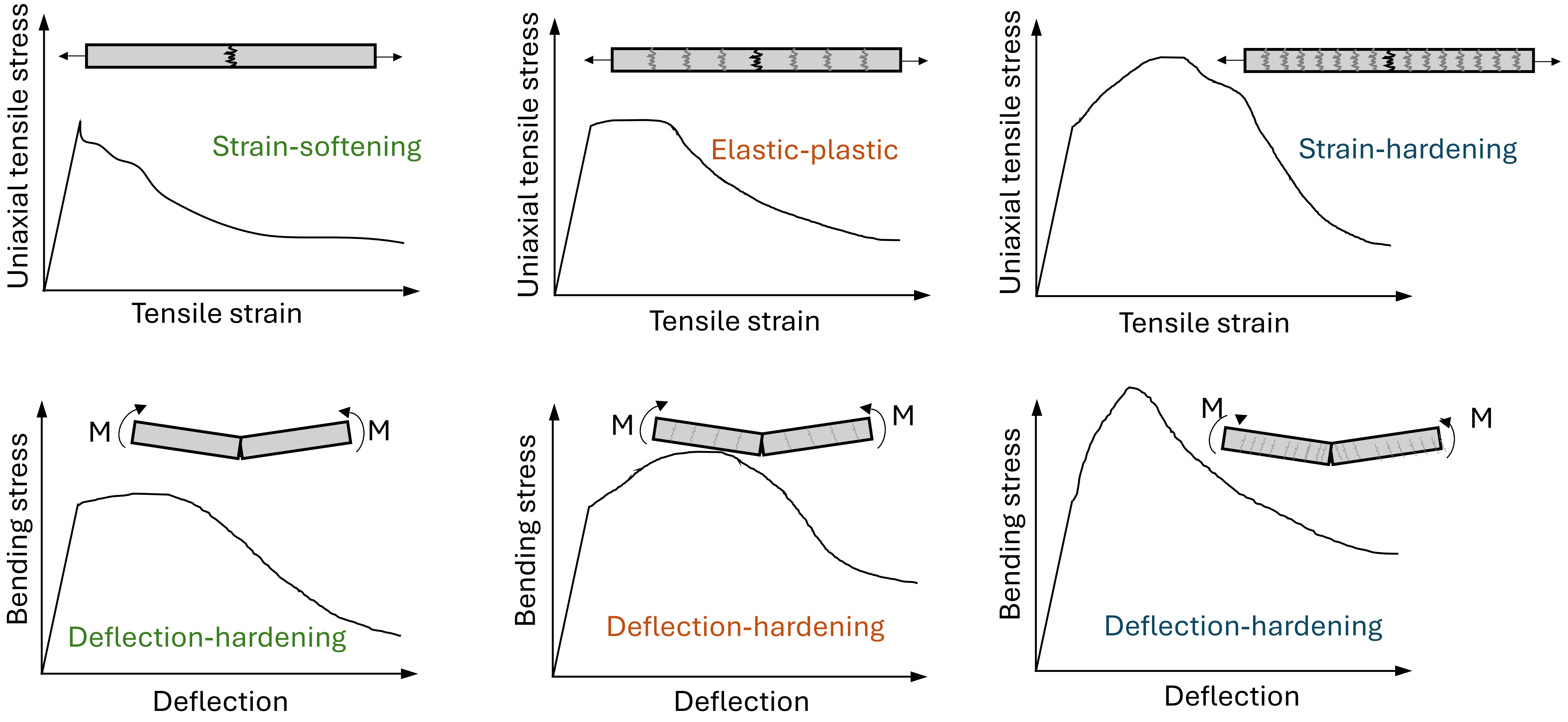
$$\overline{E}_{c1} = \frac{f_{c1}}{\varepsilon_{c1}} \qquad \overline{E}_{c2} = \frac{f_{c2}}{\varepsilon_{c2}}$$



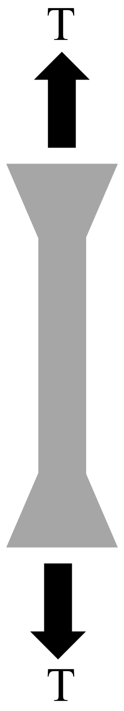
$$\overline{G}_c = \frac{\overline{E}_{c1} \cdot \overline{E}_{c2}}{\overline{E}_{c1} + \overline{E}_{c2}}$$

El-Helou, R. G., & Graybeal, B. A. (2022). Shear behavior of ultrahigh-performance concrete pretensioned bridge girders. *Journal of Structural Engineering*, *148*(4), 04022017.

UHPC Tension Response



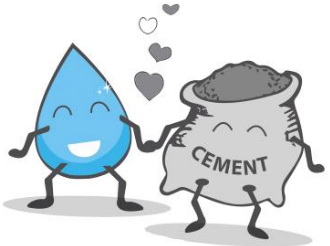
UHPC Direct Tension Database

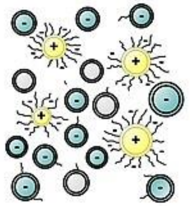


SCMs

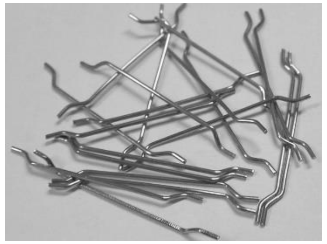
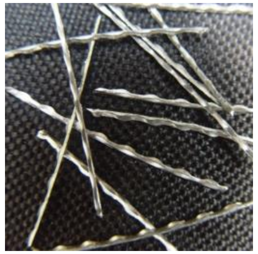


W/C & SP

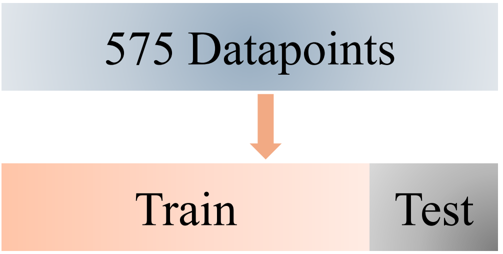




Steel fibers

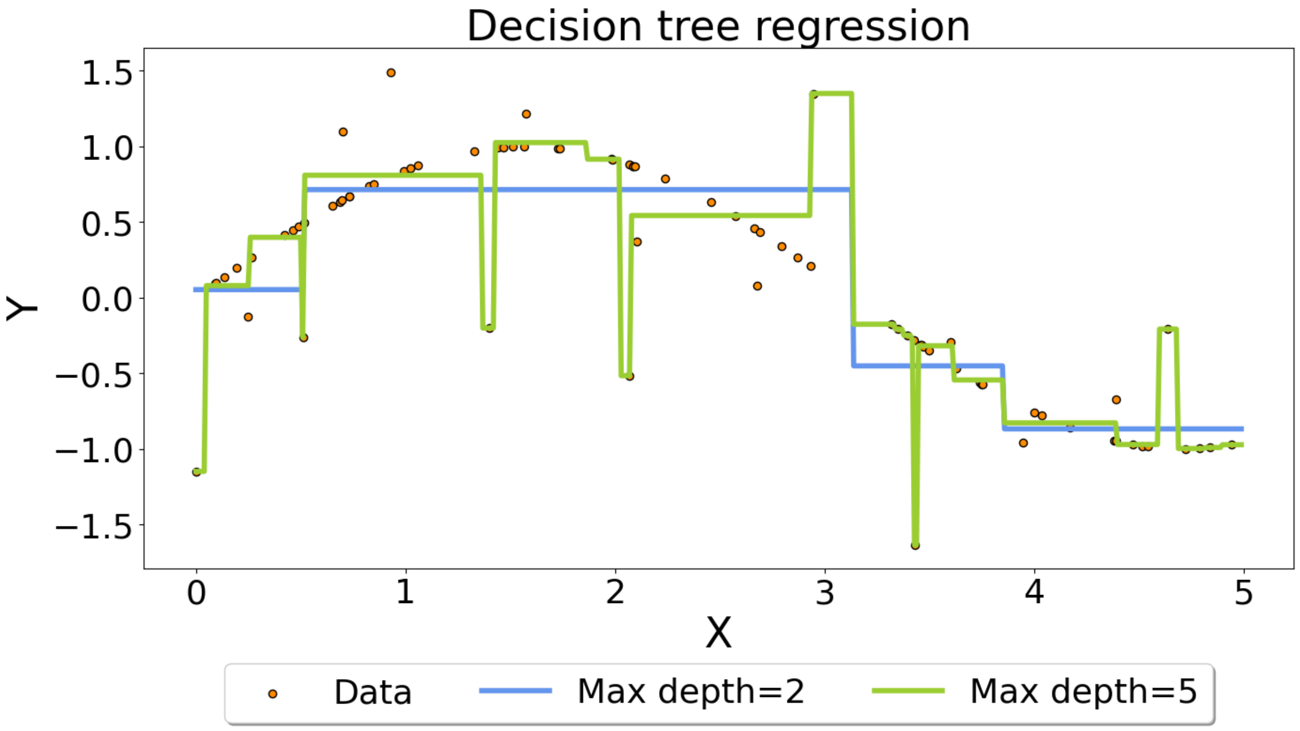




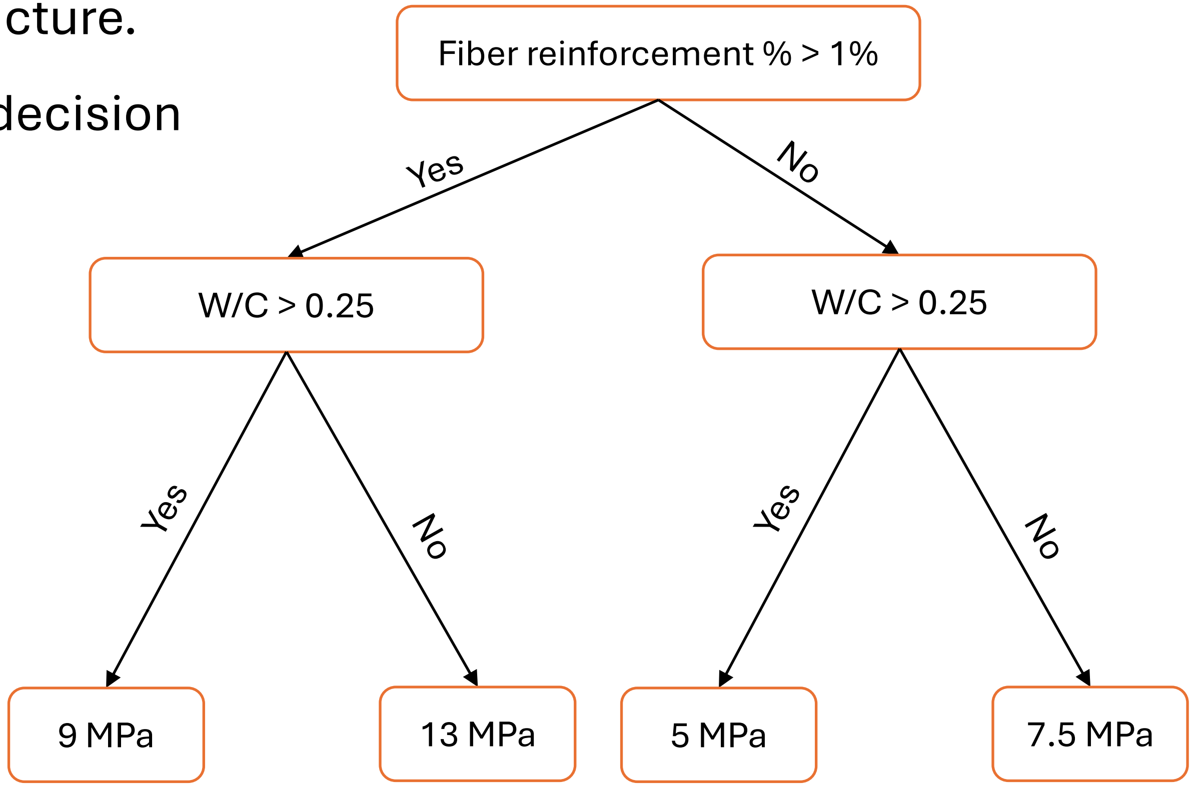
PE fibers



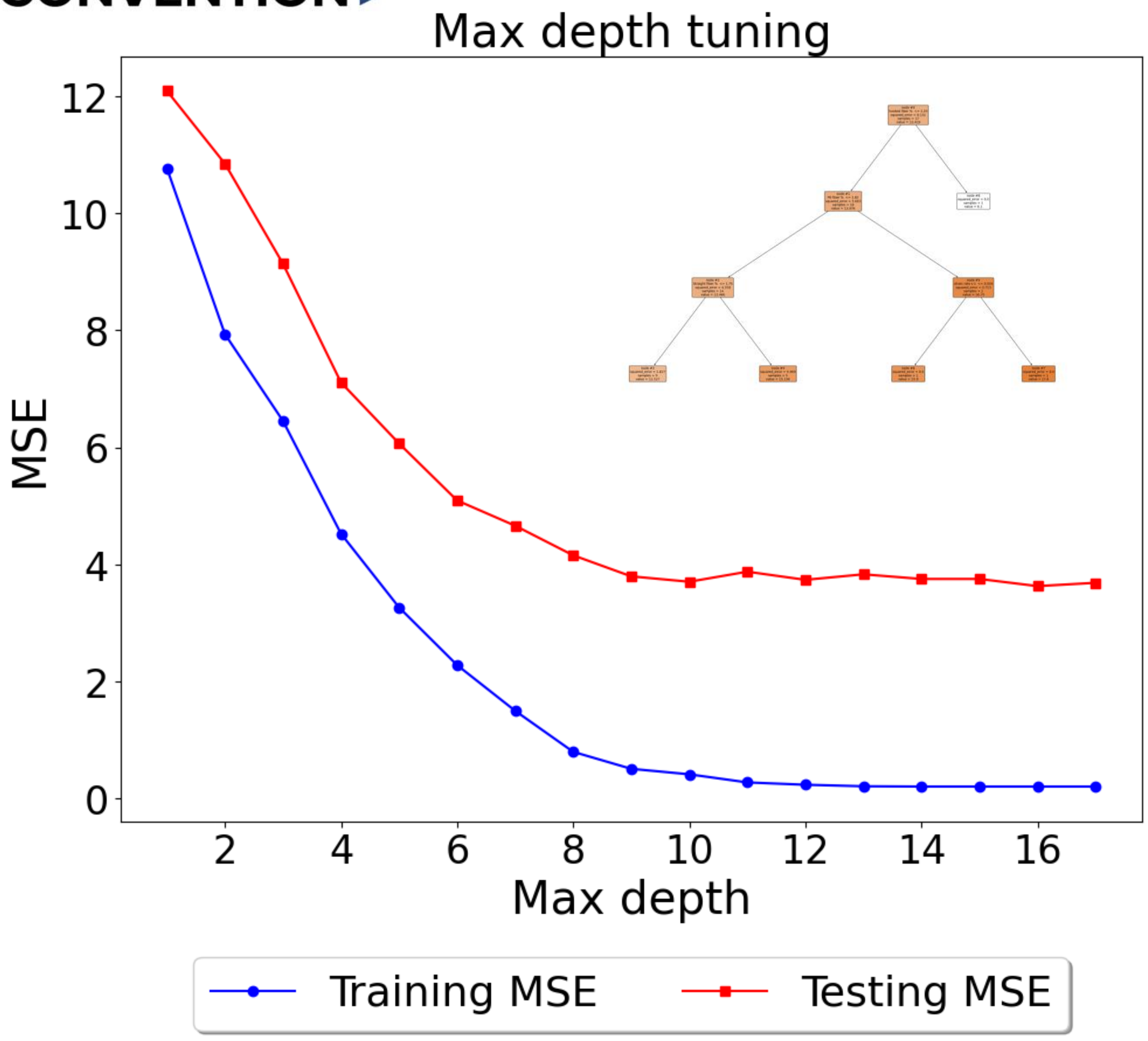
Regression Decision Trees

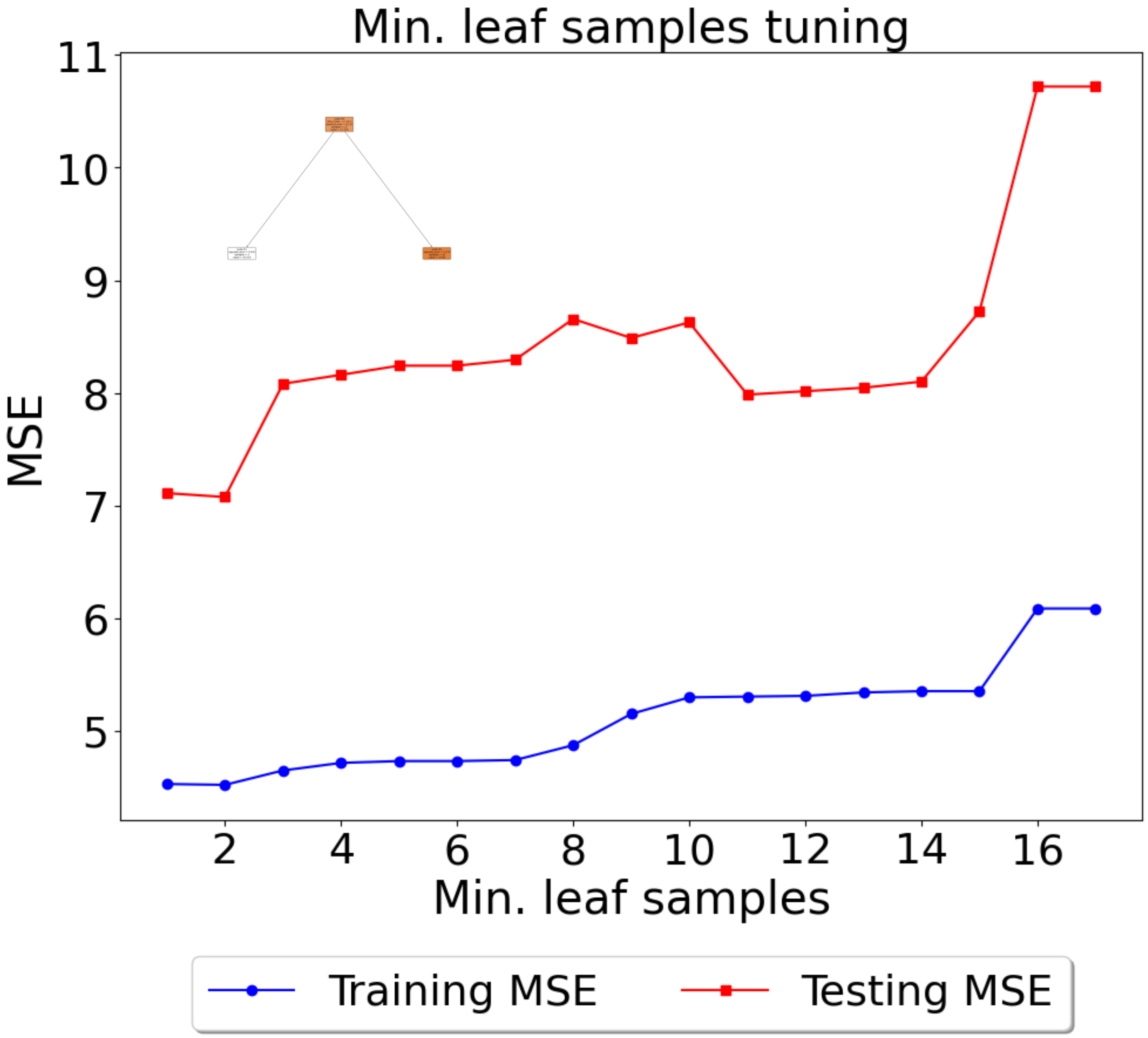
- RDT builds regression models in the form of a tree structure.
- RDT breaks down a dataset into smaller subsets with decision nodes and leaf nodes.



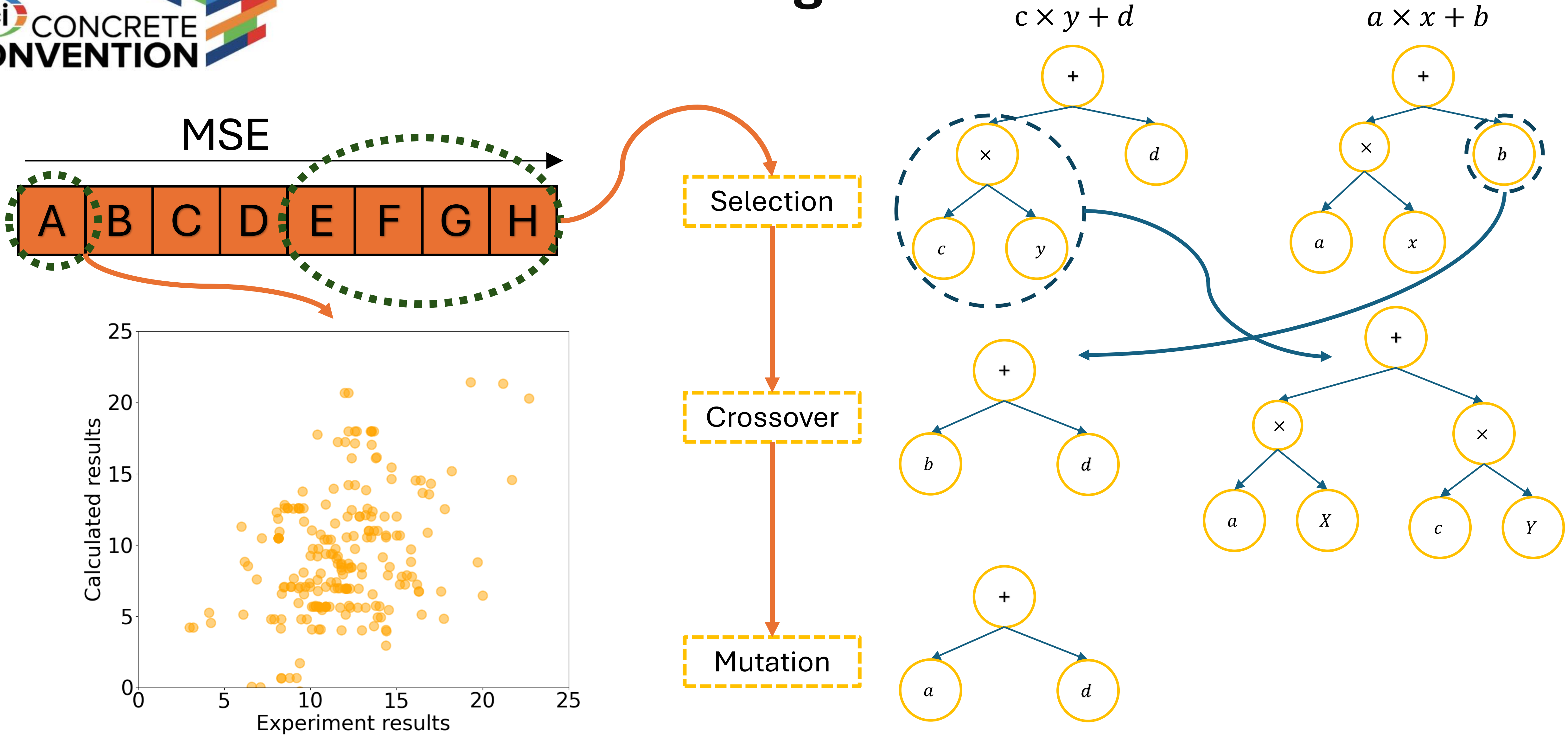


RDT Parameter Tuning

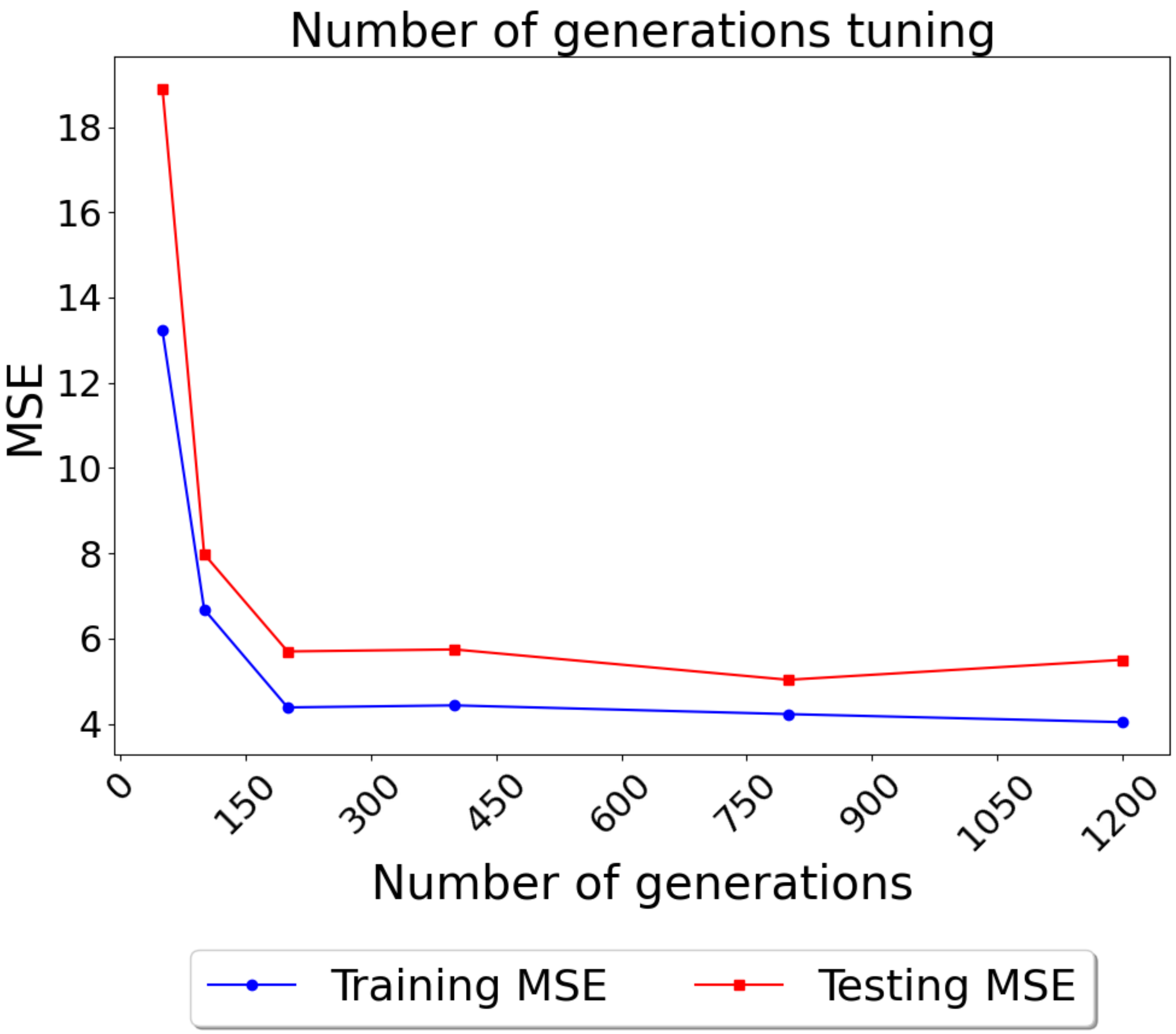


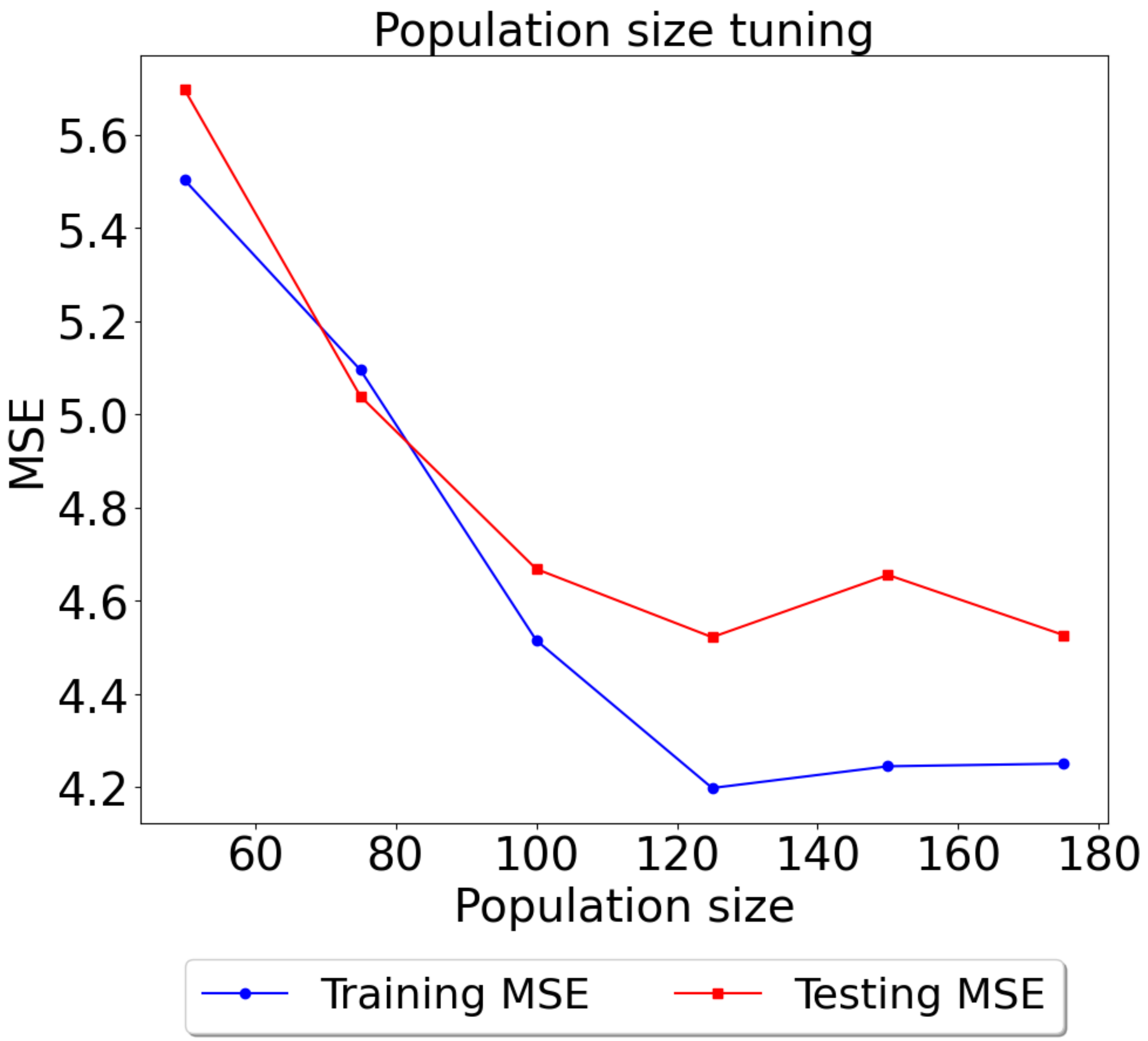


Genetic Algorithm

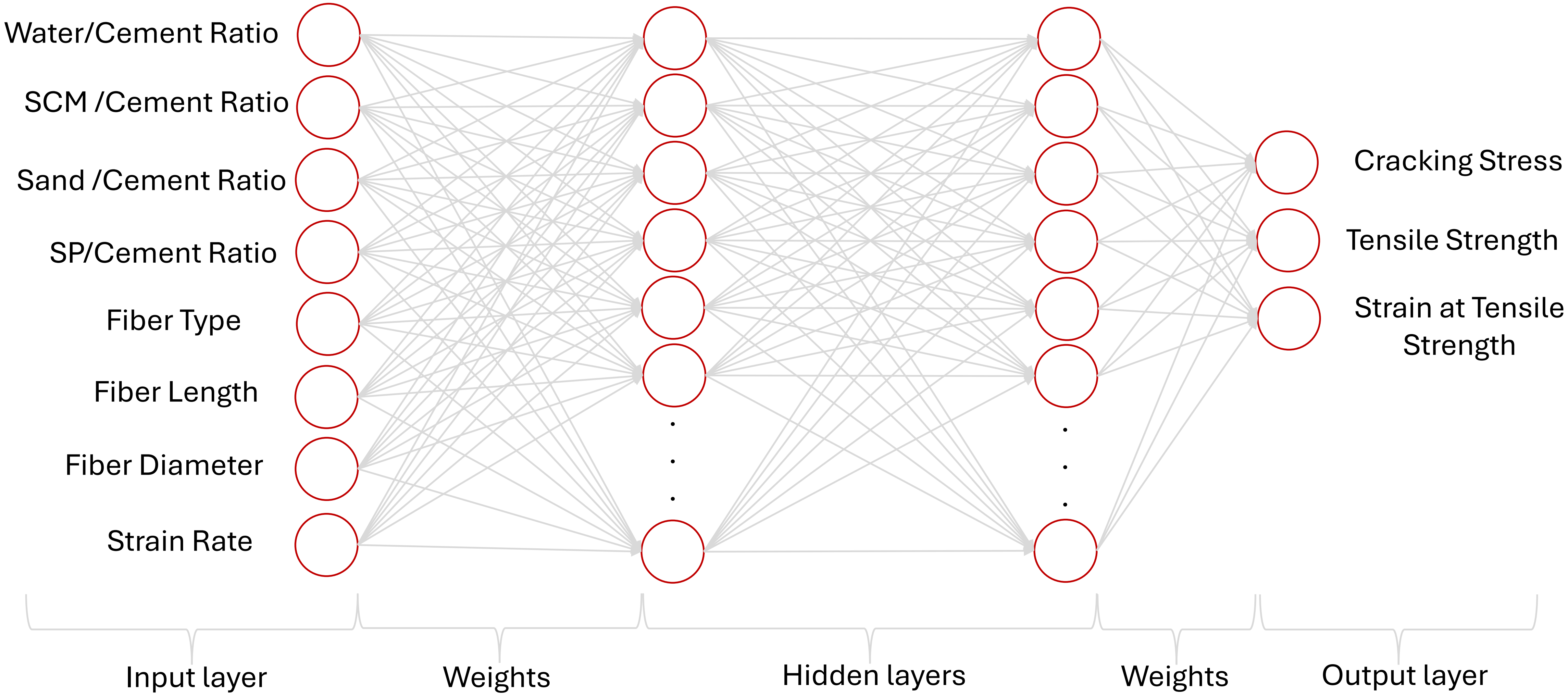


GA Parameter Tuning





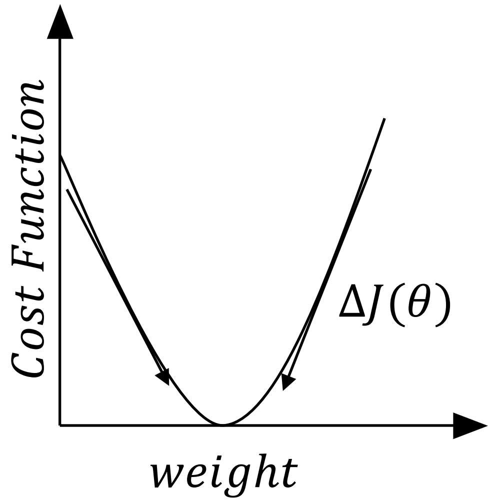
Artificial Neural Network



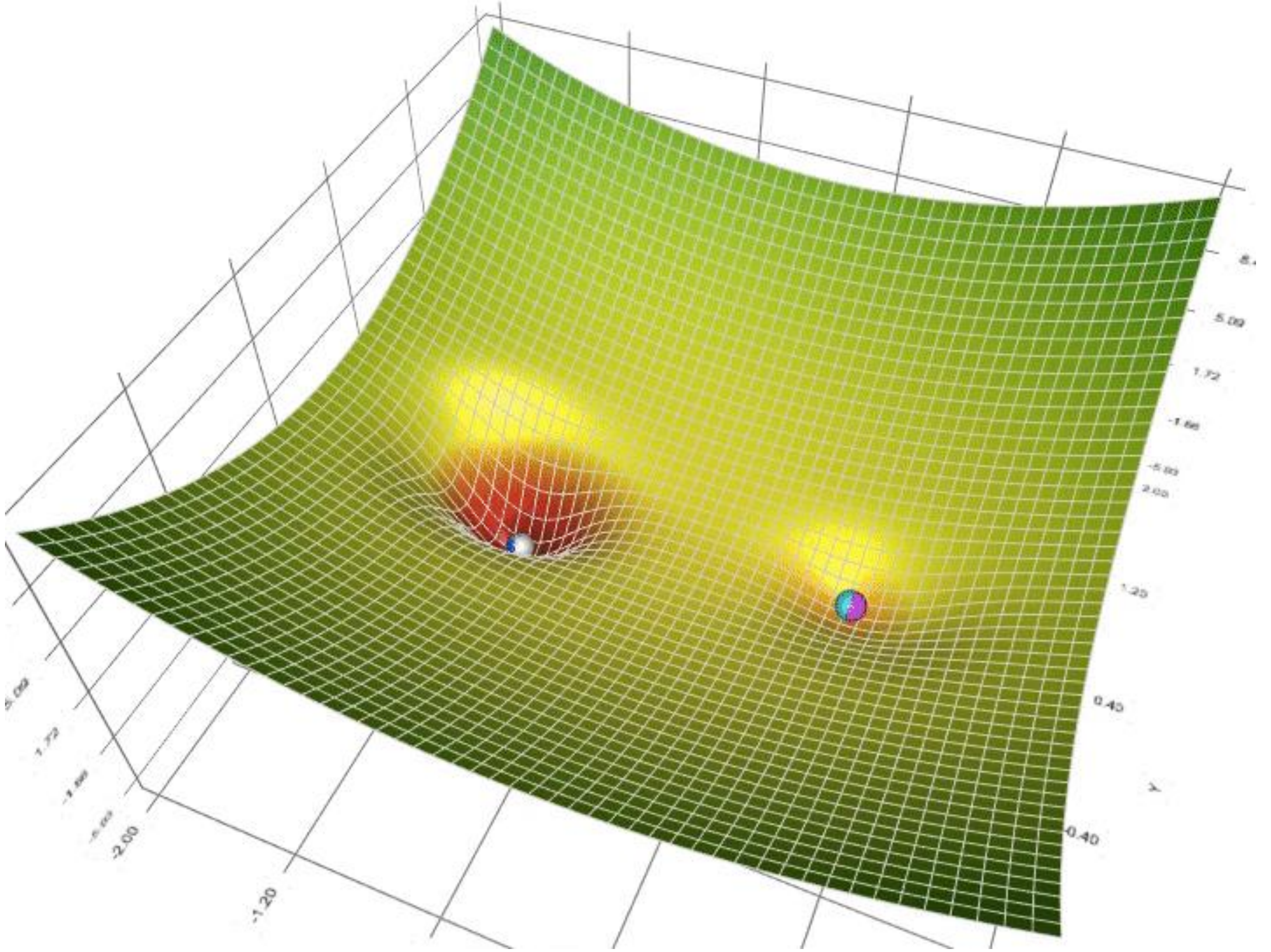
Gradient Descent

$$Cost\ Function = \frac{1}{2n}\sum_{1}^{n}(y - y^i)^2$$

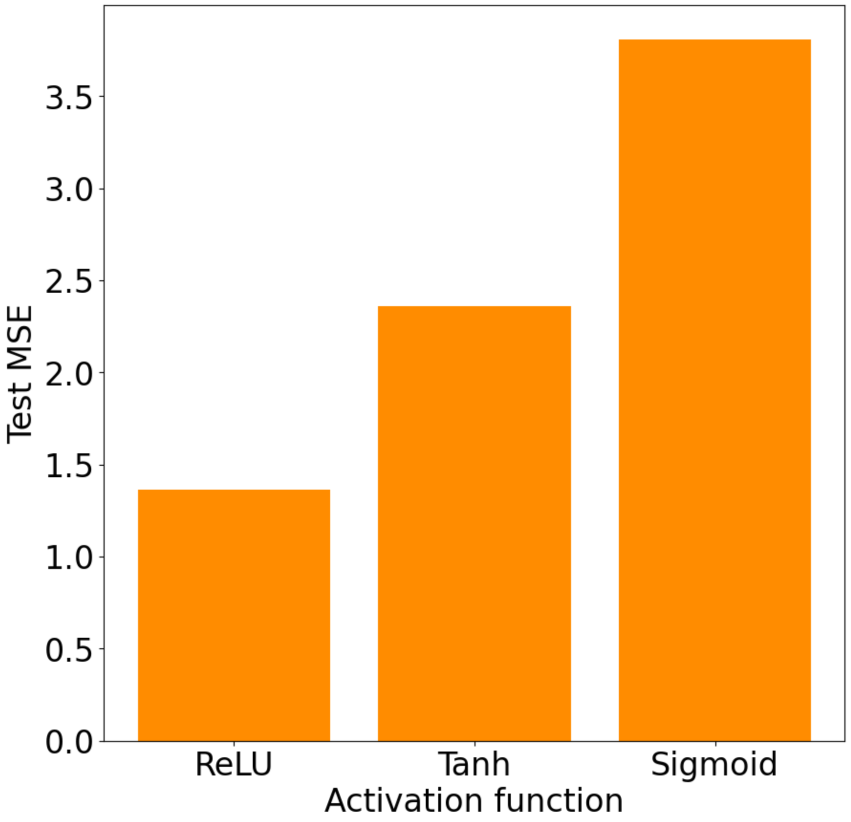
$$Goal: Minimize\ cost\ function$$

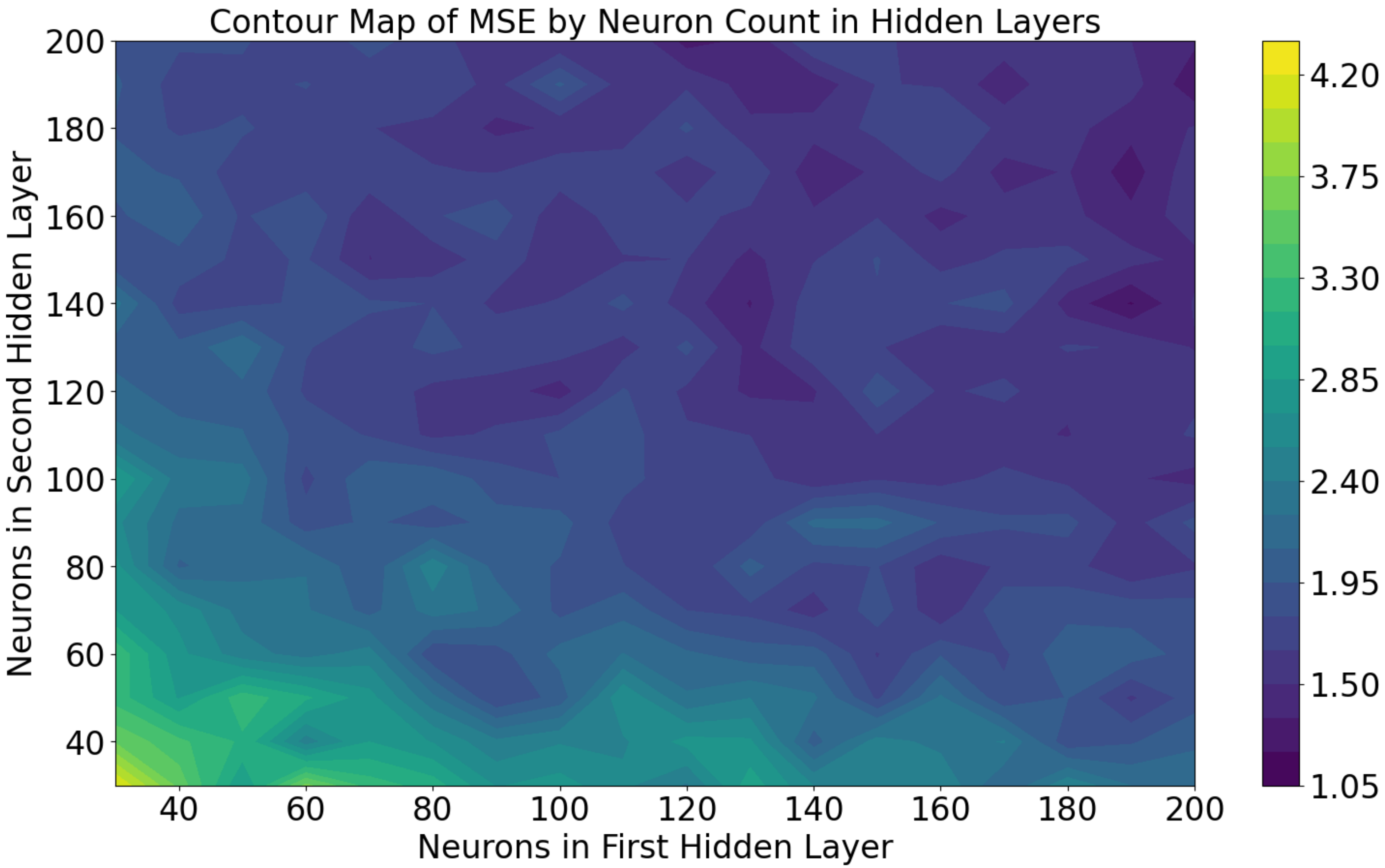


$$\theta_n = \theta_n - J(\theta_n)$$

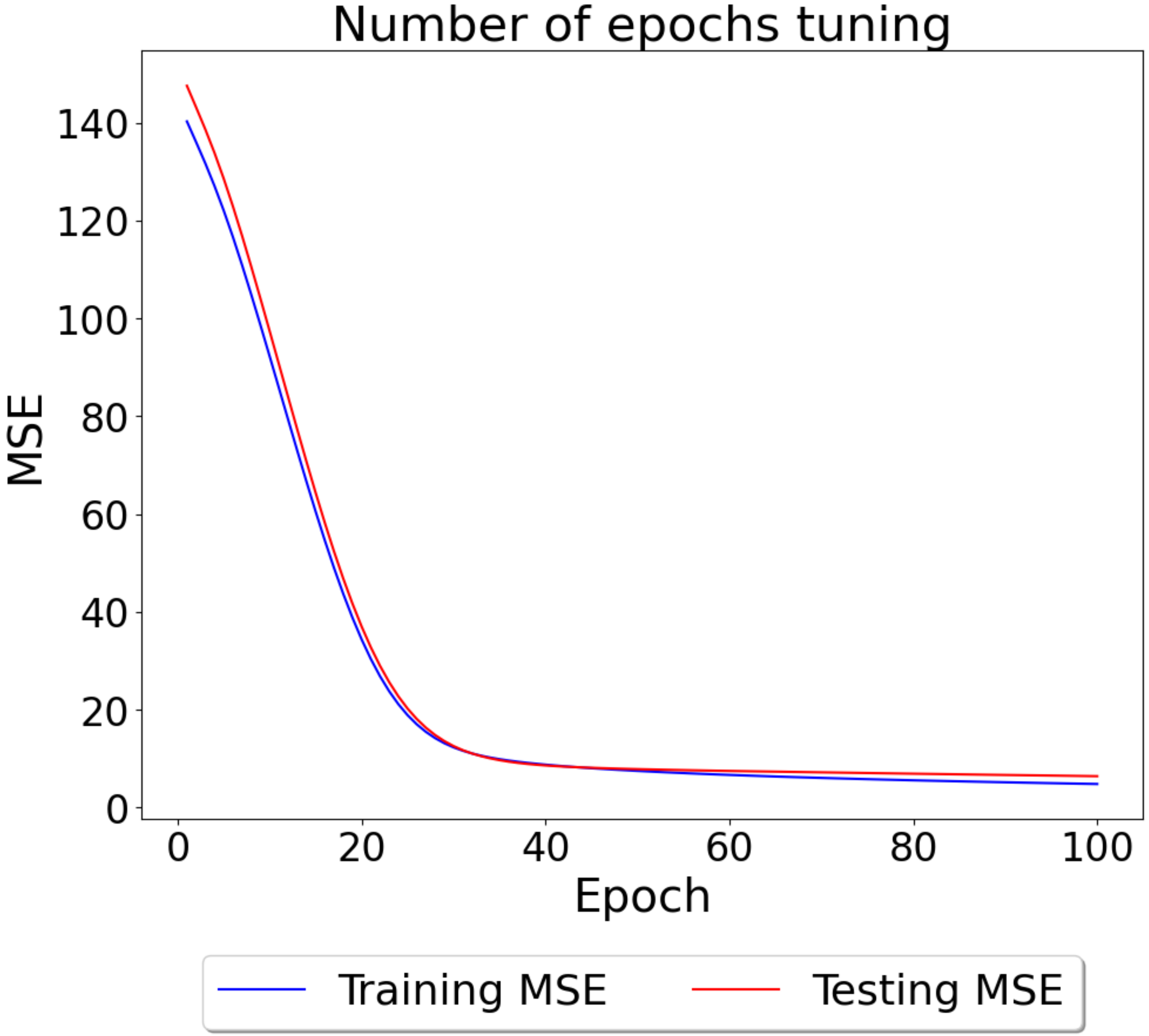


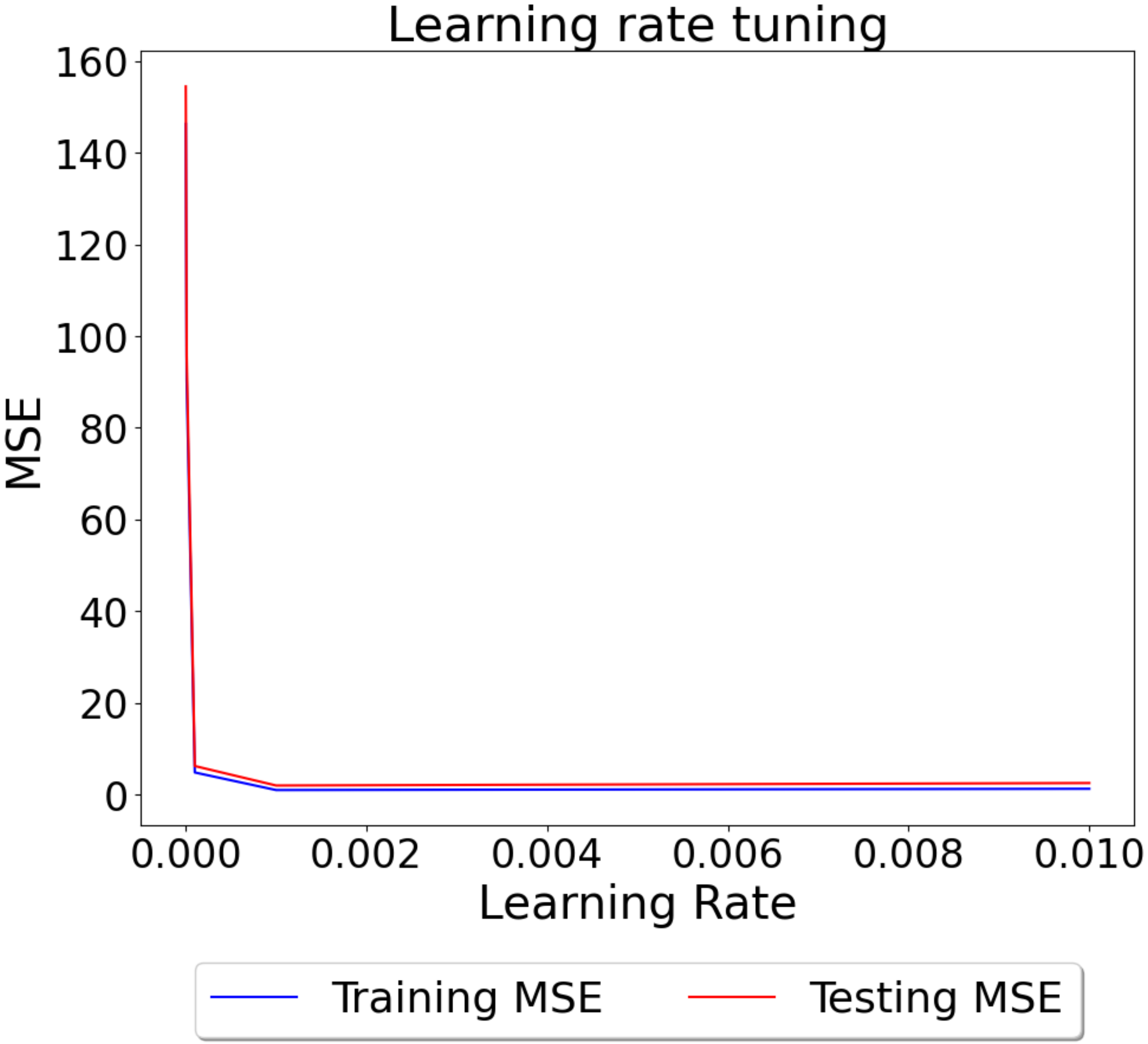
ANN Parameter Tuning



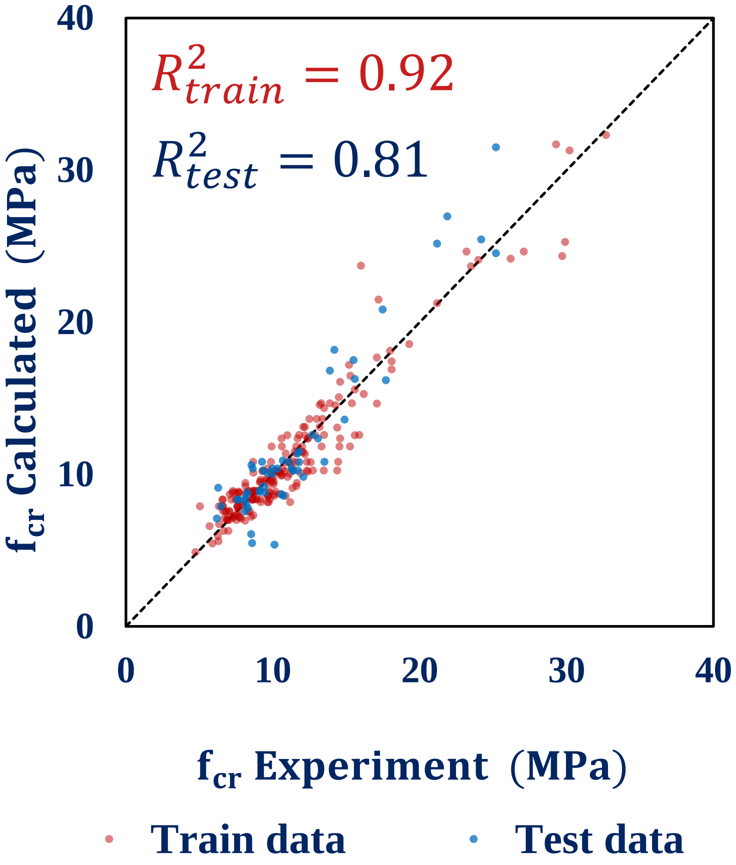


ANN Parameter Tuning

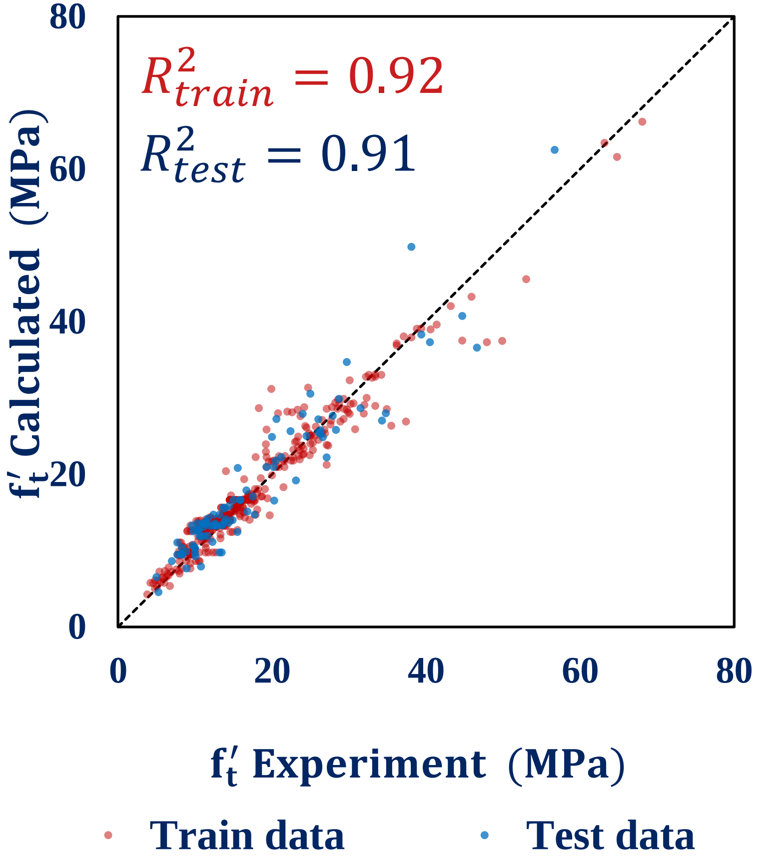




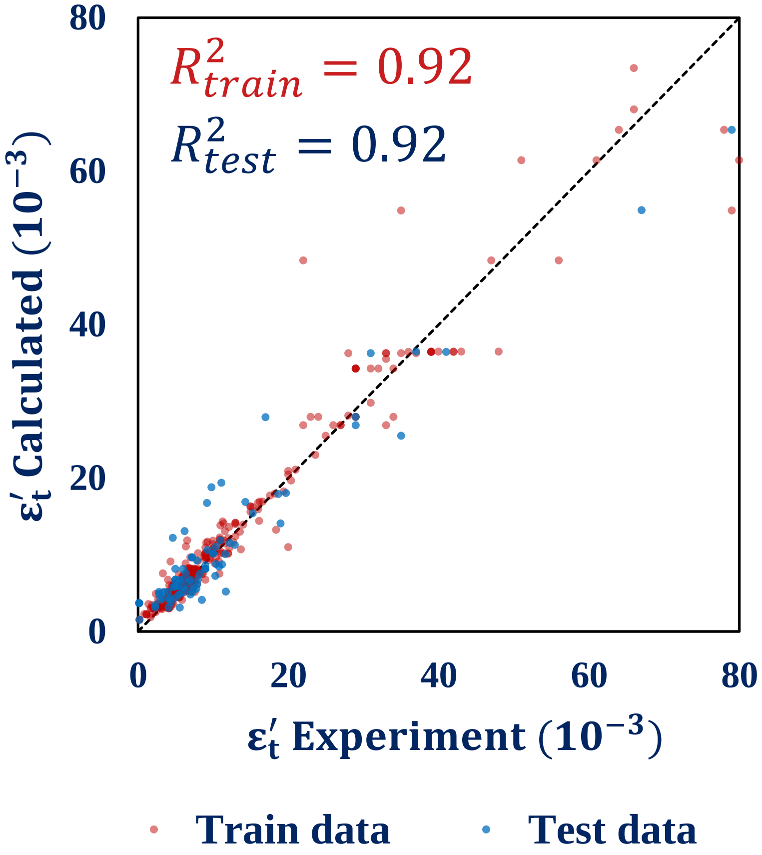
ANN Results



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



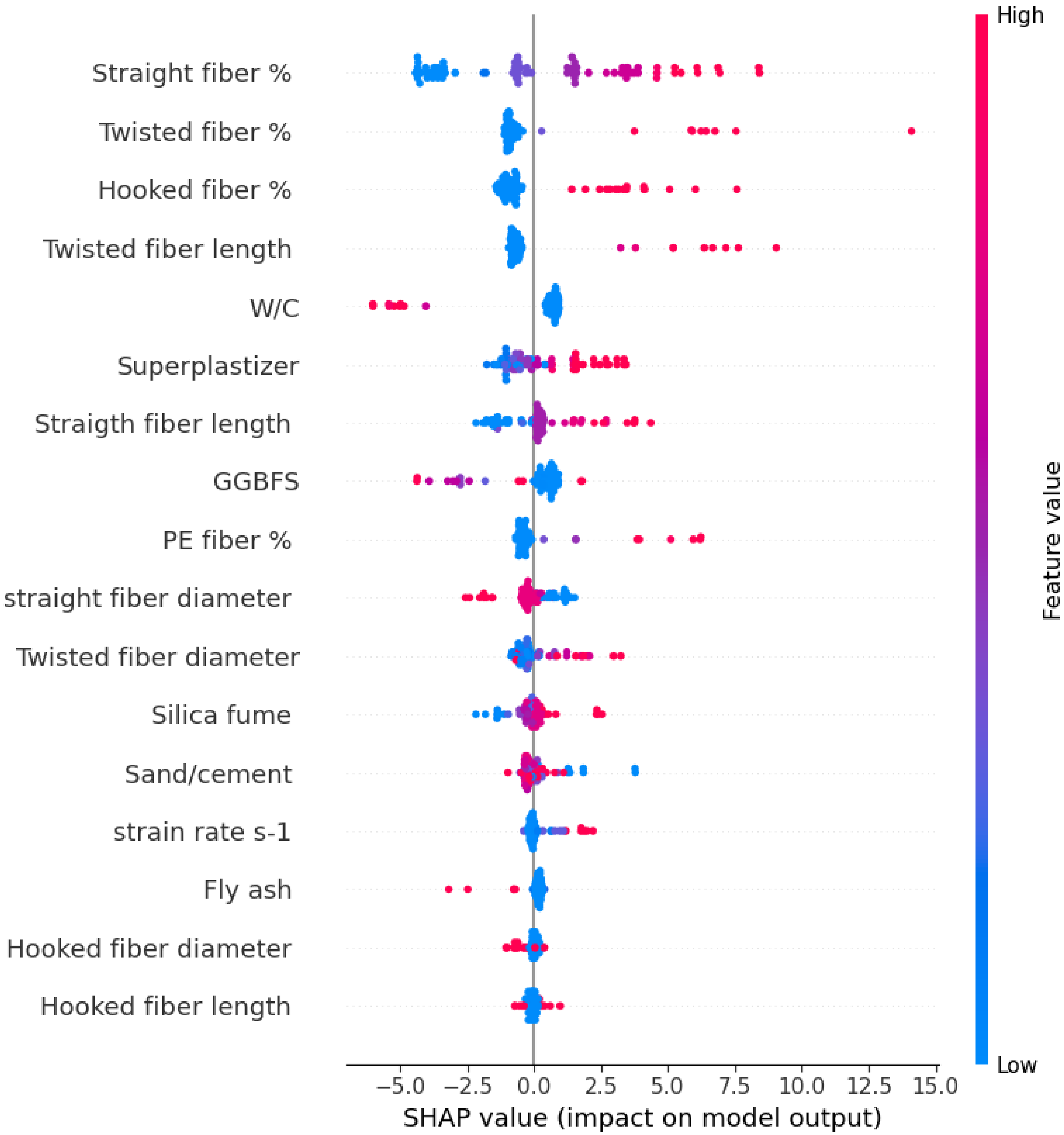
$R^2_{train} = 0.92$
$R^2_{test} = 0.91$
f'_t Calculated (MPa)
f'_t Experiment (MPa)
0
20
40
60
80
Train data
Test data



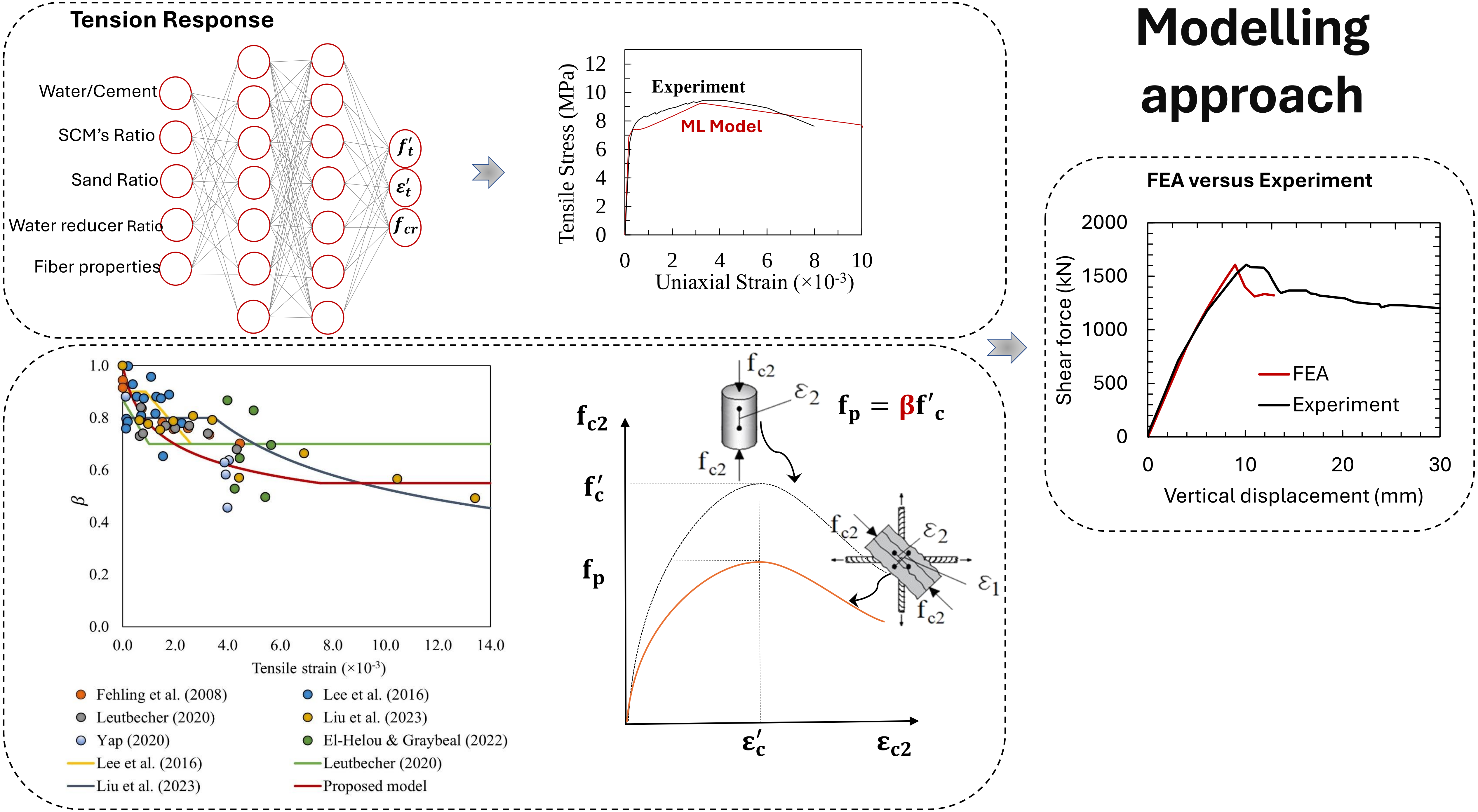
$R^2_{train} = 0.92$
$R^2_{test} = 0.92$
ε'_t Calculated (10^{-3})
ε'_t Experiment (10^{-3})
0
20
40
60
80
Train data
Test data

SHAP

- SHapley Additive exPlanations (SHAP) helps explain the output of any machine learning model.
- SHAP makes complex models more understandable by quantifying the influence of each input feature on the output.
- By understanding how a model makes its decisions, developers can identify and mitigate biases within the model.
- SHAP is generally useful to interpret the results of ANN algorithms which are generally acting as “black boxes”



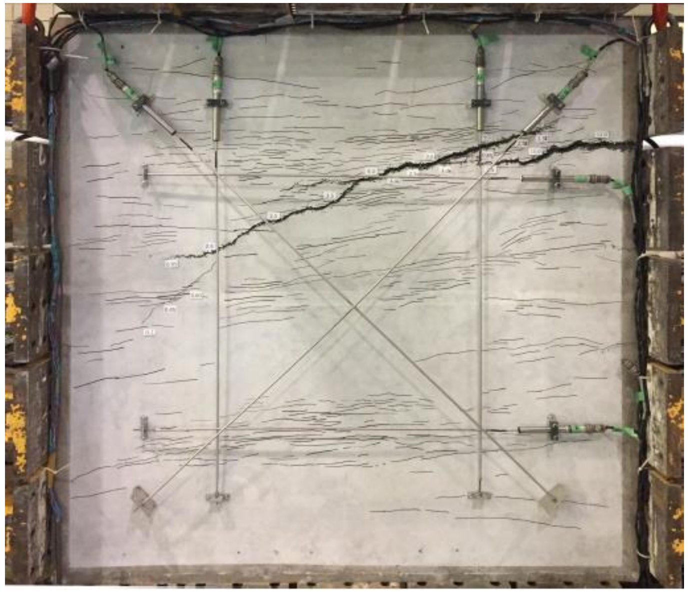
Modelling approach



Model validation – UHPC panels

UHPC panel specimens tested at the University of Toronto - subjected to pure shear

Specimen	f'_c (MPa)	Thickness (mm)	ρ_x (%)	ρ_y (%)
YS1	171.5	215	0.86	0.86
YS2	167.5	206	0.90	0.00
YS3	164.2	212	0.00	0.00
YS4	157.0	217	2.56	0.00
YS5	160.3	224	0.43	0.00



Yap, B. (2020). *Behaviour of ultra high performance fibre reinforced concrete subjected to pure shear*. University of Toronto (Canada).

Yap 2020 Panel Specimens

Specimen	f'_c (MPa)	Thickness (mm)	ρ_x (%)	ρ_y (%)
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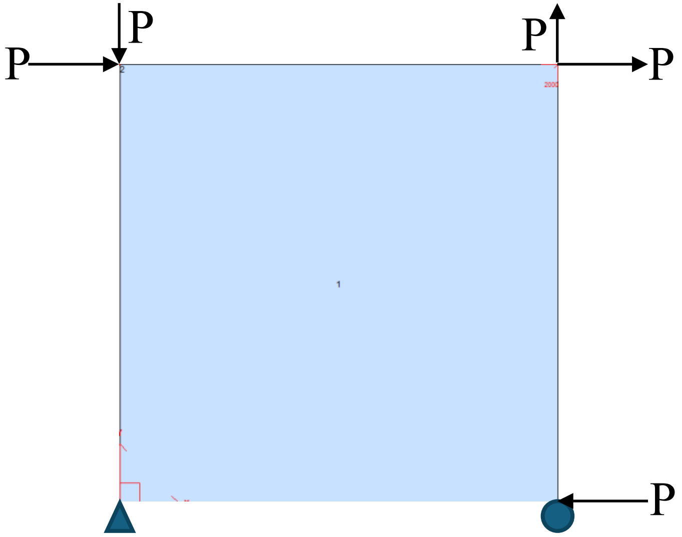
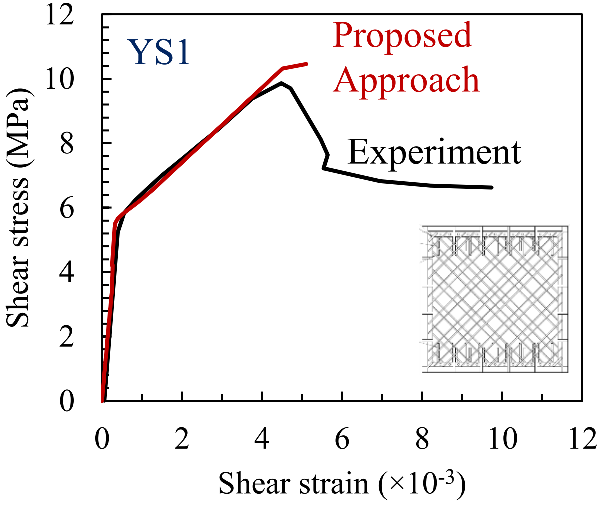
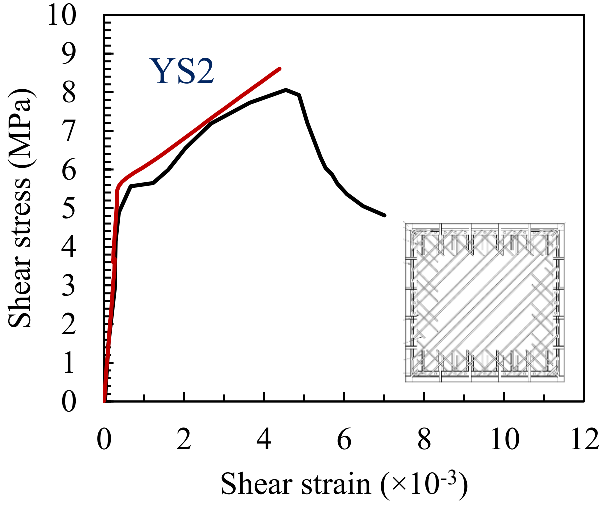
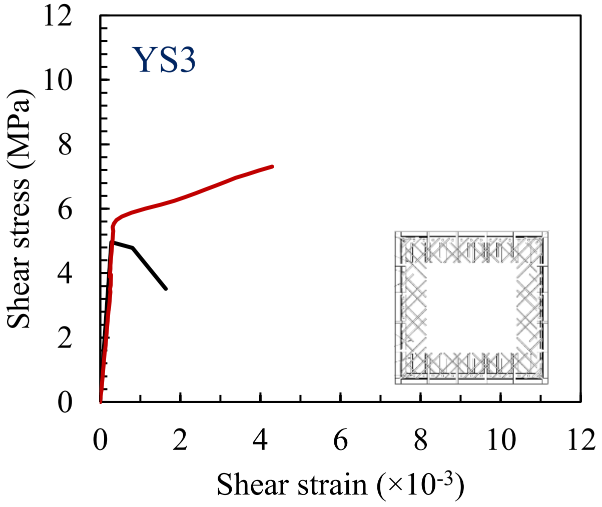
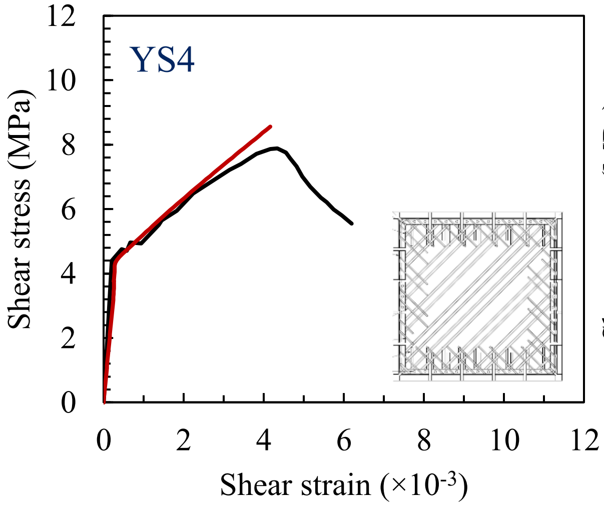
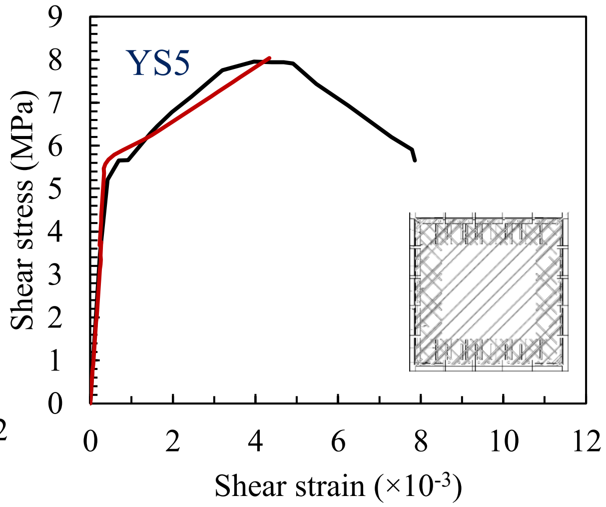




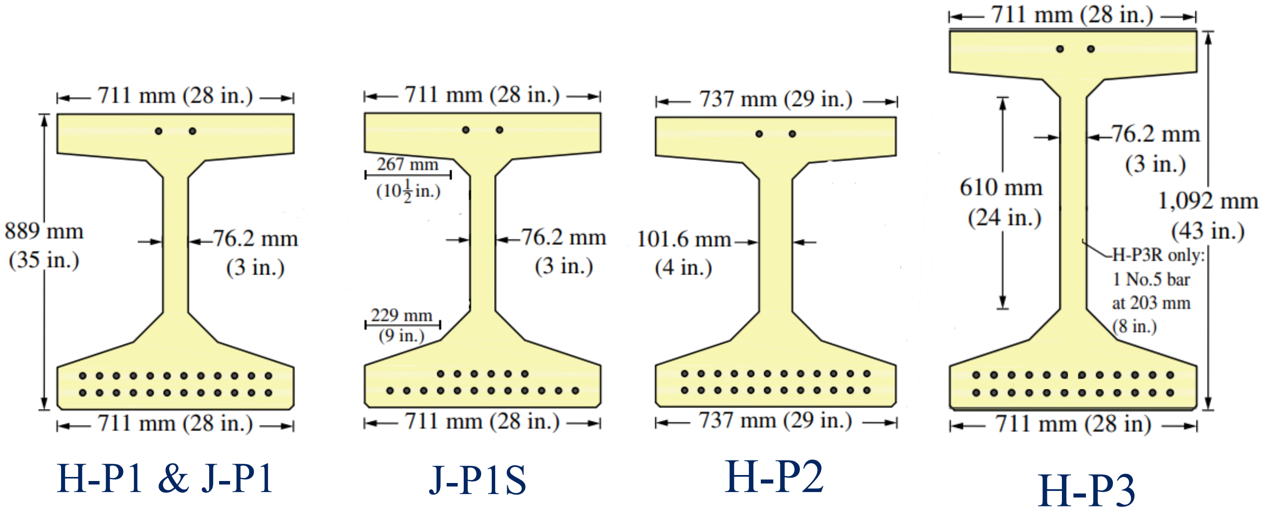




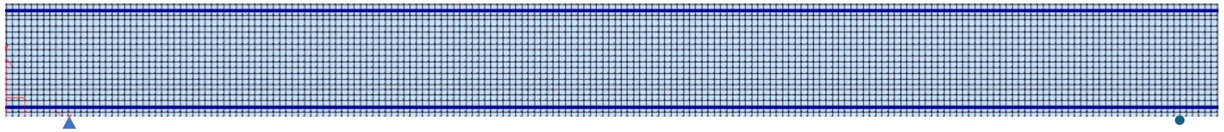


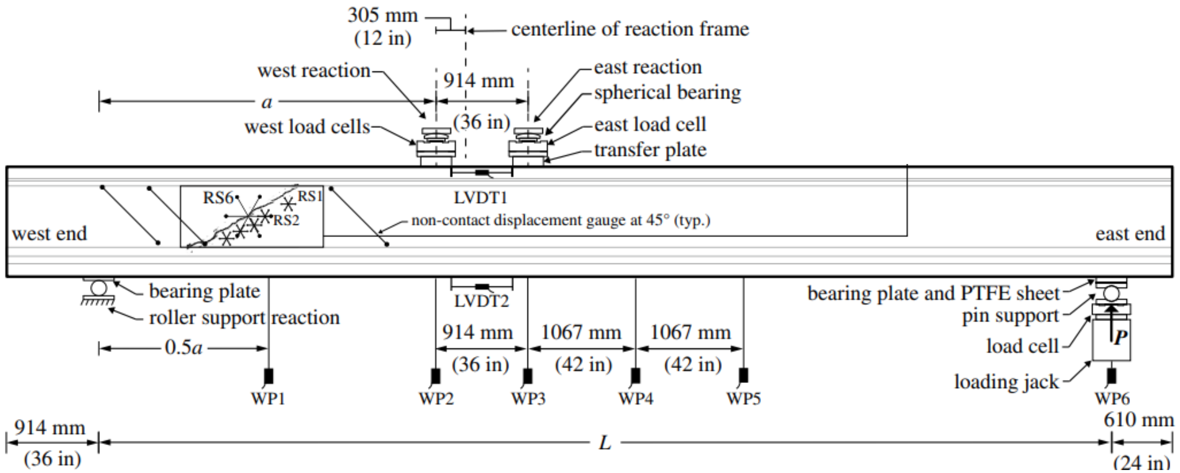


El-Helou and Graybeal 2022 Beams



ID	f'_c (MPa)	f'_t (MPa)	$A_{p_{bot}}$ (mm^2)	a/d
H-P1	137	11.3	4552.8	3.5
J-P1	158	8.6	4552.8	3.5
J-P1S	152	9.3	3414.6	3.5
H-P2	140	10.7	4552.8	3.5
H-P3	160	11.5	4552.8	3.5





El-Helou, R. G., & Graybeal, B. A. (2022). Shear behavior of ultrahigh-performance concrete pretensioned bridge girders. *Journal of Structural Engineering*, *148*(4), 04022017.

El-Helou and Graybeal 2022 Beams

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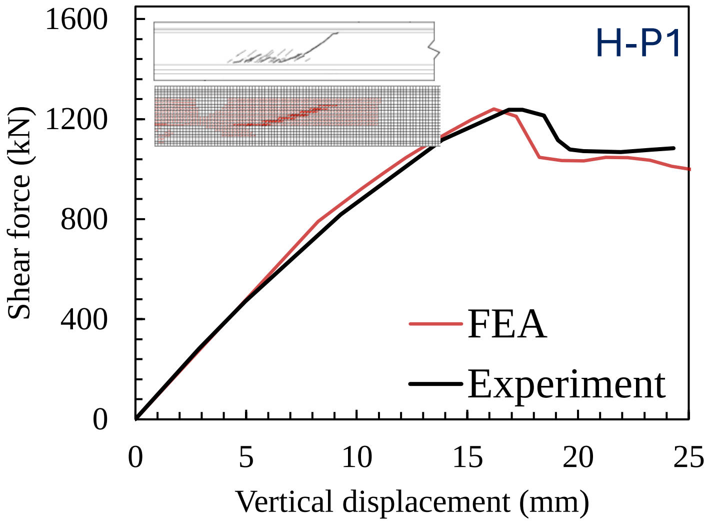
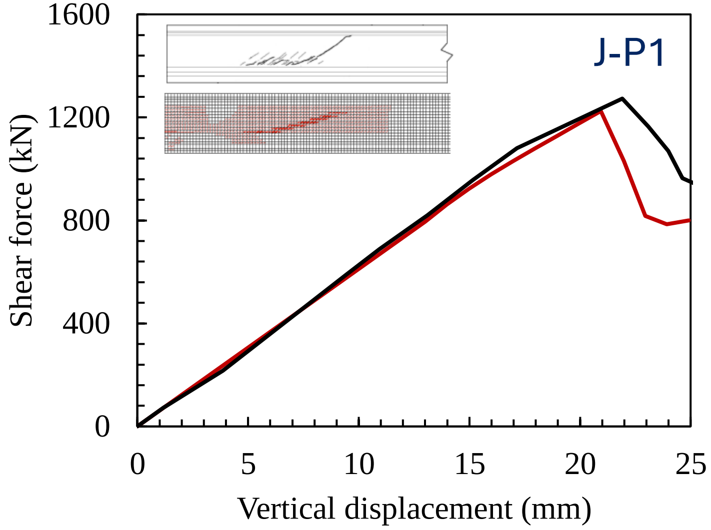
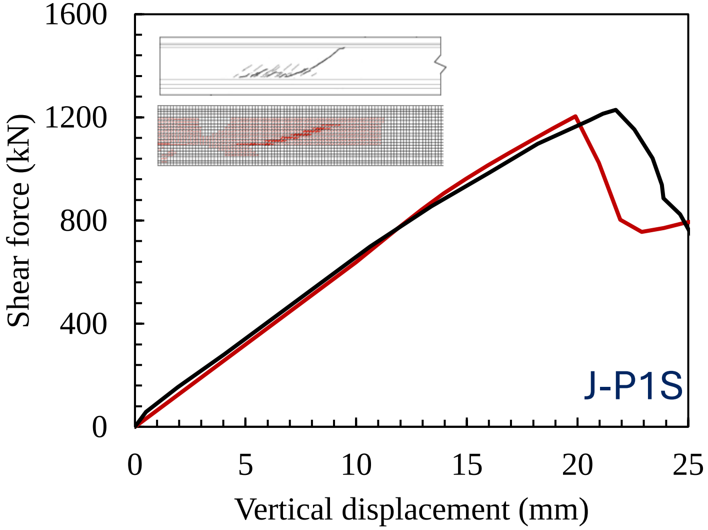
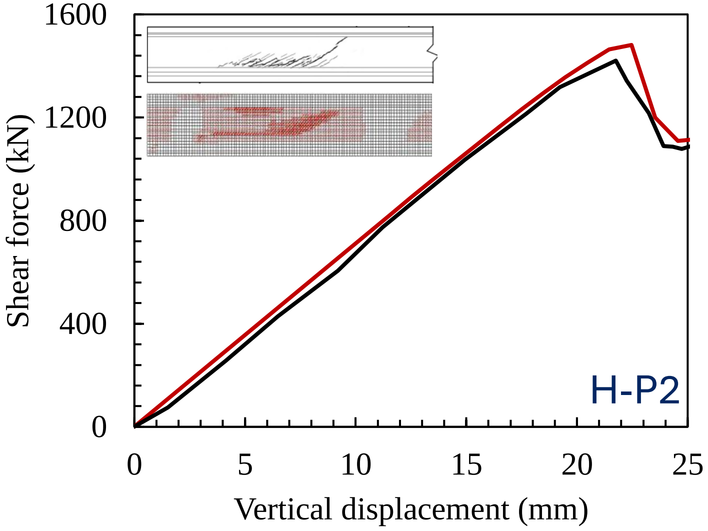
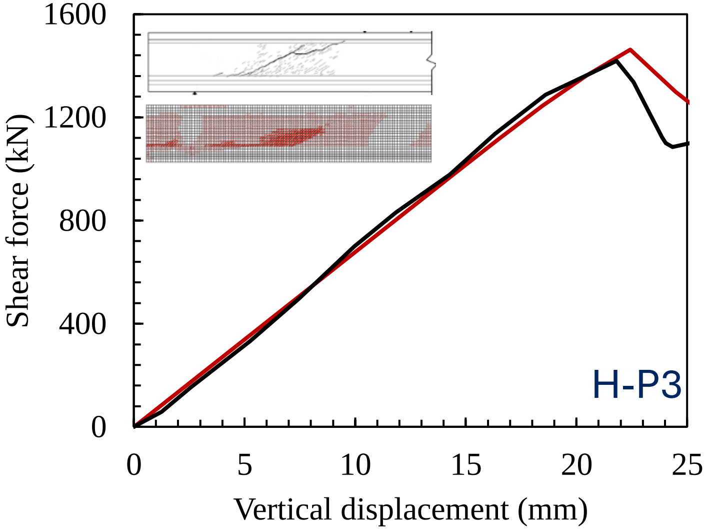


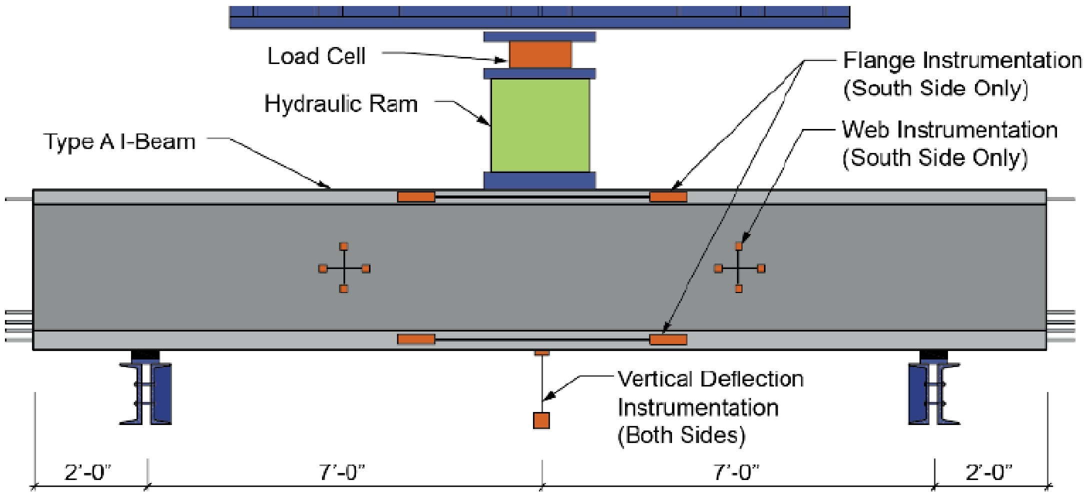


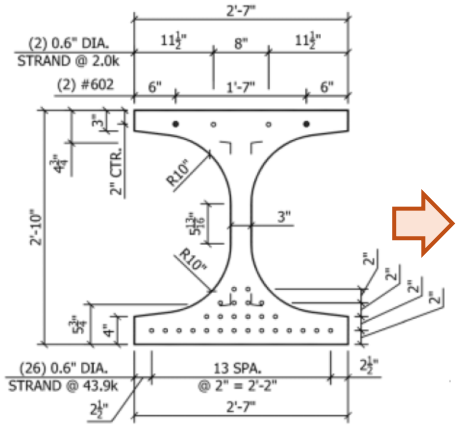




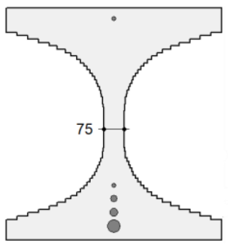


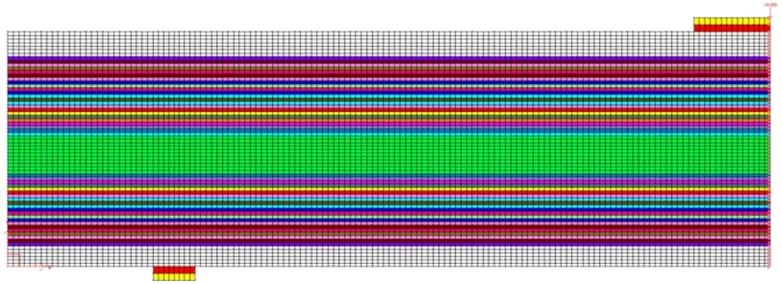
PCI 2021 BEAMS





3” web



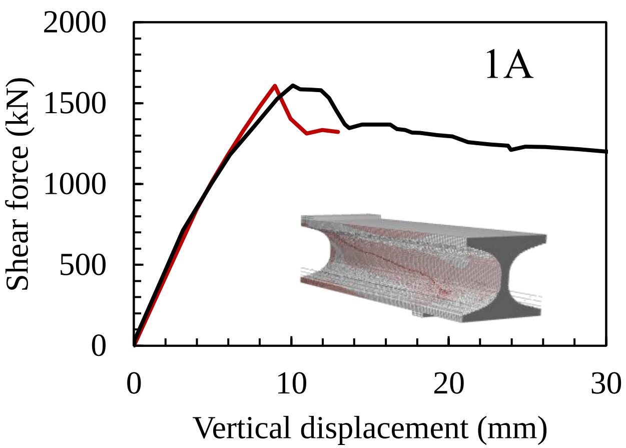


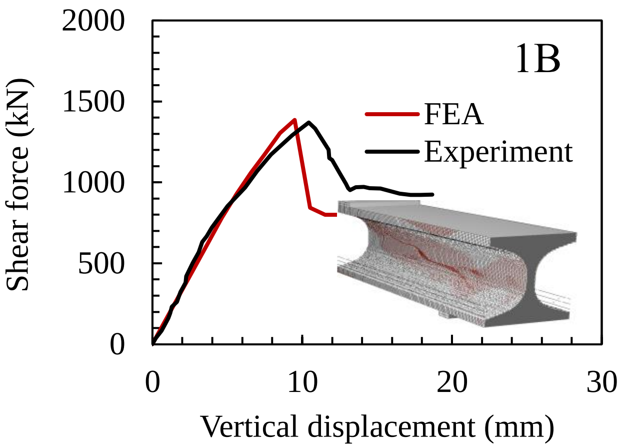
ID	f'_c (MPa)	f'_t (MPa)	A_p (mm^2)	b_w (mm)	a/d
1A	154.7	15.79	4592	75	2.5
1B	119.83	11.8	4592	75	2.5
1C	N/A	11.8	4592	75	2.5
4	118.38	11.8	2296	75	2.5
12	125.89	11.8	4592	50	2.5

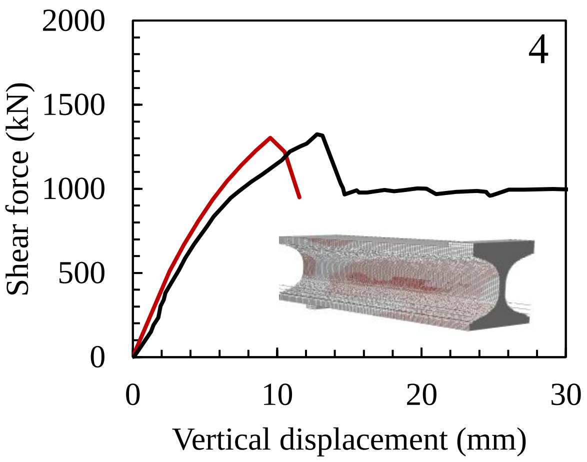
PCI. (2021). Implementation of Ultra-High Performance Concrete in Long-Span Precast Pretensioned Elements for Concrete Buildings and Bridges, Precast/Prestressed Concrete Institute.

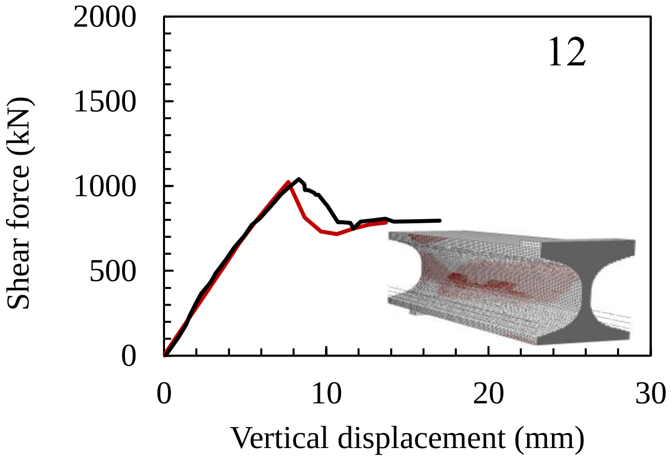
PCI 2021 Beams

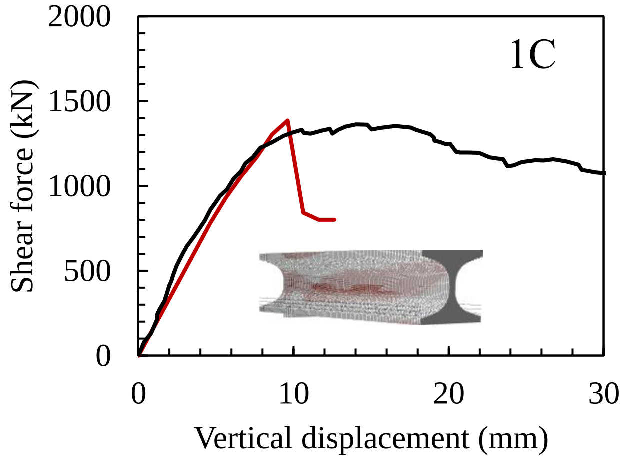
ID	f'_c (MPa)	f'_t (MPa)	A_p (mm²)	b_w (mm)	a/d
1A	155	15.8	4592	75	2.5
1B	120	11.8	4592	75	2.5
1C	120	11.8	4592	75	2.5
4	118	11.8	2296	75	2.5
12	125	11.8	4592	50	2.5











PCI. (2021). Implementation of Ultra-High Performance Concrete in Long-Span Precast Pretensioned Elements for Concrete Buildings and Bridges, Precast/Prestressed Concrete Institute.

aci CONCRETE CONVENTION

Conclusions & Future work

Conclusions:

- The ANN-based model developed for predicting the tension response of UHPC proved to be reasonably accurate for the set of specimens analyzed.
- It is feasible to employ an ANN-based tension response model of UHPC within a NLFEA framework.
- The direct tension database is available in the QR code attached.

Future work:

- Developing a Bayesian neural network to provide a probabilistic estimation of the tension characteristics of UHPC composites.
- Using the developed formulation to analyze the response of retrofitted UHPC bridge piers with UHPC jacketing.
- Analyzing the response of UHPC shear walls.

Thank You!