Nonlinear Finite Element Analysis of Reinforced Concrete Beams Strengthened in Shear with Embedded Steel Bars

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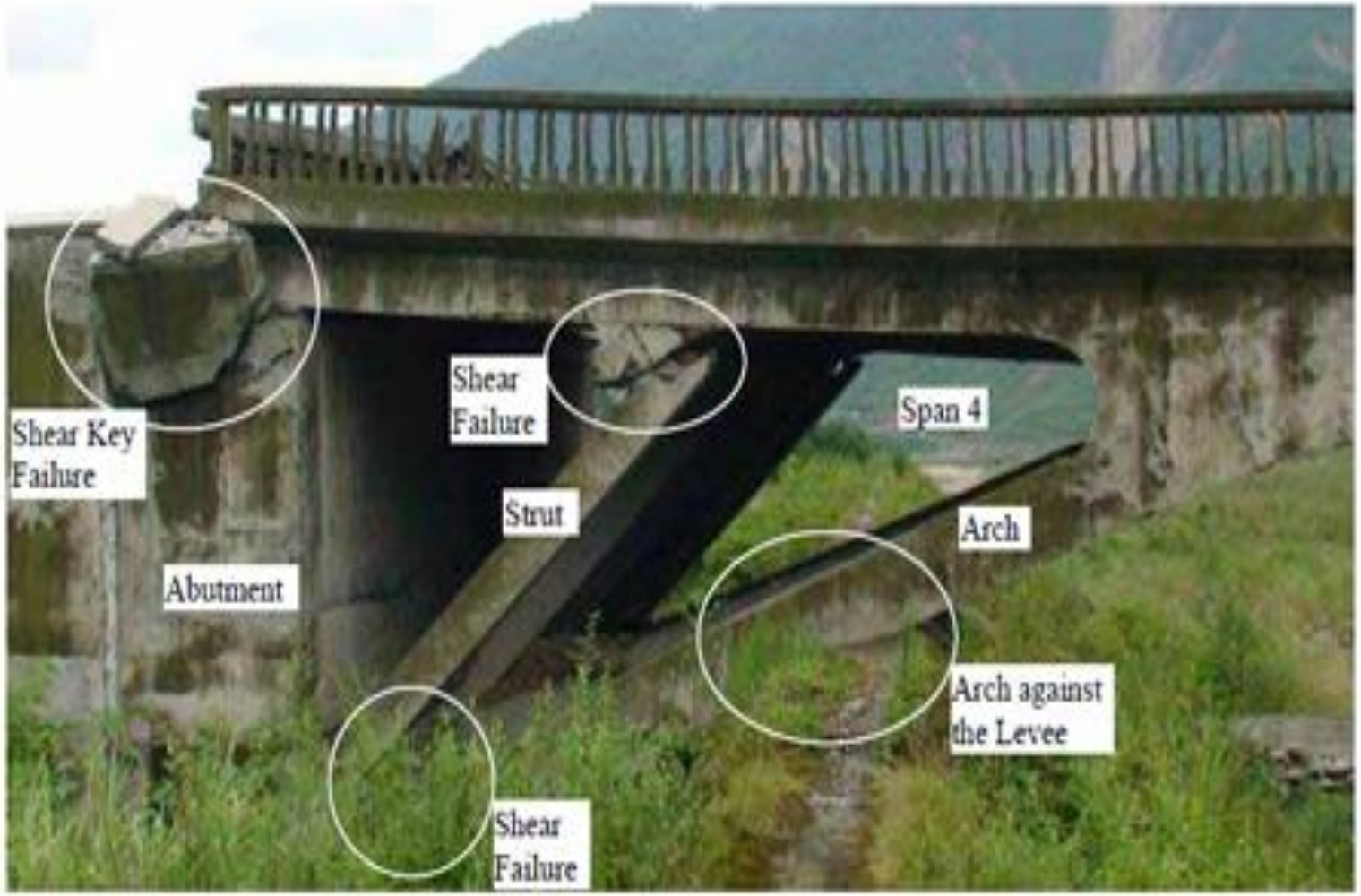
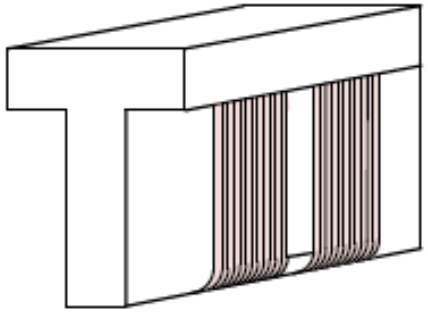
Background

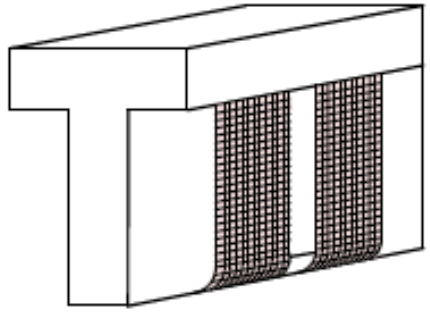


China Earthquake Reconnaissance Report: Performance of Transportation Structures During the May 12, 2008, M7.9 Wenchuan Earthquake

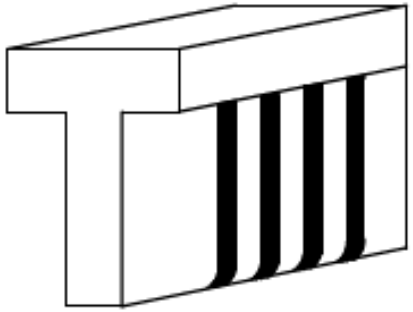
Background: Shear Strengthening of RC beams



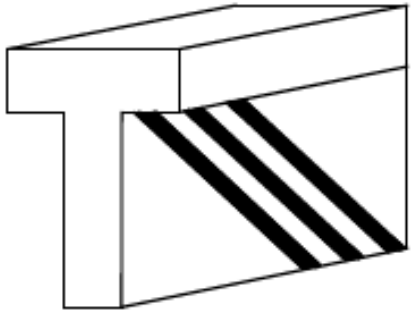
(a)EB unidirectional FRP sheets



(b)EB bi-directional FRP sheets



(c)EB laminated FRP sections

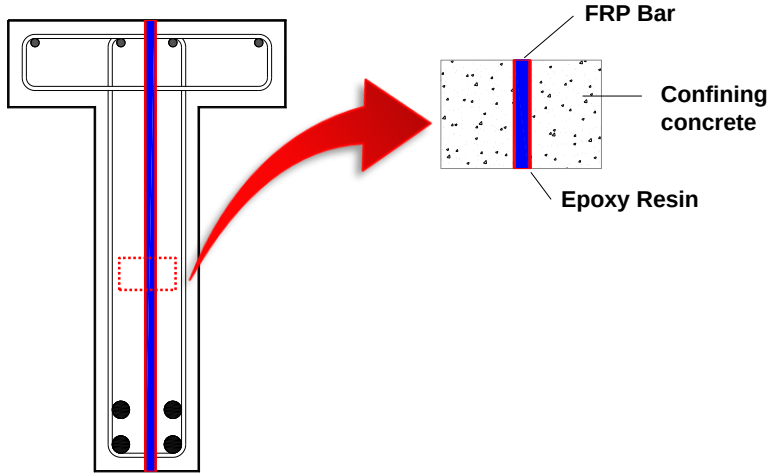


(d)NSM FRP reinforcement

Source: https://www.horseen.com/project/strengthening-rehabilitation-rc-beam-column?page=3

Background

Deep Embedment / Embedded Through-Section Technique



- ✓ **Easier to apply**
- ✓ **Less epoxy consumption**
- ✓ **Higher effectiveness**

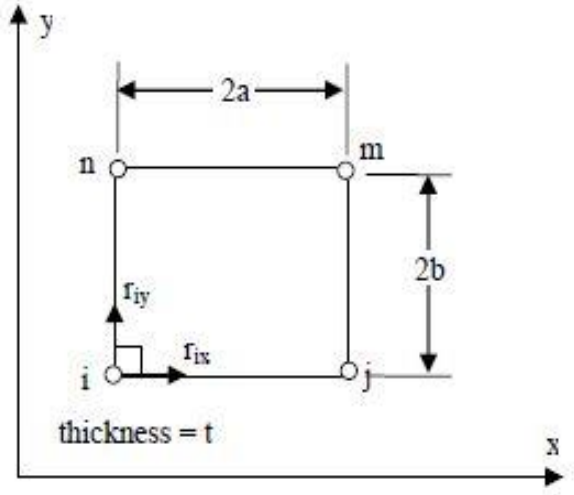
Research Questions

- **Shear behavior of continuous RC beams strengthened with DE/ETS technique is still unclear.**

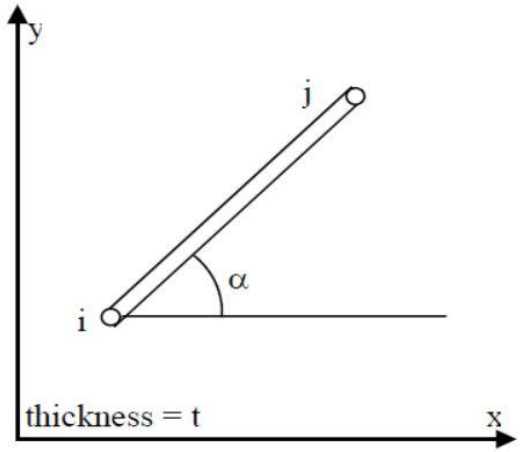
- **The effect of concrete compressive strength on the behavior of DE/ETS strengthened continuous RC beams and simply supported RC beams is not quantified.**

Finite Element Modeling

- Geometry :
  - Two-dimensional, four-node, plane stress rectangular elements were used to model the concrete, loading plate and support plate.
  - The steel reinforcement; comprising longitudinal reinforcement, shear links and DE/ETS bars; was modelled using two-node truss elements.



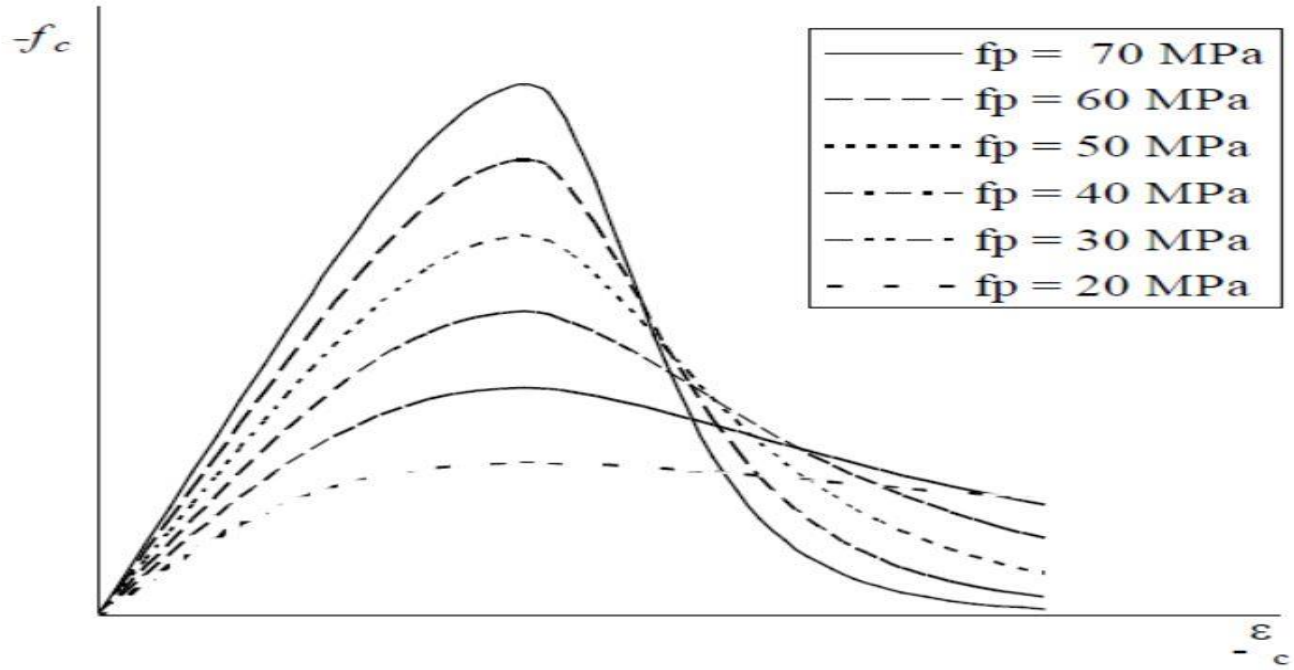
Plane Stress Rectangular Element



Truss Bar Element

Finite Element Modeling

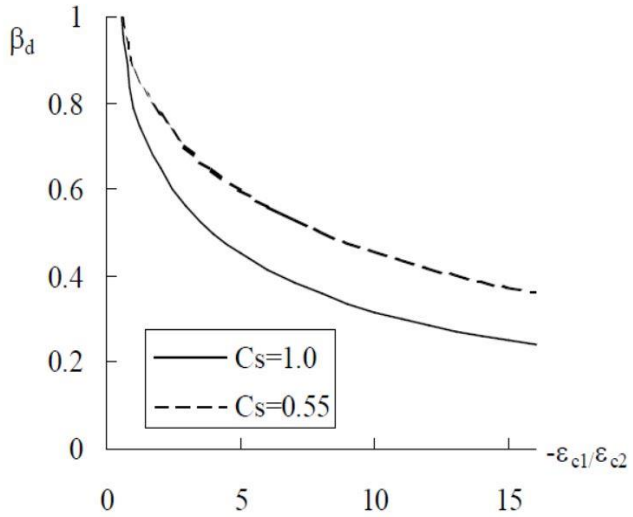
- Material :



Popovics high strength pre-peak and post-peak concrete compression response

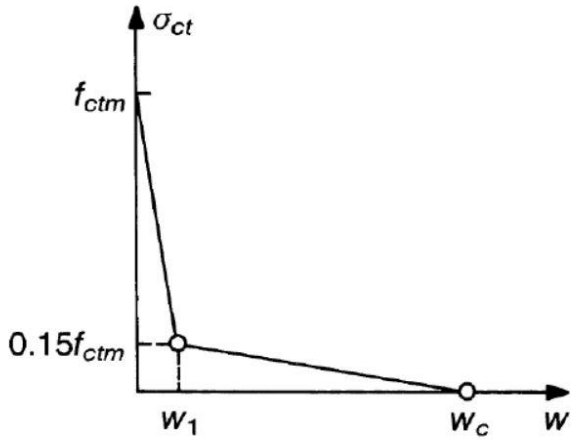
Finite Element Modeling

Compression Softening



Vecchio 1992-B (e1/e0-Form) Compression softening model

Tension Softening

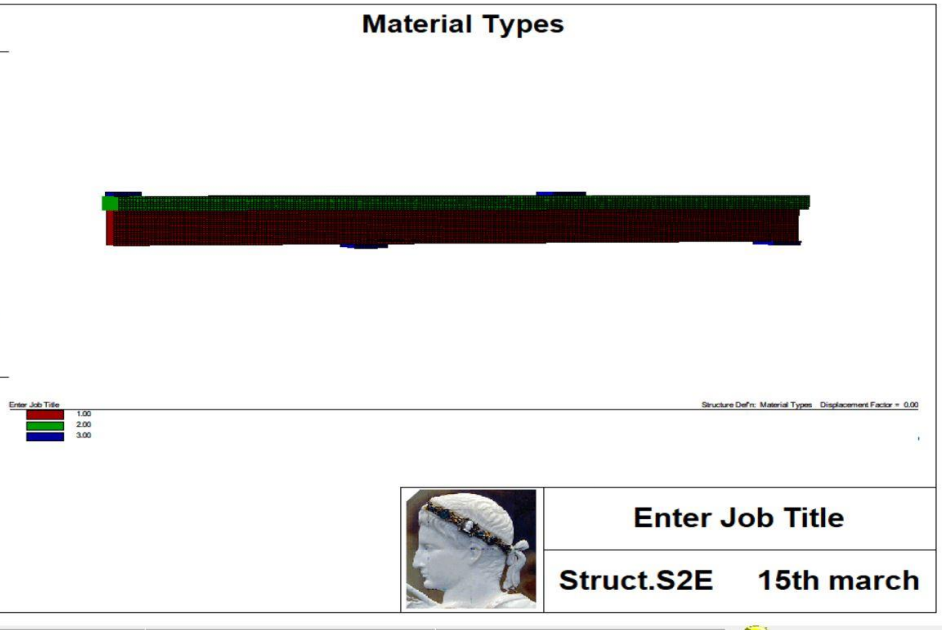


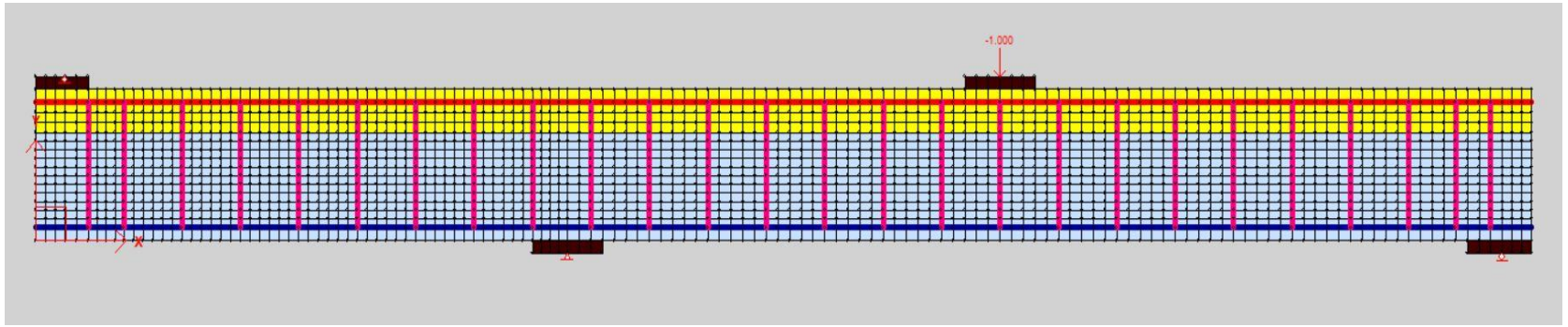
CEB-FIP tension softening curve (CEB-FIP, 1990)

Finite Element Modeling

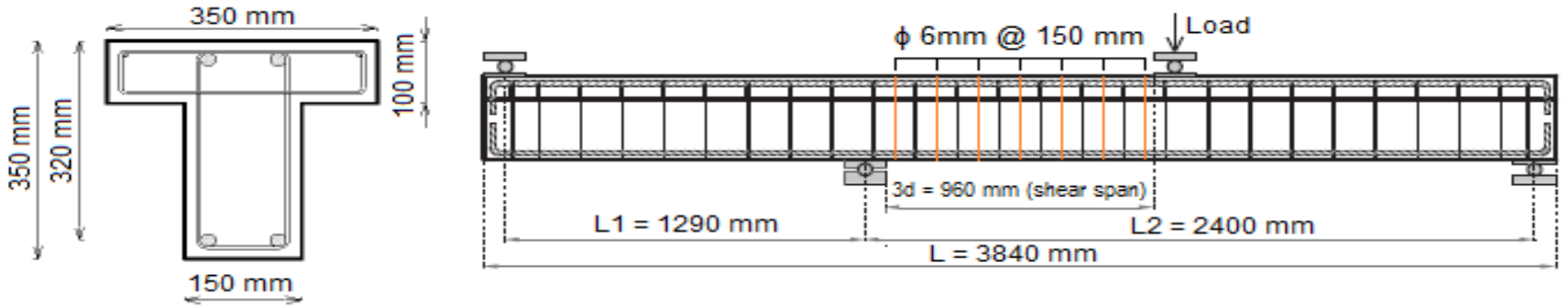
Analysis Details	
Total Number of Nodes:	6521
Total Number of Elements:	7264
Number of Triangular elements:	0
Number of Rectangular Elements	6232
Number of Truss Elements:	1032
Number of Linkage Elements:	0
Number of Contact Elements:	0
Number of Concrete Types:	3
Number of Load Stages:	1
Analysis Type:	VecTor2 V.4

Analysis Parameters	
Convergence Criteria	Displacements - Weighted
Compression Base Curve	Popovics (HSC)
Compression Post-Peak	Popovics / Mander
Compression Softening	Vecchio 1992-B
Tension Stiffening	Modified Bentz 2003
Tension Softening	Bilinear
FRC Post-Crack Tension	SDEM (Monotonic)
Confinement Strength	Kupfer / Richart
Concrete Dilatation	Variable - Isotropic
Cracking Criterion	Mohr-Coulomb (Stress)
Crack Stress Calc	Basic (DSFM/MCFT)
Crack Width Check	Crack Limit (10 mm)
Concrete Bond	Perfect Bond
Concrete Creep / Relax	Not Considered





Finite Element Modeling:Model Validation

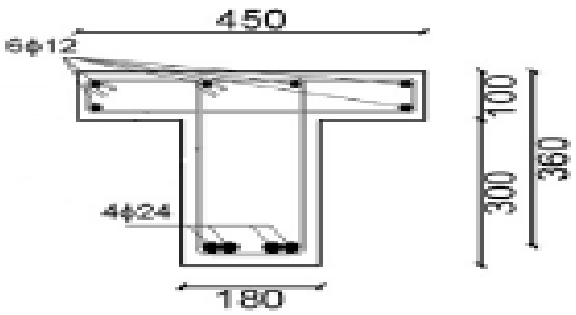


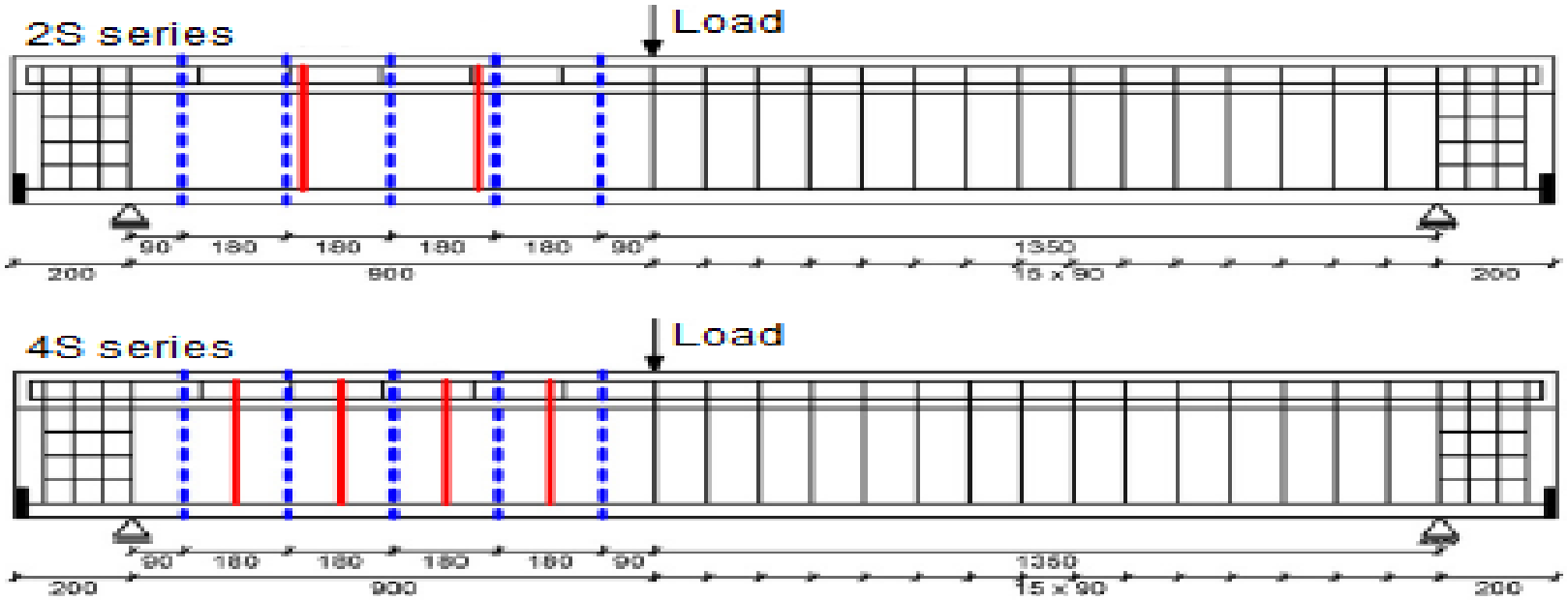
•The first set comprised the two continuous RC beams CON and S150 tested by Raicic et al. (2017)

•CON as control beam whereas S150 is strengthened with 6 mm diameter DE/ETS steel bars.

•Both beams had two 20 mm diameter tension and compression reinforcement together with 4 mm diameter shear links spaced at 150 mm.

Finite Element Modeling:Model Validation



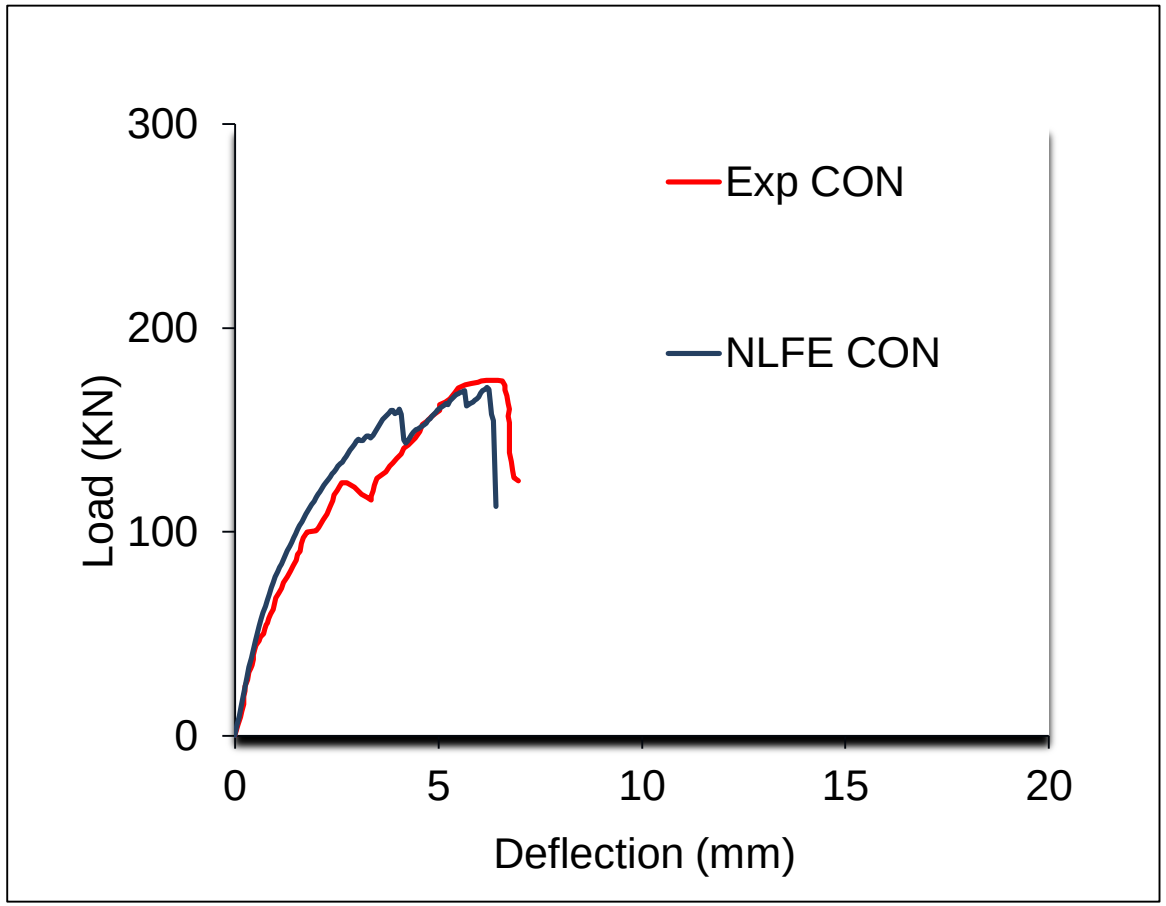


•The second set included the four simply supported RC beams 2S-Ref, 2S-S180-90,4S-Ref and 4S-S180-90 tested by Breveglieri et al.(2015)

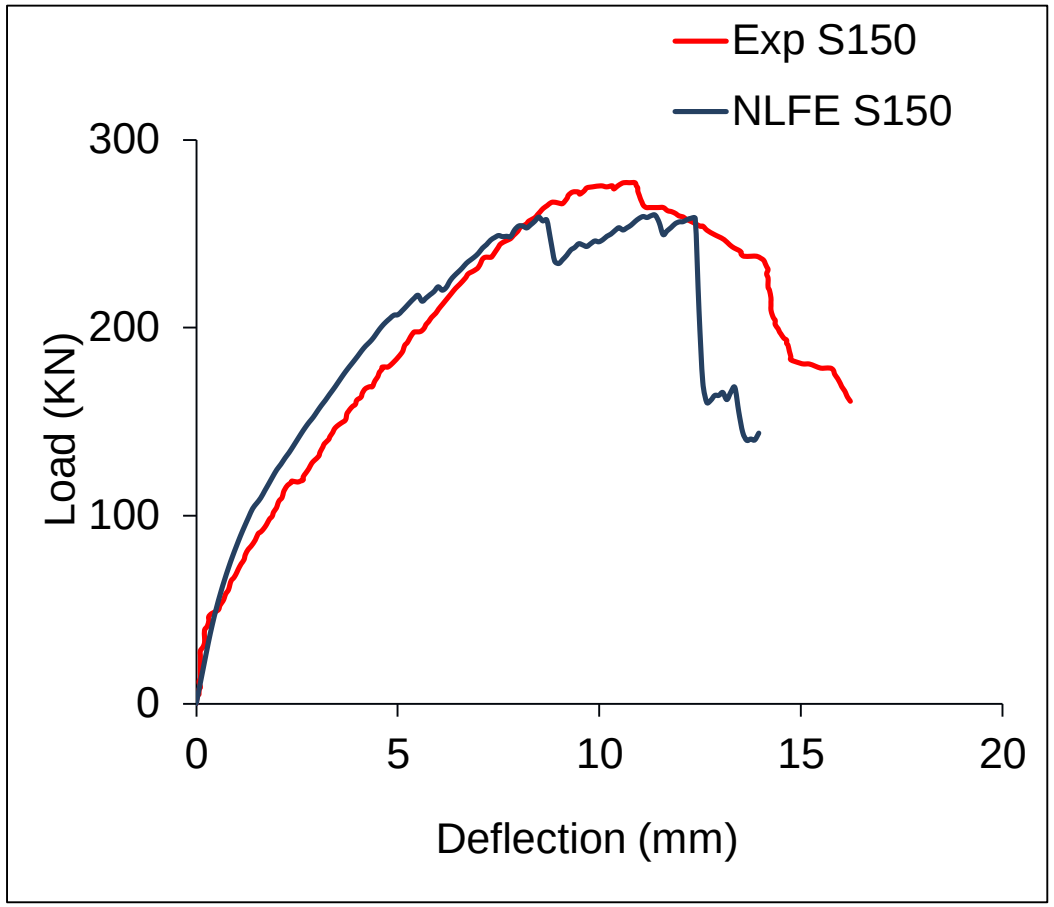
•The difference between the two series is that the beams in series 2S had 6 mm diameter shear links spaced at 300 mm, corresponding to a shear reinforcement ratio of 0.10% whereas the beams in series 4S had 6 mm diameter shear links spaced at 180 mm, corresponding to a shear reinforcement ratio of 0.17%.

• 2S-Ref and 4S-Ref are unstrengthened control beams whereas 2SS180-90 and 4S-S180-90 are strengthened with 10 mm diameter DE/ETS steel bars.

Results : Load-Deflection

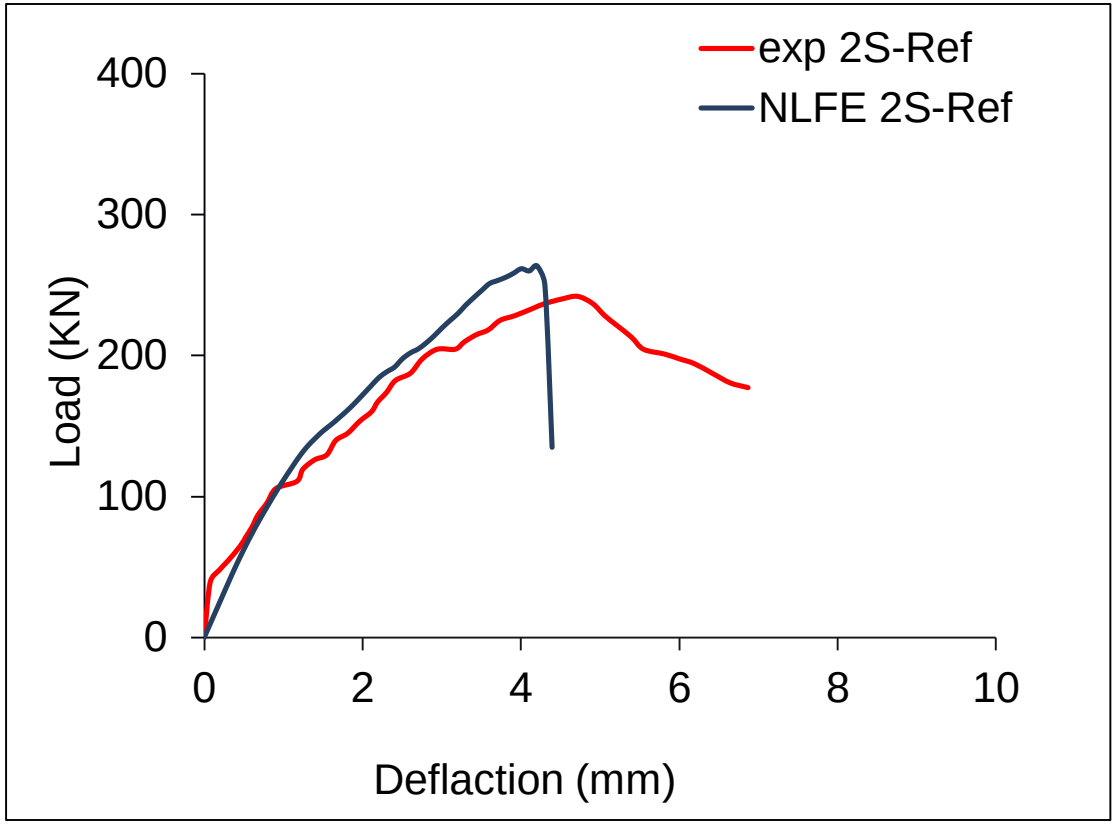


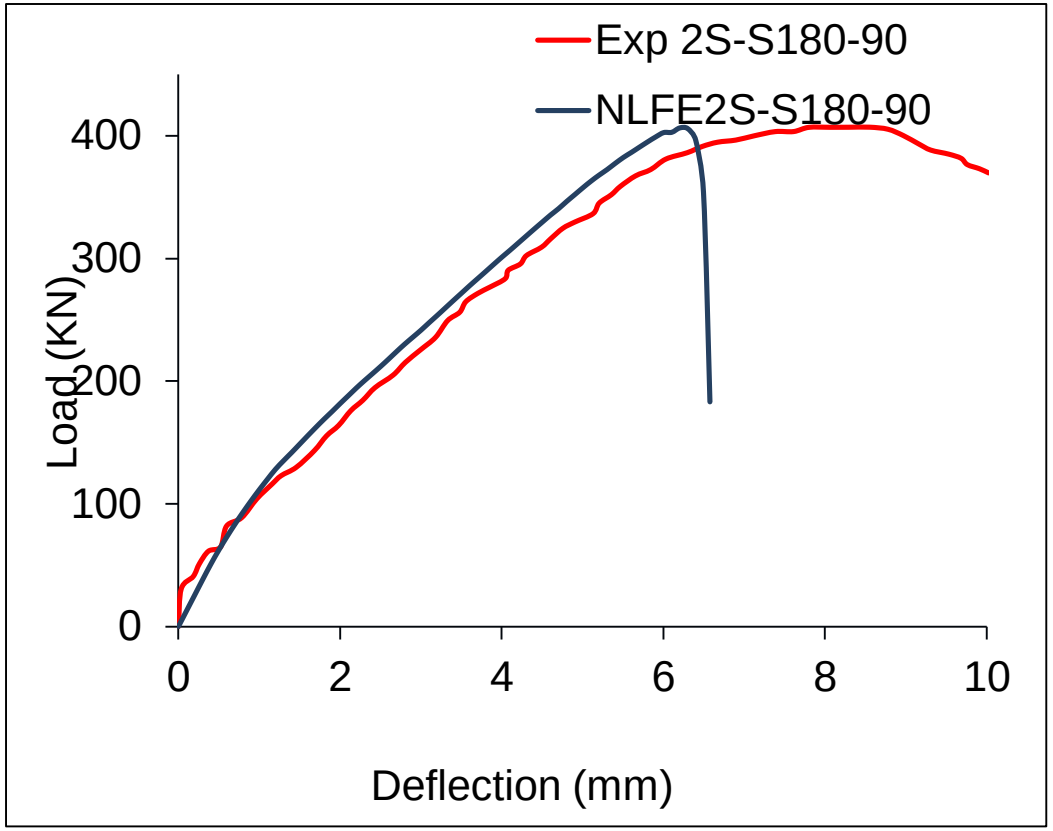
Control Continuous T Beam



Continuous T beam Strengthened with Steel bar

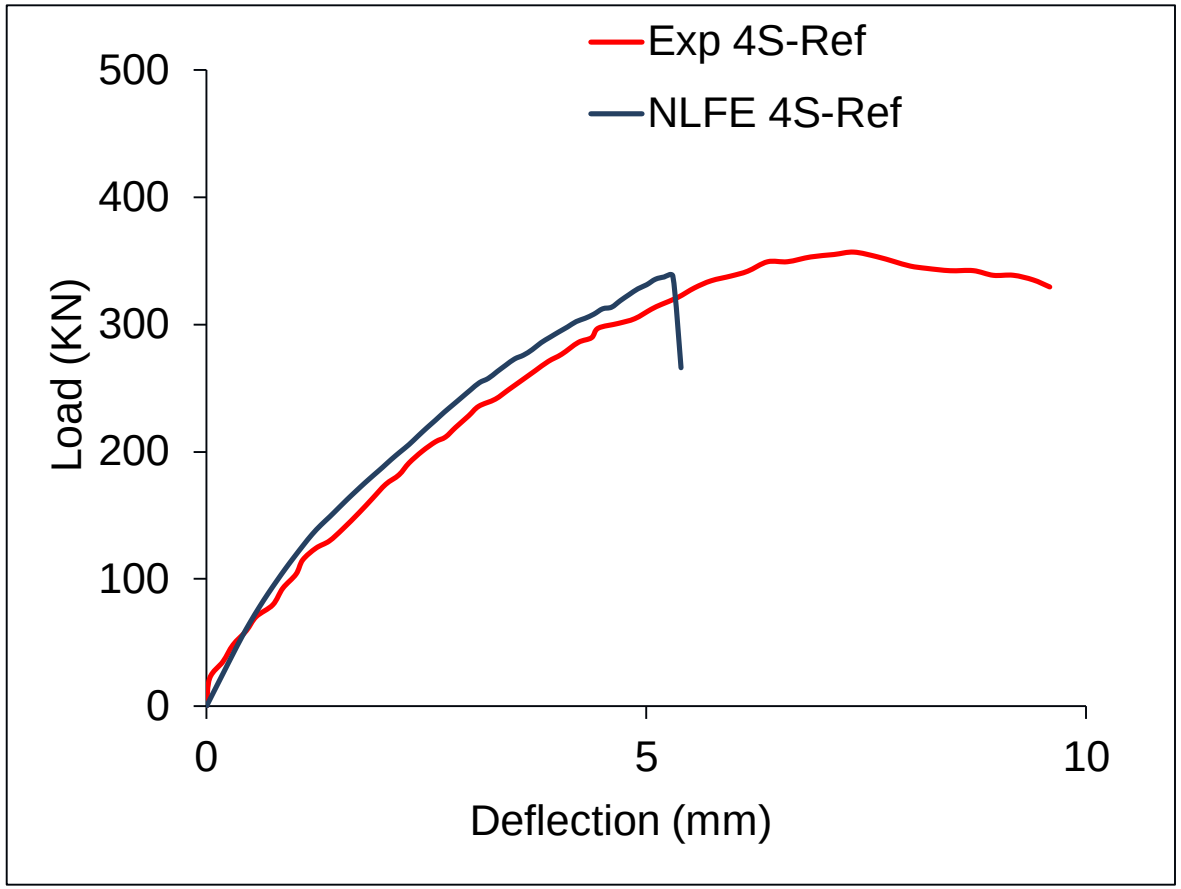
Results : Load-Deflection

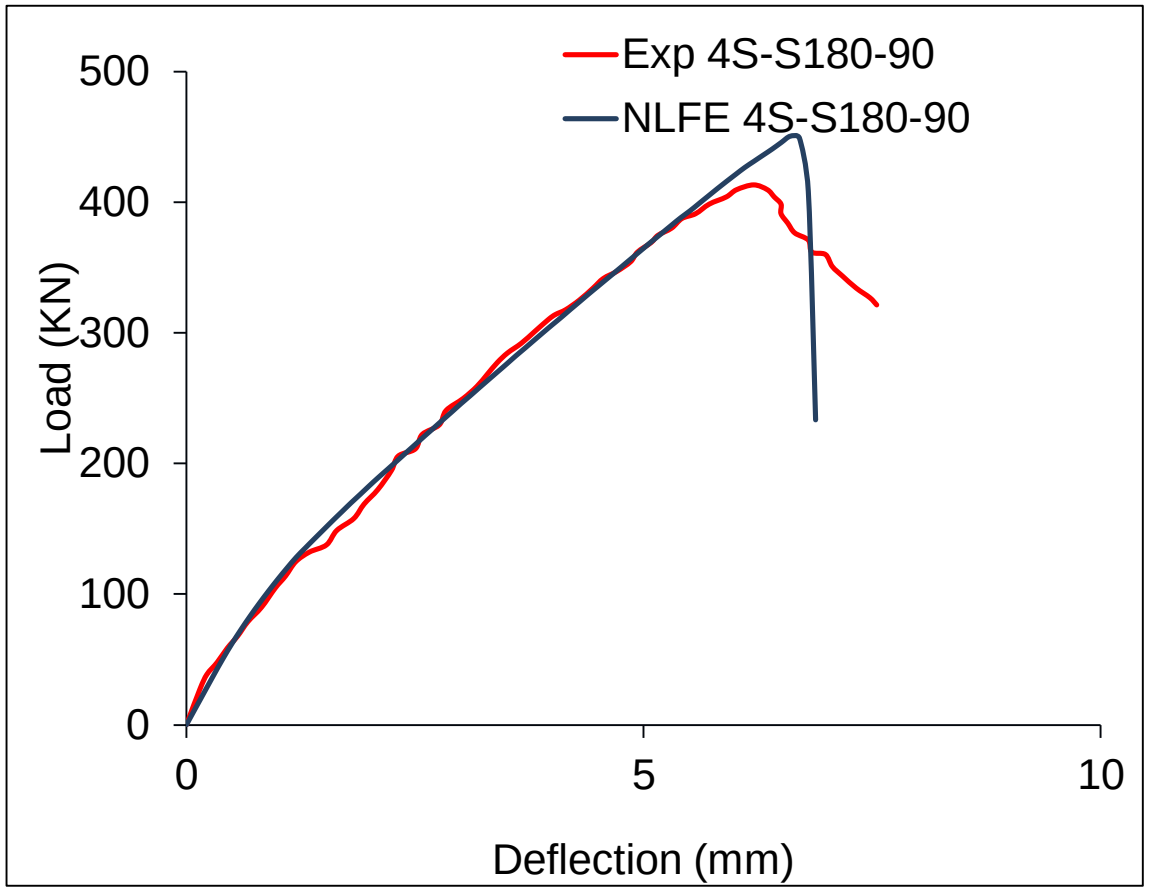




Simply supported T beam (2S – Series)

Results : Load-Deflection





Simply supported T beam (4S – Series)

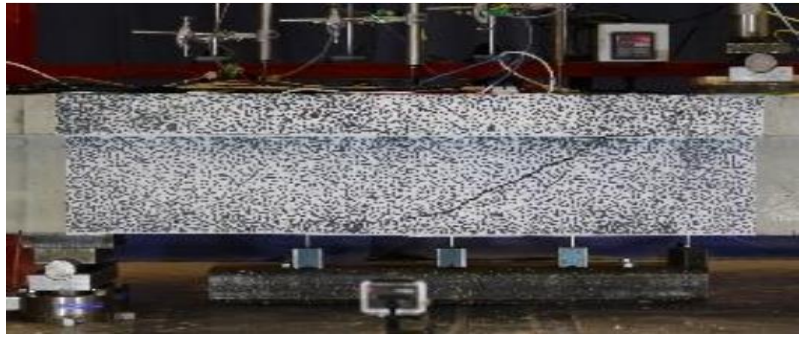
Results : Load-Deflection

Specimen	Load at Failure (KN) Experimental	Load at Failure (KN) NLFE	NLFE/Experimental	Deflection at failure load [mm] Experimental	Deflection at failure load [mm] NLFE	NLFE/Experimental
CON	173	169.32	0.98	5.7	5.637	0.98
S 150	278	258.96	0.93	10.7	8.5	0.79
2S-Ref	242.1	263.626	1.08	4.70	4.204	0.89
2S-S180-90	406.8	406.428	0.99	8.27	6.205	0.75
4S-Ref	353.8	338.036	0.95	7.35	5.301	0.72
4S-S180-90	413.2	450.569	1.09	6.32	6.607	1.04

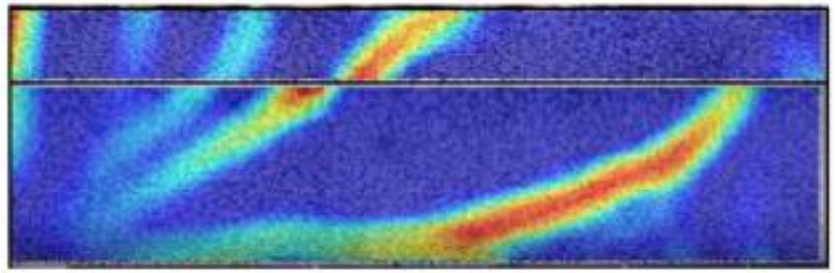
1.003 with a standard deviation of 0.061. (Load)
0.861 with a standard deviation of 0.118. (Deflection)

Results : Failure Mode

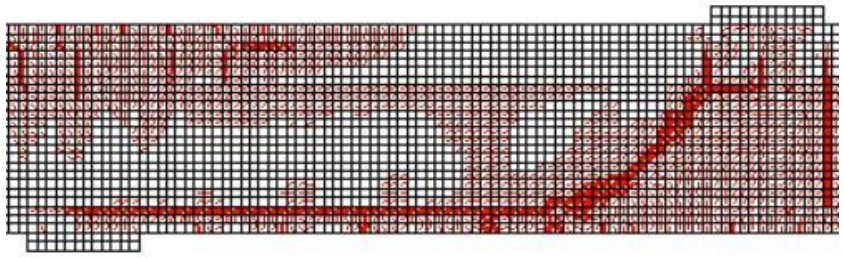
- Crack Patterns of Continuous T Beam

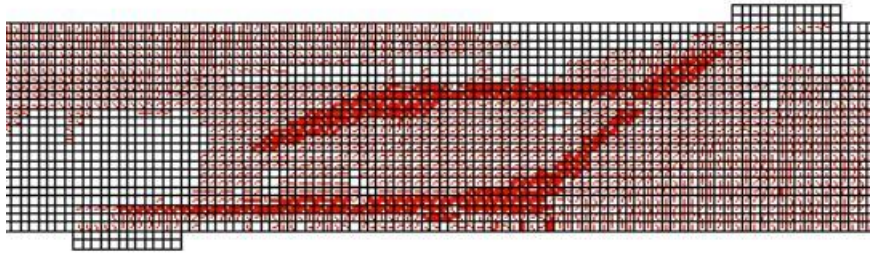


CON



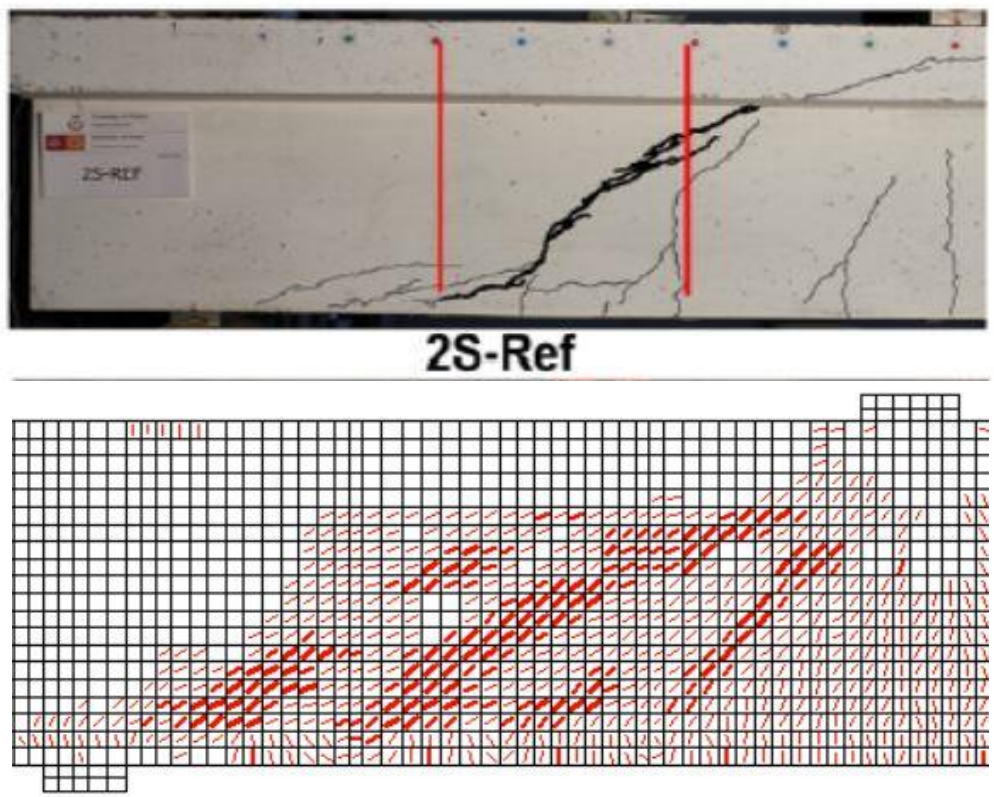
DE150

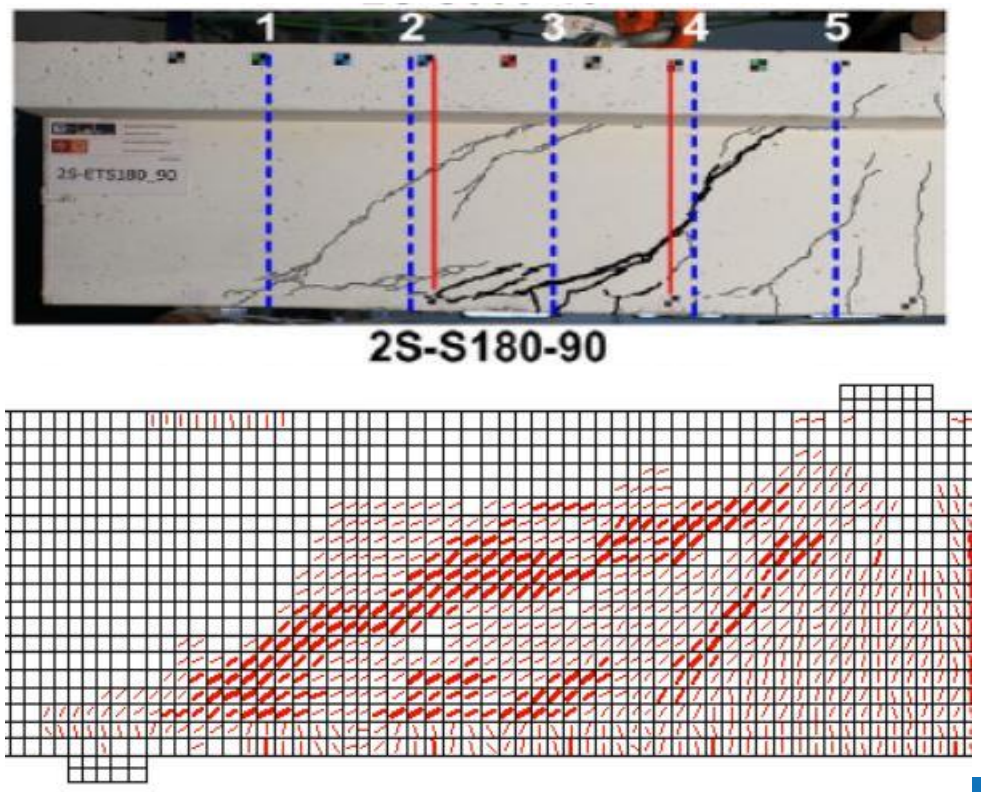




Results : Failure Mode

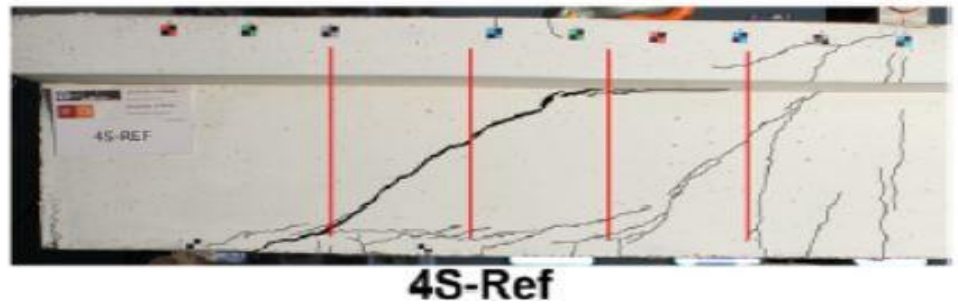
- Crack Patterns of Simply supported T Beam (2S series)



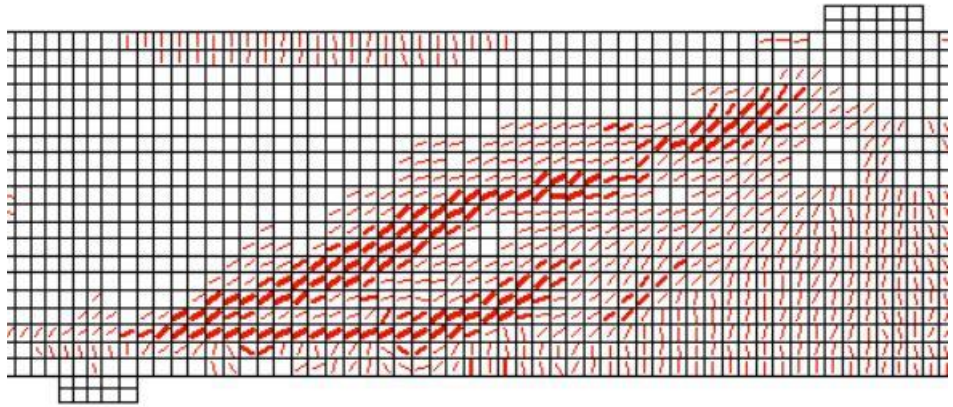


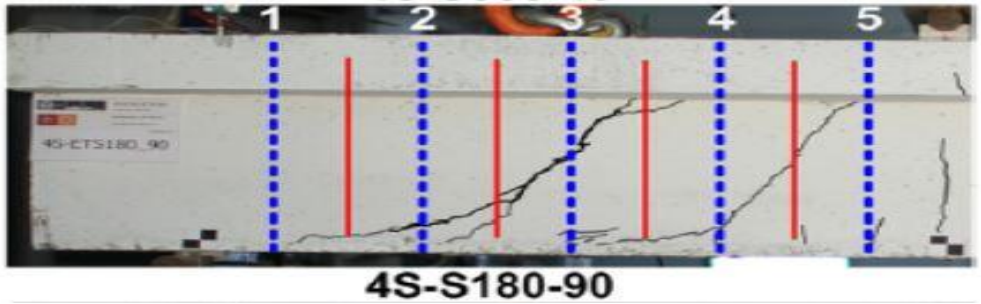
Results : Failure Mode

- Crack Patterns of Simply supported T Beam (4S series)

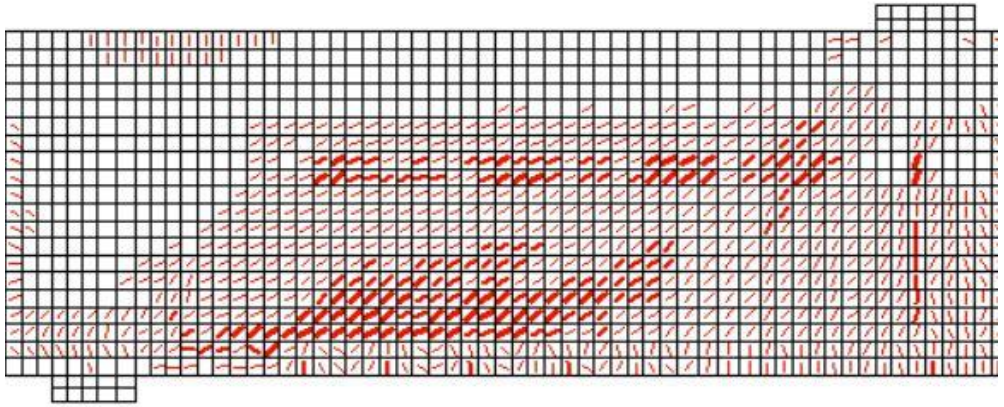


4S-Ref

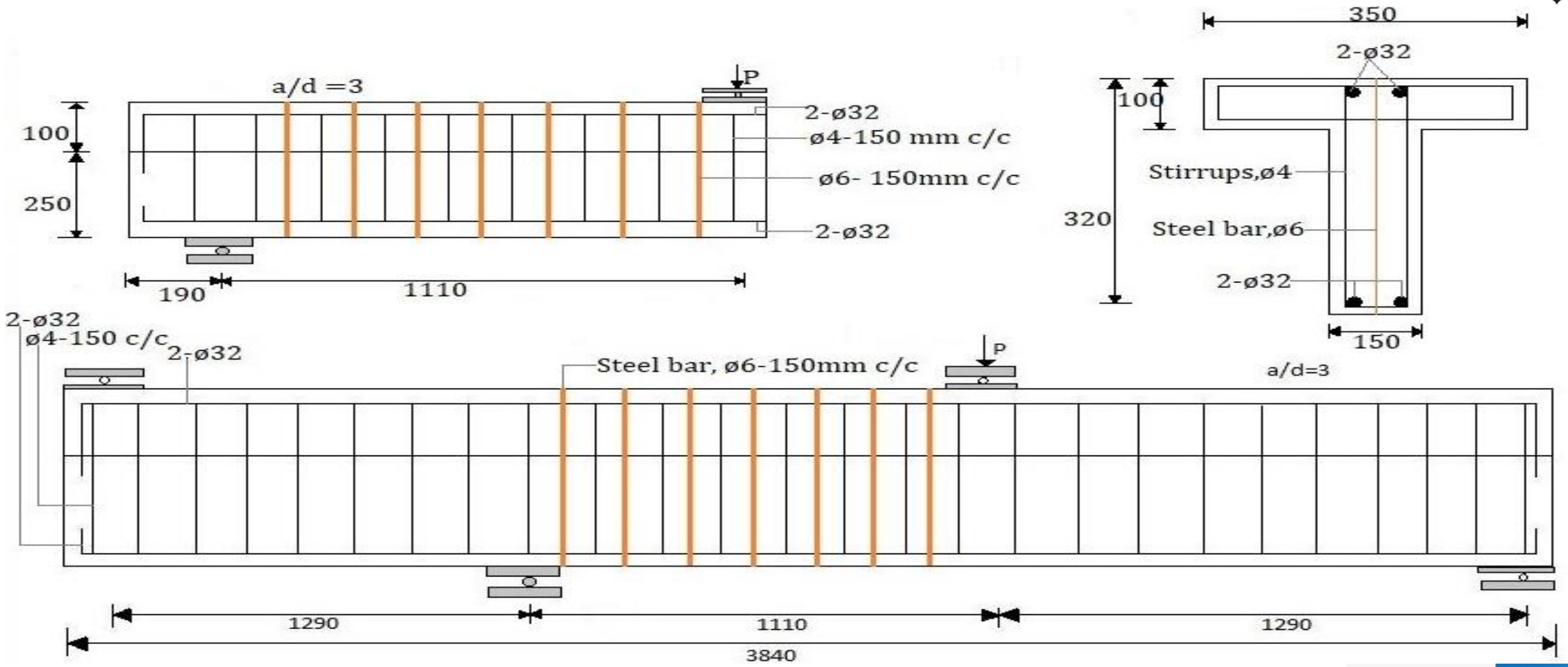




4S-S180-90



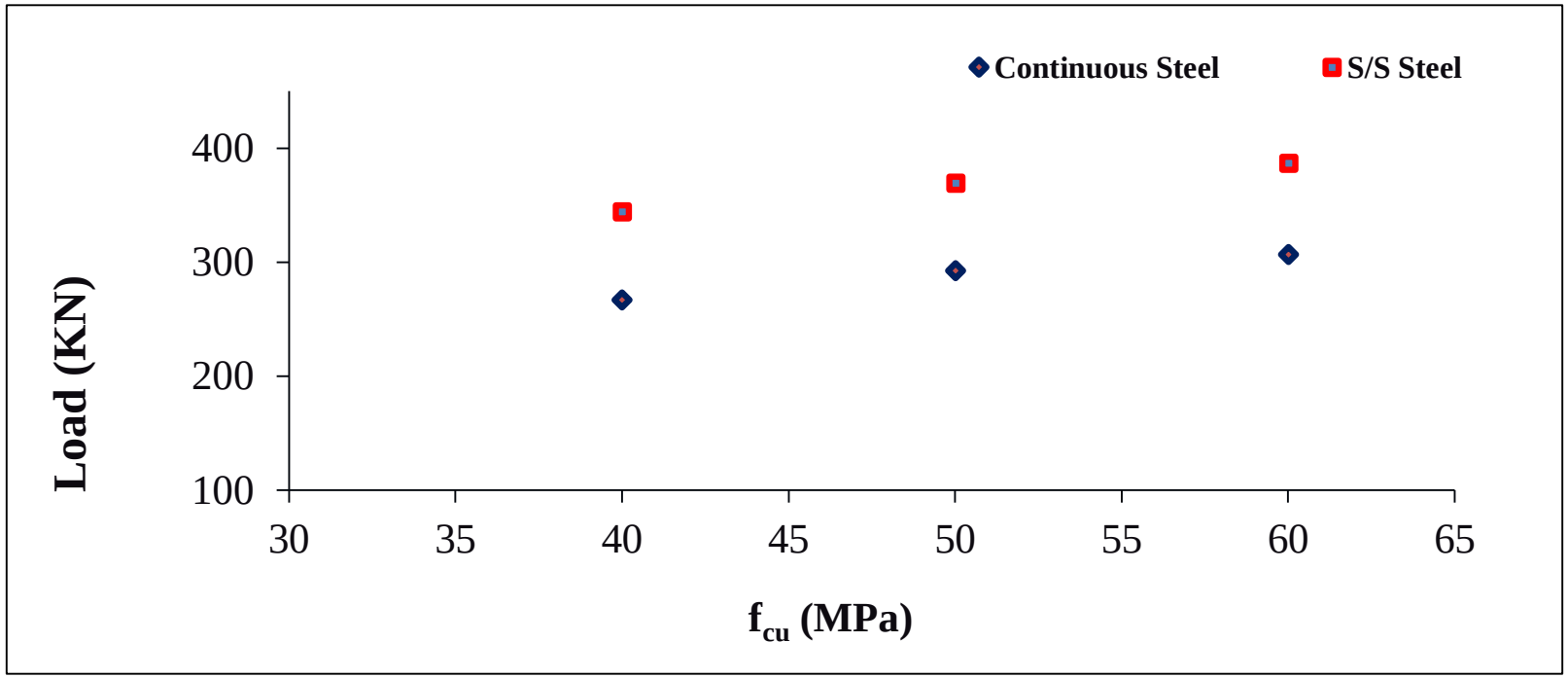
Results: Parametric Study



Results: Parametric Study

- Effect of beam type and concrete compressive strength :

Concrete cube compressive strength (f_{cu}) values of 40, 50 and 60 MPa were considered.



Summary

- A two-dimensional nonlinear FE models for DE/ETS-strengthened simply supported and continuous RC beams were validated using experimental results from the published literature.

- A parametric study was carried out to investigate the effect of beam type and concrete compressive strength on the predicted load carrying capacity.

- The load carrying capacities of the strengthened continuous beams were 20-22% lower than those of the corresponding simply supported beams.

- The predicted load carrying capacities of both beam types increased by 12-15% with the increase in concrete cube compressive strength from 40 to 60 MPa.

Thank You

Any questions?