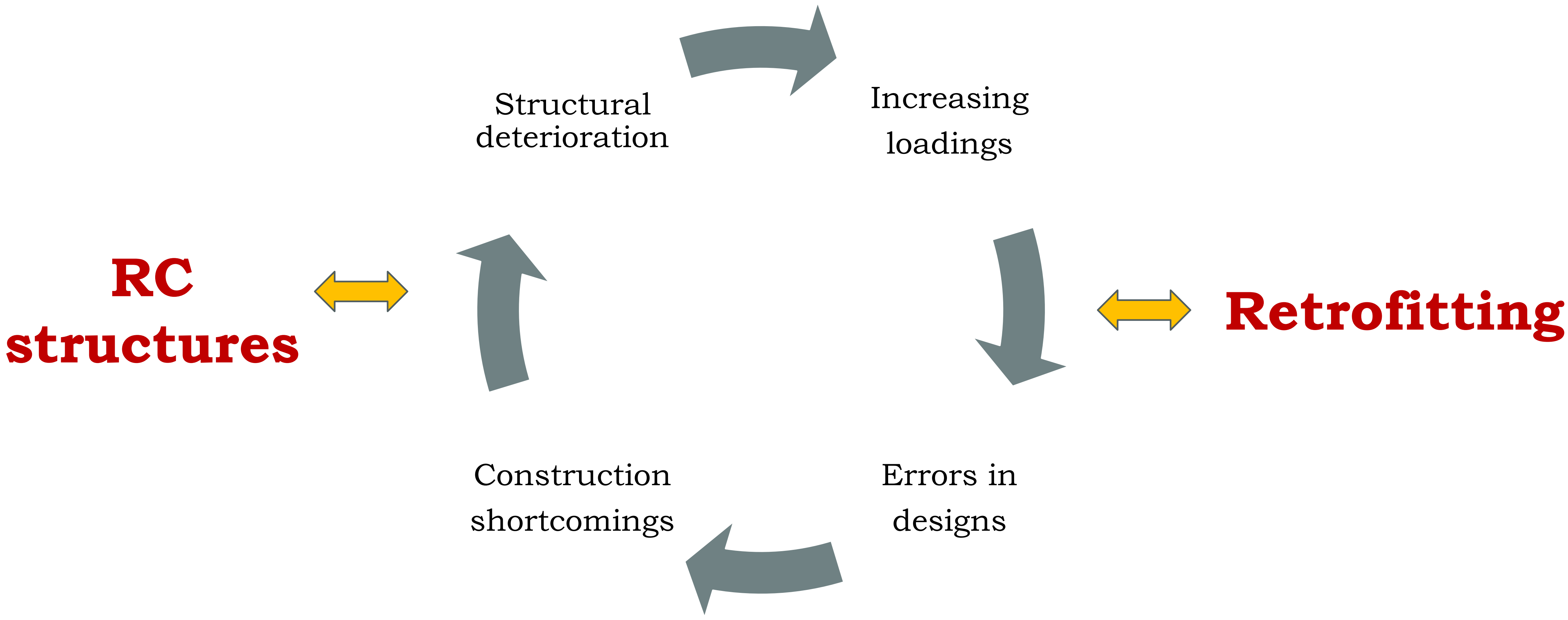

RC structures
Structural deterioration
Increasing loadings
Errors in designs
Construction shortcomings
Retrofitting

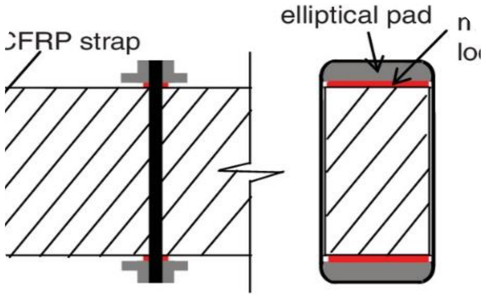
# Efficient Shear Retrofitting of RC Beams using Prestressed Deep Embedded (DE) FRP Bars

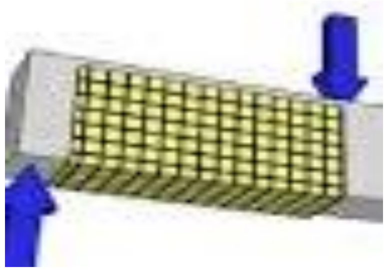
**Hiran Yapa**

**University of Peradeniya**

**Sri Lanka**

# Shear retrofitting options

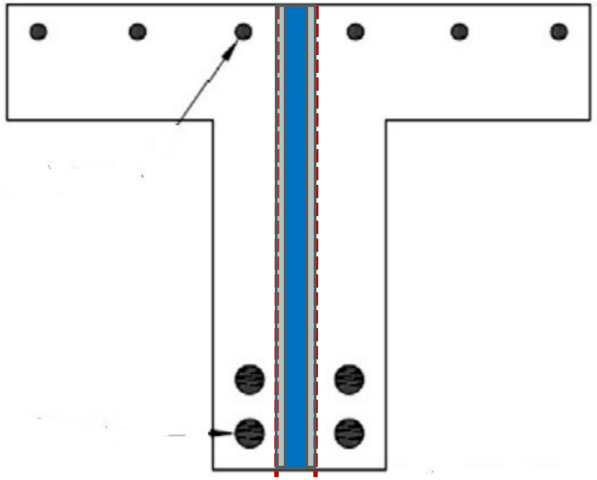


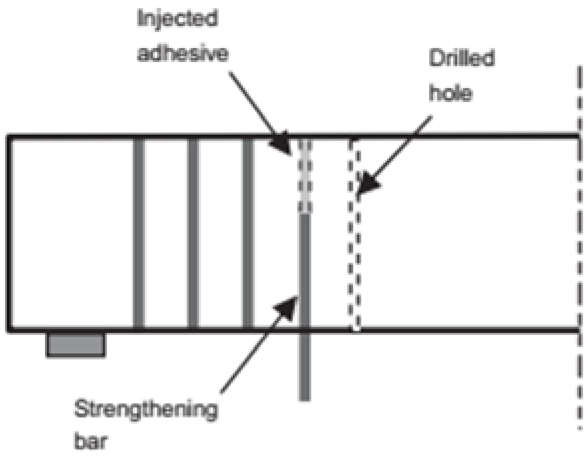



DE

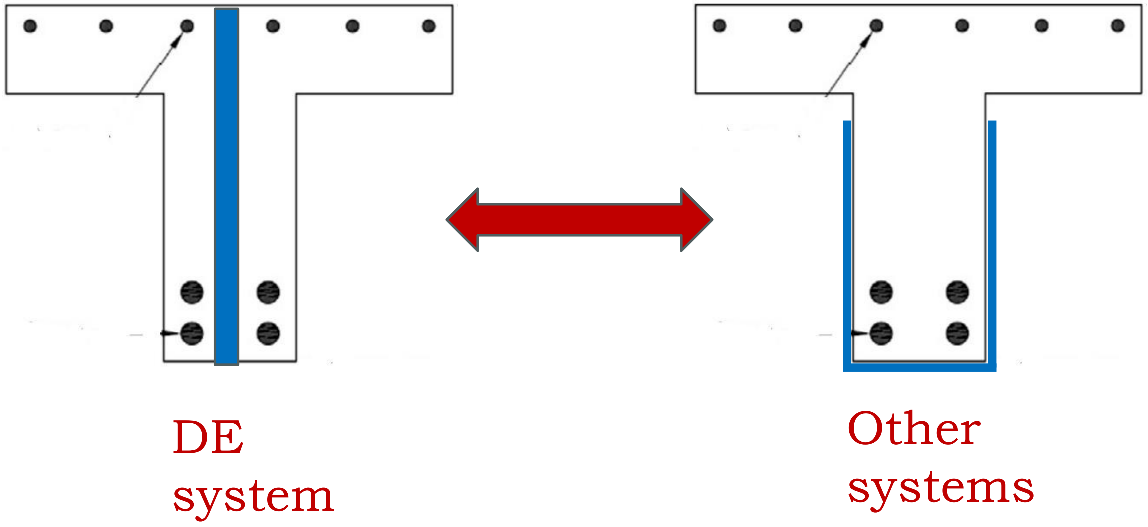
# Deep Embedment (DE) technique

- First proposed by Valerio and Ibell in 2003
- Holes are drilled from the soffit
- Void is filled with epoxy resin
- DE reinforcement is then installed



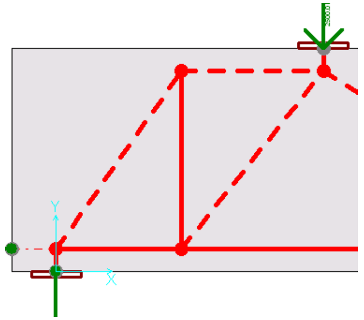


# DE system attributes




**The core installation**

- Facilitates truss action



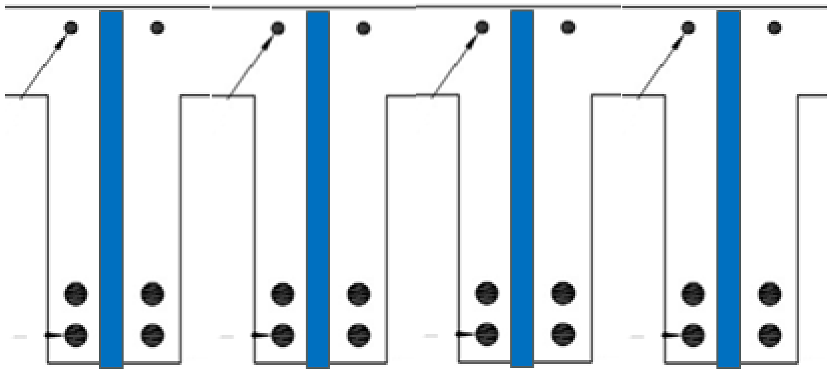
- More confinement to the r/f
  - Less de-bonding issues

**more shear enhancement!**

- Limited external exposure
  - Steel can also be used
  - Less vulnerability for damage

# Further attributes…

- No need of web/slab approach

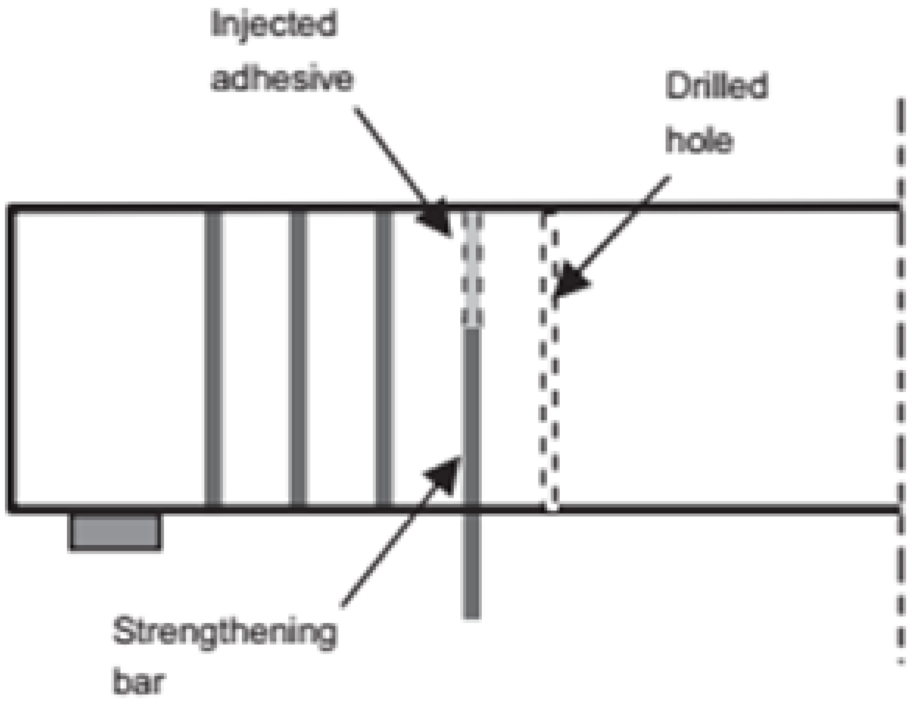


- No surface preparation

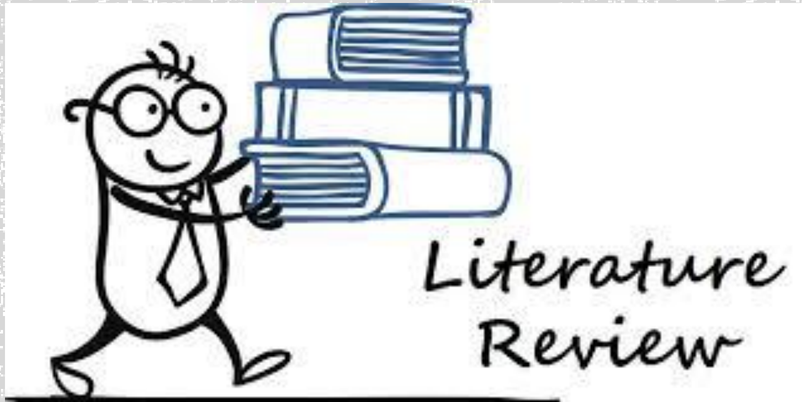
# DE materials

- FRP bars
  - CFRP
  - GFRP
  - AFRP

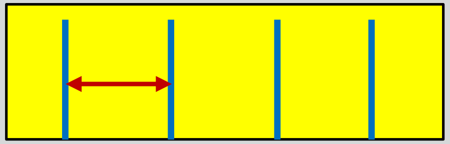
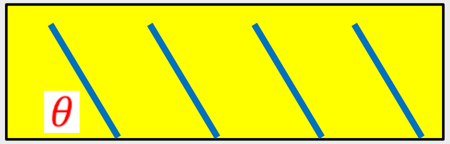
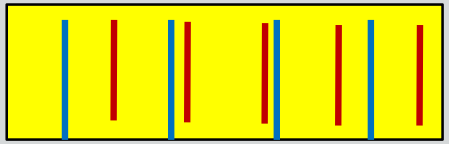
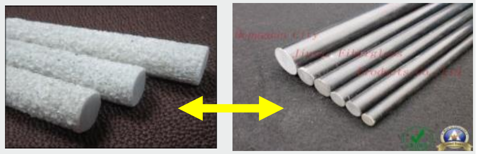
- Steel



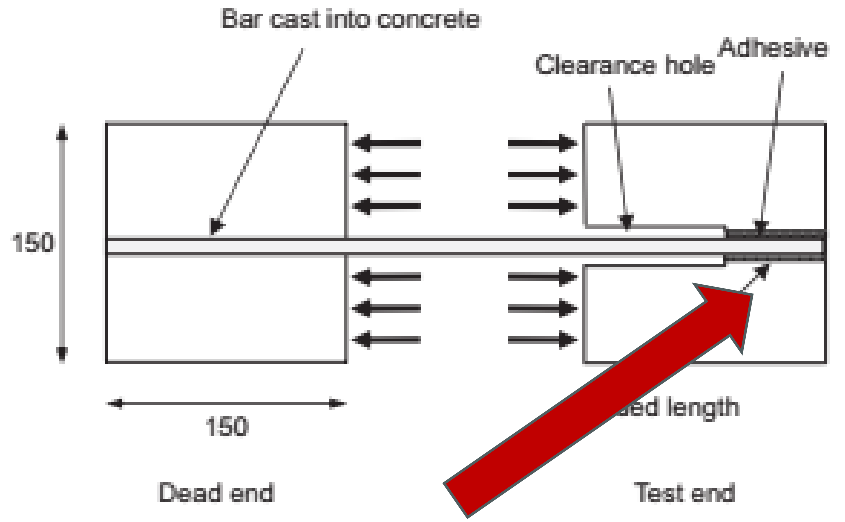
8 Past investigations



# Influencing DE parameters

| Parameter | | Influence | Investigators |
|---|---|---|---|
| Bar spacing |  | wider spacing is less effective | *Mofidi et al. (2012)* |
| Bar inclination |  | inclined bars are more effective | *Baros et al. (2012)* |
| Interaction with internal shear reinforcement |  | higher the internal shear r/f density, lower is the DE effectiveness | *Mofidi et al. (2012)* |
| Bar surface texture |  | plain surface is more effective than sand coated surface | *Mofidi et al. (2012)* |
| Bond | | | |

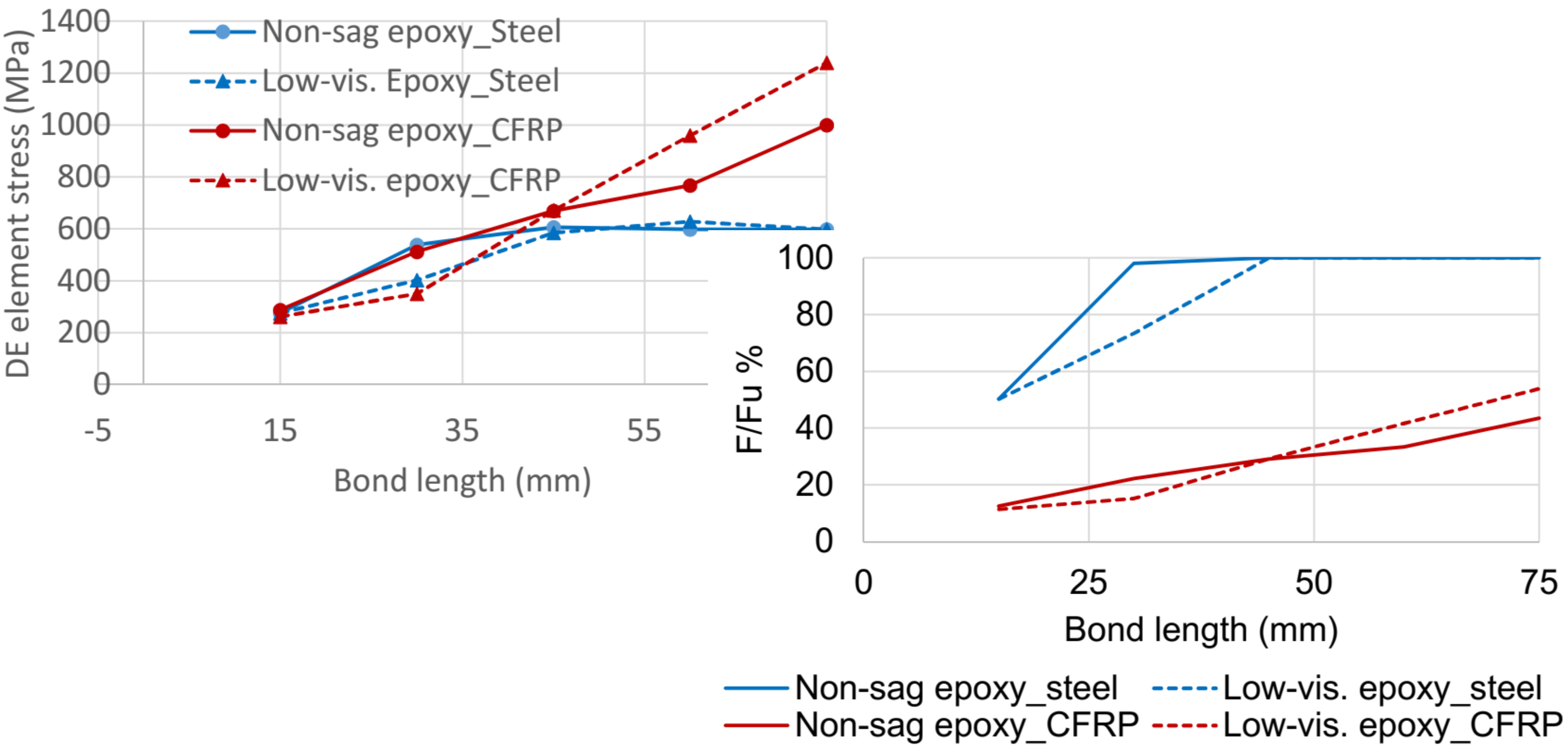
# Bond



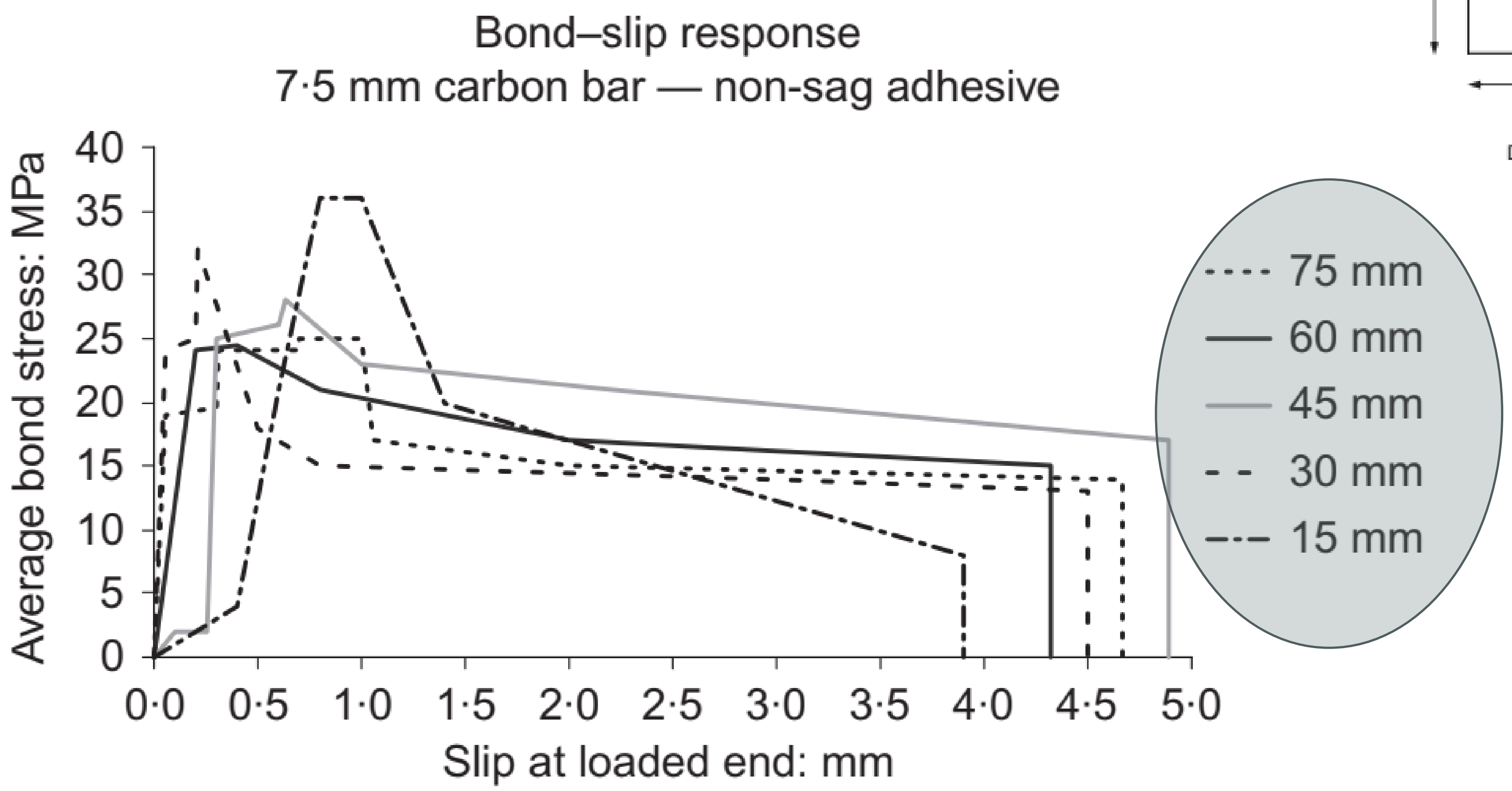

| Bar type | Average bond strength (MPa) – failure mode | | | | |
|---|---|---|---|---|---|
| | 15 mm | 30 mm | 45 mm | 60 mm | 75 mm |
| | | | Non-sag epoxy (Hilti 500[19]) | | |
| Steel 8 | 37-SR | 36-BY | 27-BY | 20-BY | 16-BY |
| Carbon 7·5 | 36-IS | 32-IS | 28-IS | 24-IS | 25-IS |
| Carbon 6 | 33-IS | 30-IS | 27-IS | 23-IS | 21-IS |
| Glass 9 | 25-IS | 27-IS | 24-IS | 20-IS | 16-BR |
| Aramid 7·5 | 17-IS | 14-IS | 10-IS | 07-IS | 07-IS |
| | | | Low-viscosity epoxy (Araldite[17]) | | |
| Steel 8 | 37-SR | 27-SR | 26-BY | 21-BY | 16-BY |
| Carbon 7·5 | 33-IS | 22-IS | 28-IS | 30-IS | 31-IS |
| Glass 9 | 36-IS | 4-IS | 27-IS | 22-IS | 25-BR |
| Aramid 7·5 | 26-IS | 20-IS | 18-IS | 17-IS | 13-IS |
| | | | Medium strength paste (Hilti 150[20]) | | |
| Steel 8 | 10-SR | 17-SR | 26-BY | 21-BY | 16-BY |
| Carbon 7·5 | 17-IS | 17-IS | 16-IS | 19-IS | 19-IS |
| Glass 9 | 16-IS | 16-IS | 17-IS | 17-IS | 17-IS |
| Aramid 7·5 | 07-IS | 06-IS | 08-IS | 08-IS | 05-IS |

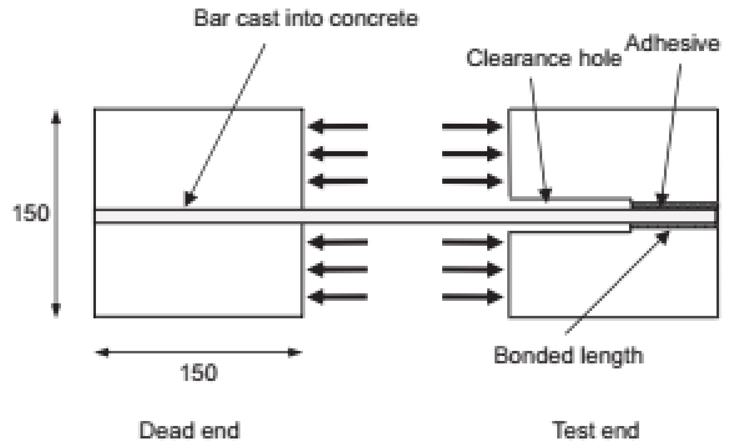
*Valerio et al. (2009)*

# Steel 8 mm vs. CFRP 7.5 mm



# Bond-slip behaviour



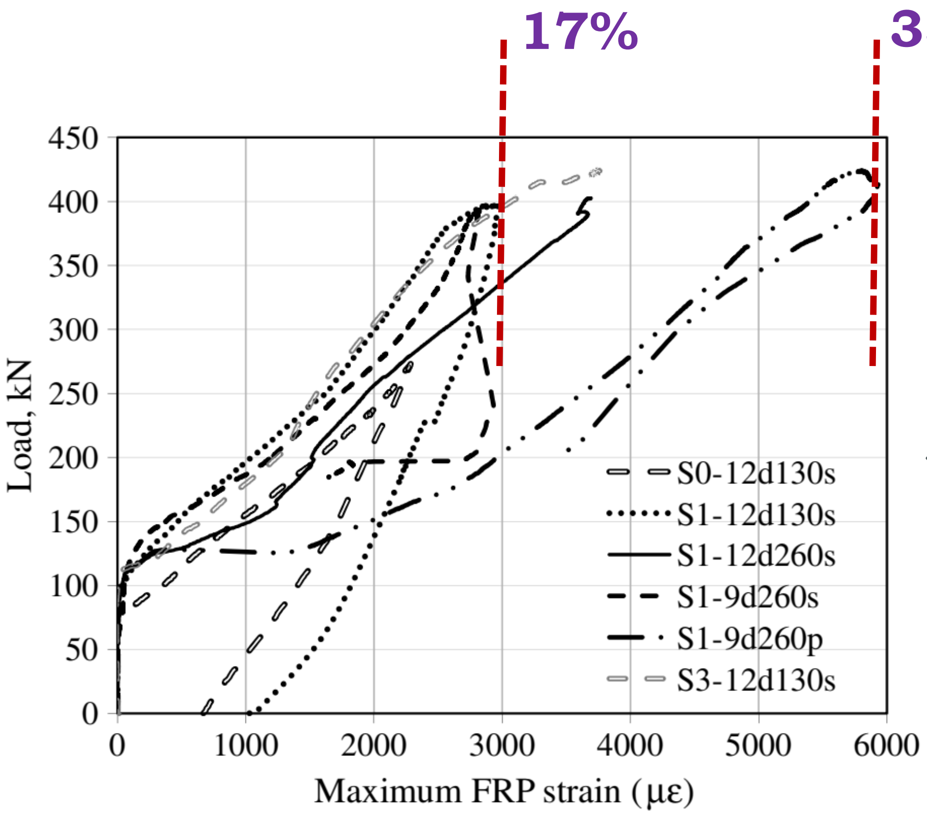



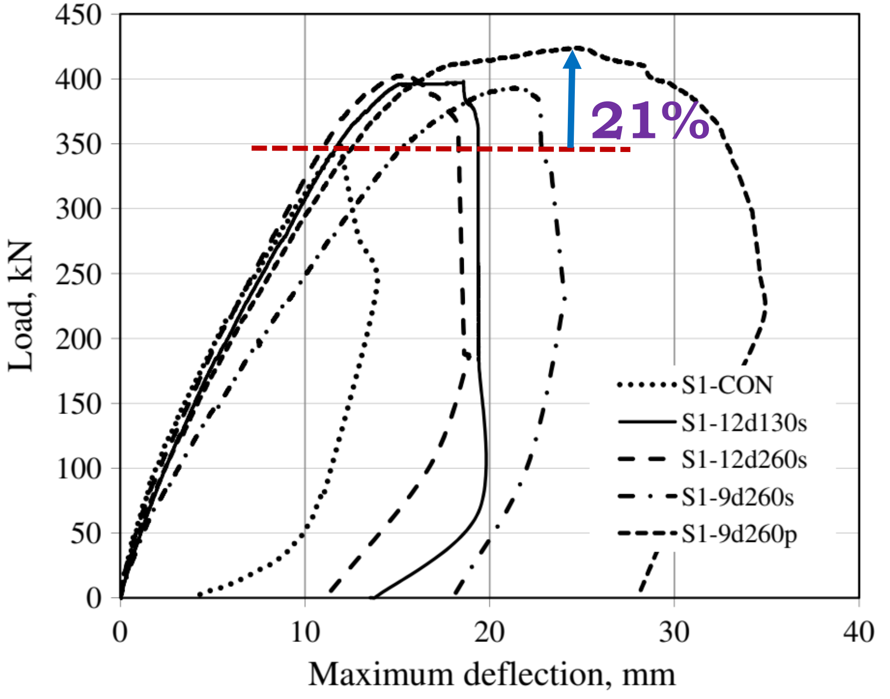

*Valerio et al. (2009)*

# Shear enhancement

| Investigation | Remarks | Shear enhancement |
|---|---|---|
| Valerio and Ibell (2003) | 10 beams retrofitted with AFRP and steel | 85% (up to flexure failure) |
| Mofidi et al. (2012) | Large scale T beams | 45% |
| Raicic et al. (2017) | Continuous T beams | 70% |
| Dirar and Theofanous (2017) | Large scale: Deep beams | 33% |
| | Shallow beams | 96% |

# DE element contribution?

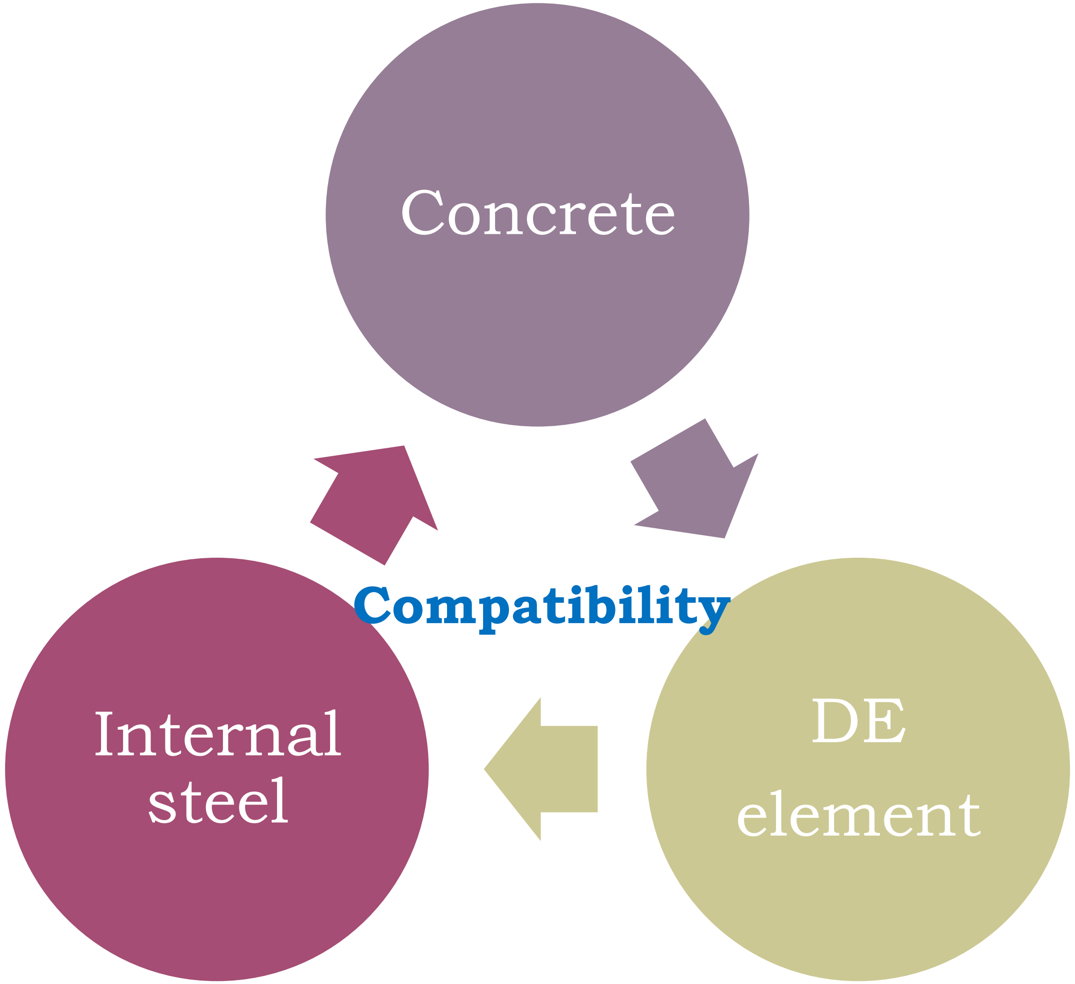


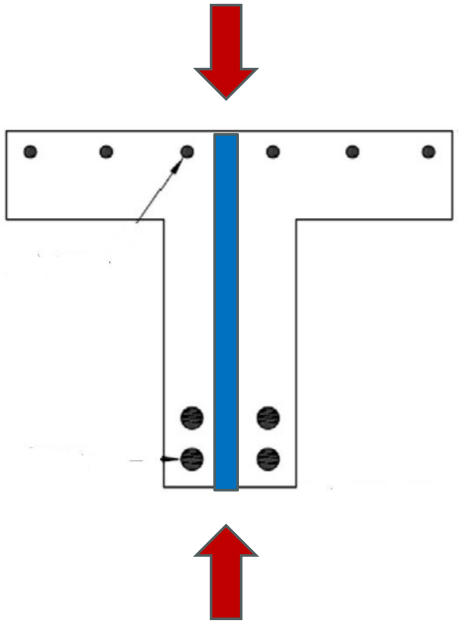

Mofidi et al. (2012)

# Efficiency?

| Material | Strain capacity ($10^{-6}$) |
|---|---|
| CFRP | 18000 |
| AFRP | 25000 |
| GFRP | |
| Prestressing steel | 10000 |



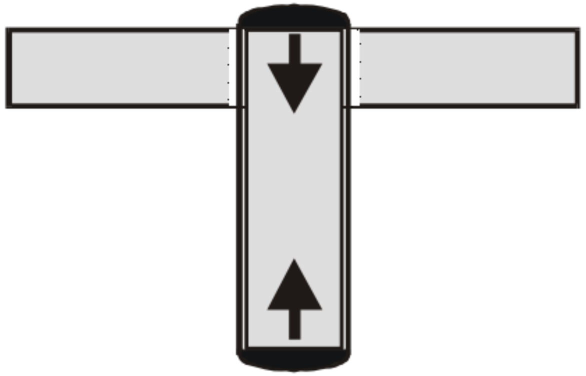
# How would it be if the DE bar is PRESTRESSED?



# Experience of prestressed shear retrofitting

## Work by:

- Lees et al. (2002)
- Kesse and Lees (2007)
- Hould and Lees (2009)
- Dirar et al. (2012)
- Yapa and Lees (2014)
- Etc.



CFRP strap system

Prestress application was impressive in terms of:

- ✓ Shear enhancement
- ✓ Serviceability performance
- ✓ Material usage
- ✓ Etc.

# Initial objective

*Assess the potential of application of prestress to the DE shear retrofitting system*

Options

- via experiments
- via predictions

# Initial objective

*Assess the potential of application of prestress to the DE shear retrofitting system*

Options

via experiments

via predictions

20

# Prediction of DE behaviour

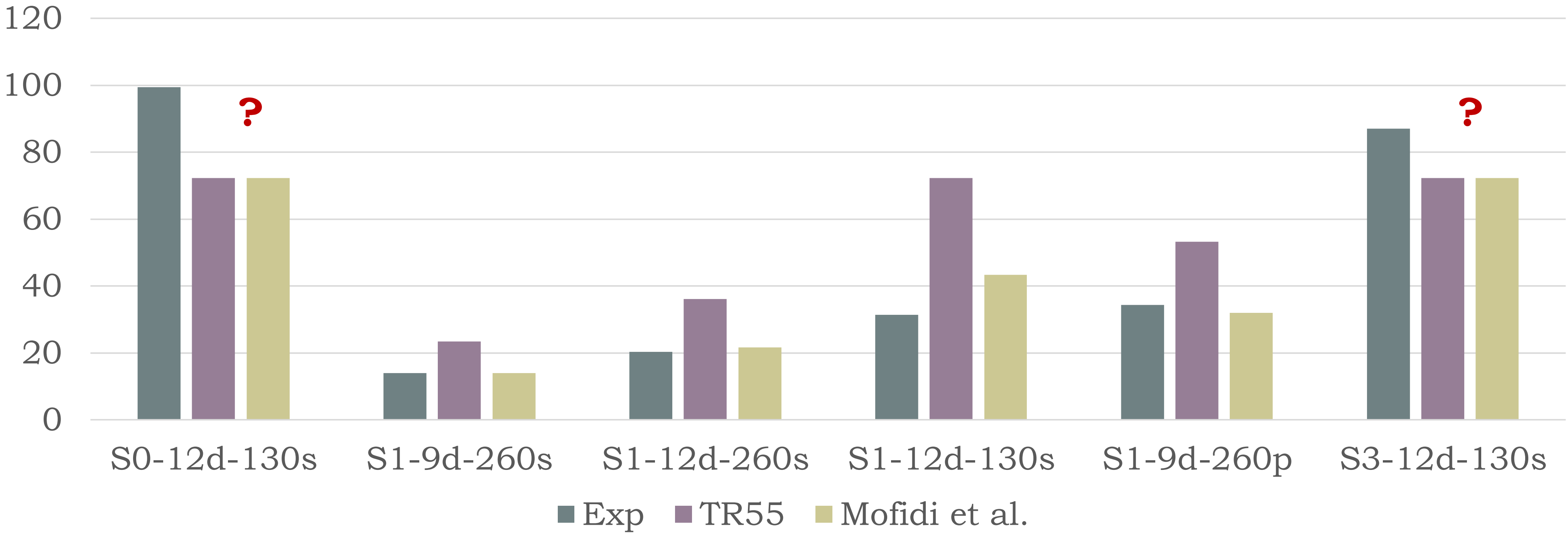
# Technical Report 55 (TR 55)

$$V_f = \frac{\varepsilon_{fse} E_{fd} A_f (cos\alpha + sin\alpha)}{s_b} d_{eff}$$


*Mofidi et al. (2012)*

# Technical Report 55 (TR 55)

$$V_f = \frac{\varepsilon_{fse} E_{fd} A_f (cos\alpha + sin\alpha)}{s_b} d_{eff} \quad \Rightarrow \quad V_f = \frac{k_L\, k_s \varepsilon_{frp} E_{fd} A_f (cos\alpha + sin\alpha)}{s_b} d_{eff}$$

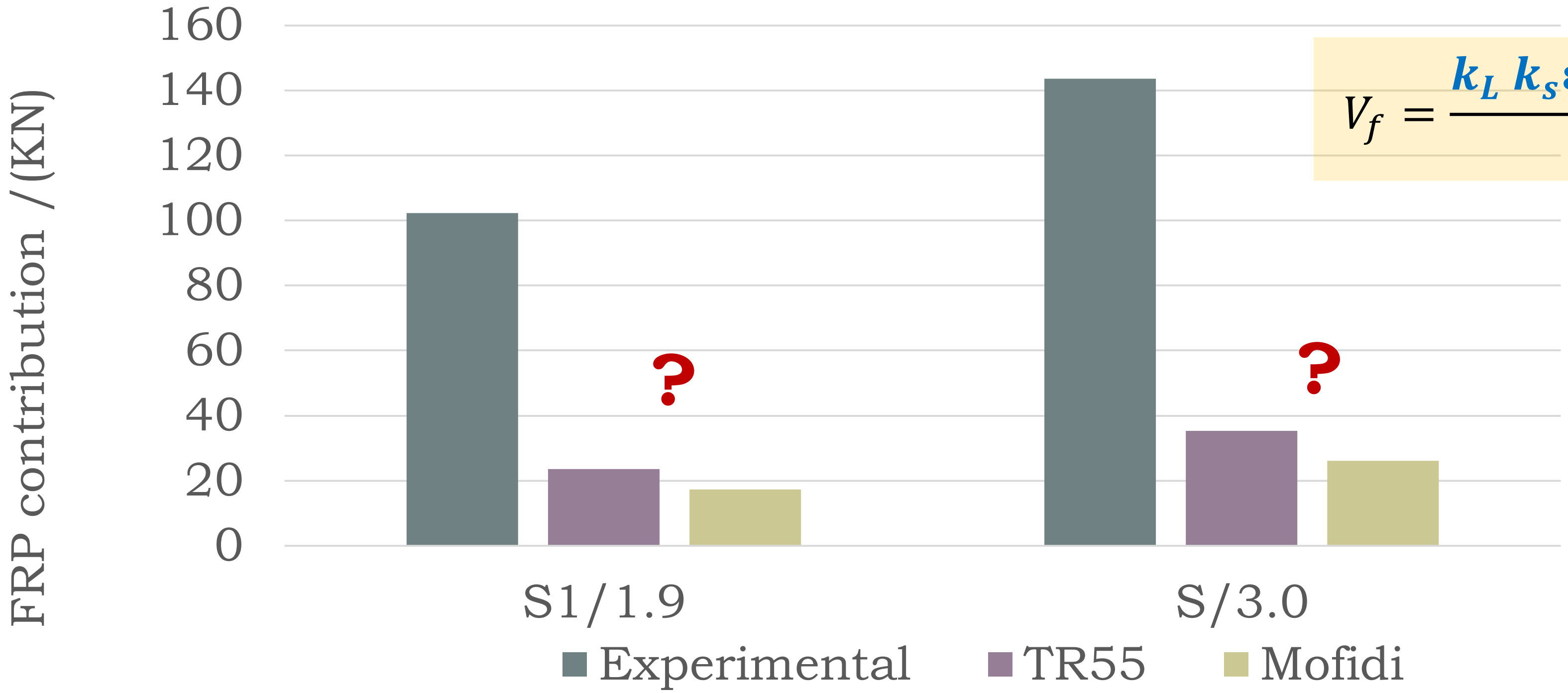



*Mofidi et al. (2012)*

## *"Large-scale Reinforced Concrete T-beams Strengthened in Shear with Embedded GFRP Bars"*, (Dirar and Theofanous, 2017)

$$V_f = \frac{\varepsilon_{fse} E_{fd} A_f (cos\alpha + sin\alpha)}{s_b} d_{eff}$$

$$V_f = \frac{\boldsymbol{k_L}\ \boldsymbol{k_s \varepsilon_{frp}} E_{fd} A_f (cos\alpha + sin\alpha)}{s_b} d_{eff}$$



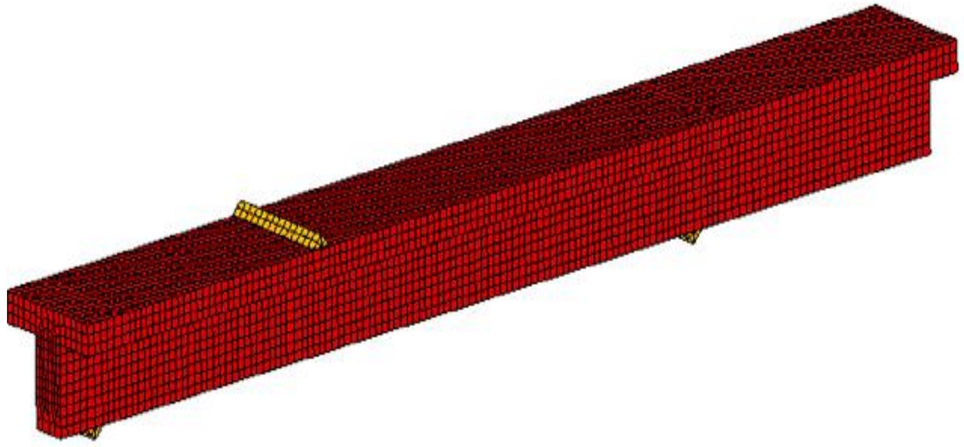
# Numerical Modelling

Qapo et al. (2016) developed

3D Finite Element Model for:

- Valerio and Ibell (2003)
- Mofidi et al. (2012)
- Qin et al. (2014)

experiments



| Geometry | Element Model |
|---|---|
| Concrete | 3D Isoparametric<br>8 Node<br>Solid Brick |
| Steel Plate | 3D Isoparametric<br>6 Node<br>Solid Wedge |
| Longitudinal & Stirrups | Truss like Elements |
| FRP | 3D Truss like<br>2 Node |

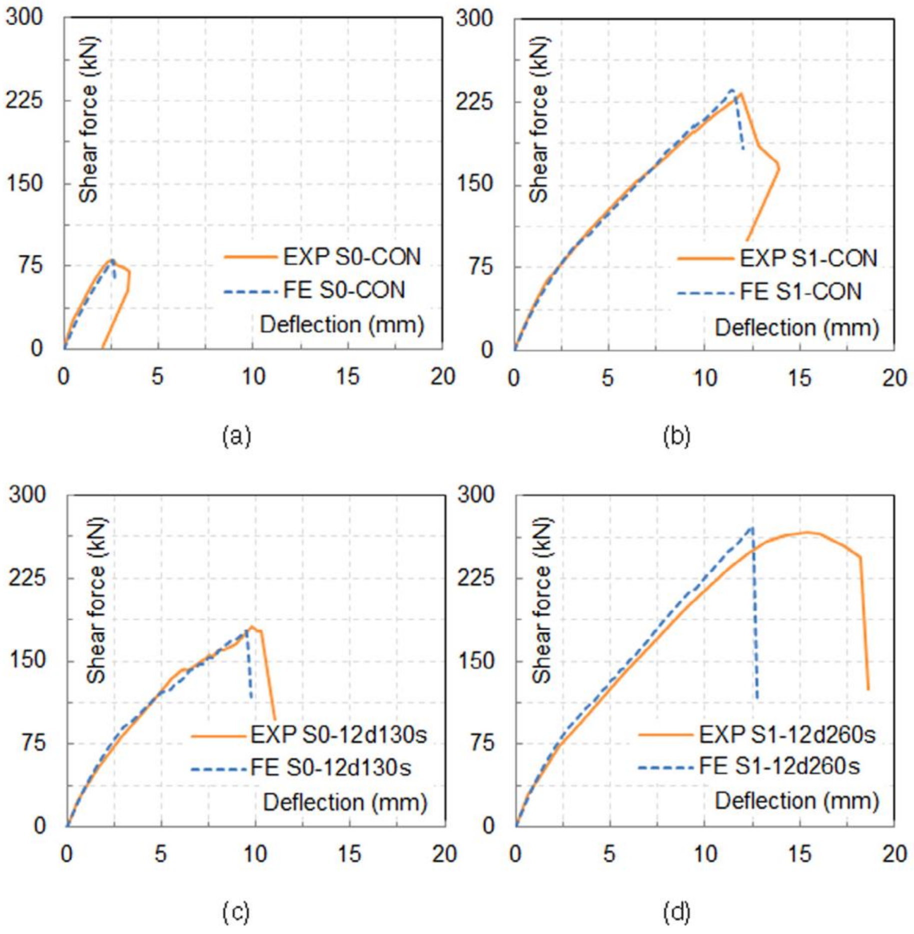
| **Concrete** | **Total Strain Crack (Smeared Rotating)** |
|---|---|
| Compression & Softening | Thorenfeldt – Vecchio Collins |
| Tension Softening | Linear |
| Shear | **Explicit model was not required** |

| Steel Stirrup & Plates | Elastic-Perfectly Plastic Stress-Strain Model |
|---|---|
| FRP Bars | Linear – Brittle Stress- Strain Model |

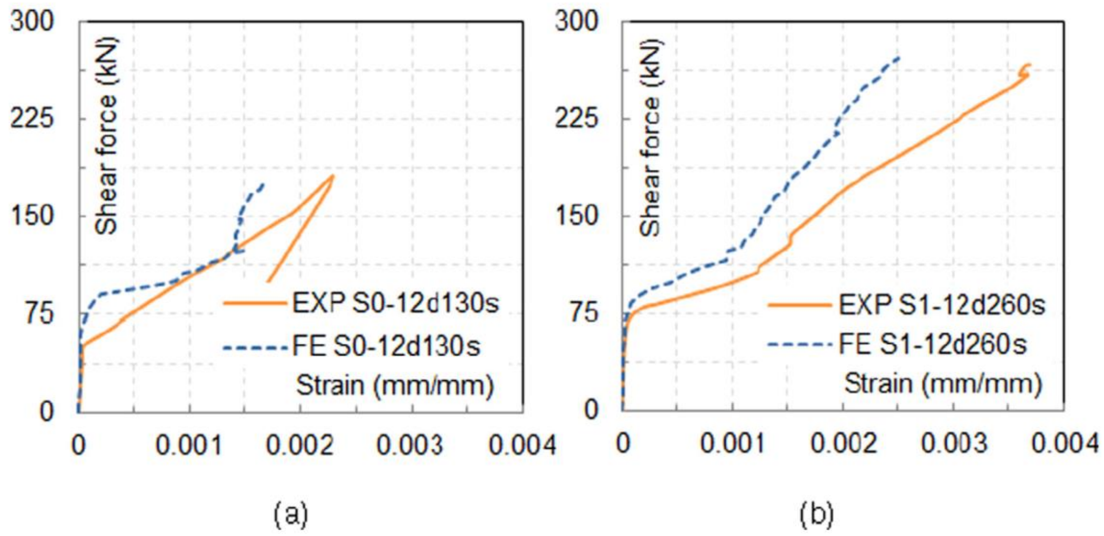
| **Interface** | **Model** |
|---|---|
| Steel Stirrup - Concrete | Perfect Bond |
| FRP - Concrete | 4 Node 3D Interface Elements<br>BPE Bond-Slip Model |

# Qapo et al.'s results

## Load-displacement behaviour

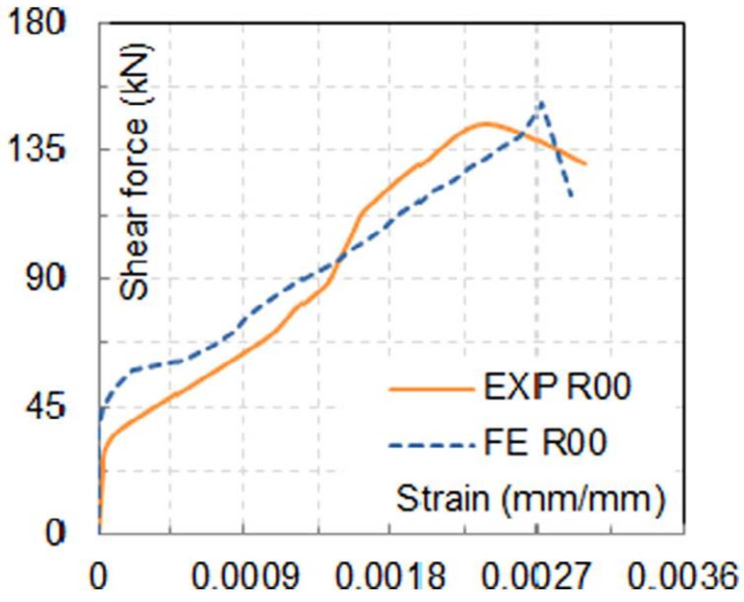


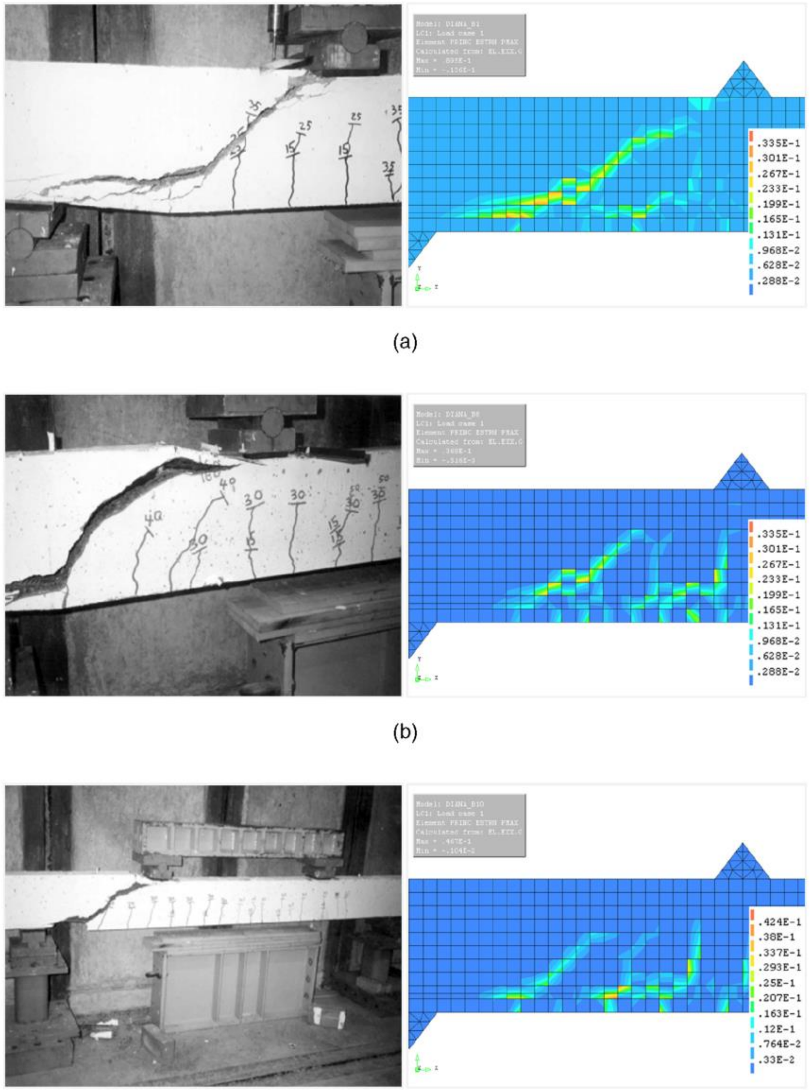

## DE strains



# Qapo et al.'s results

Shear link strains



(a)

(b)

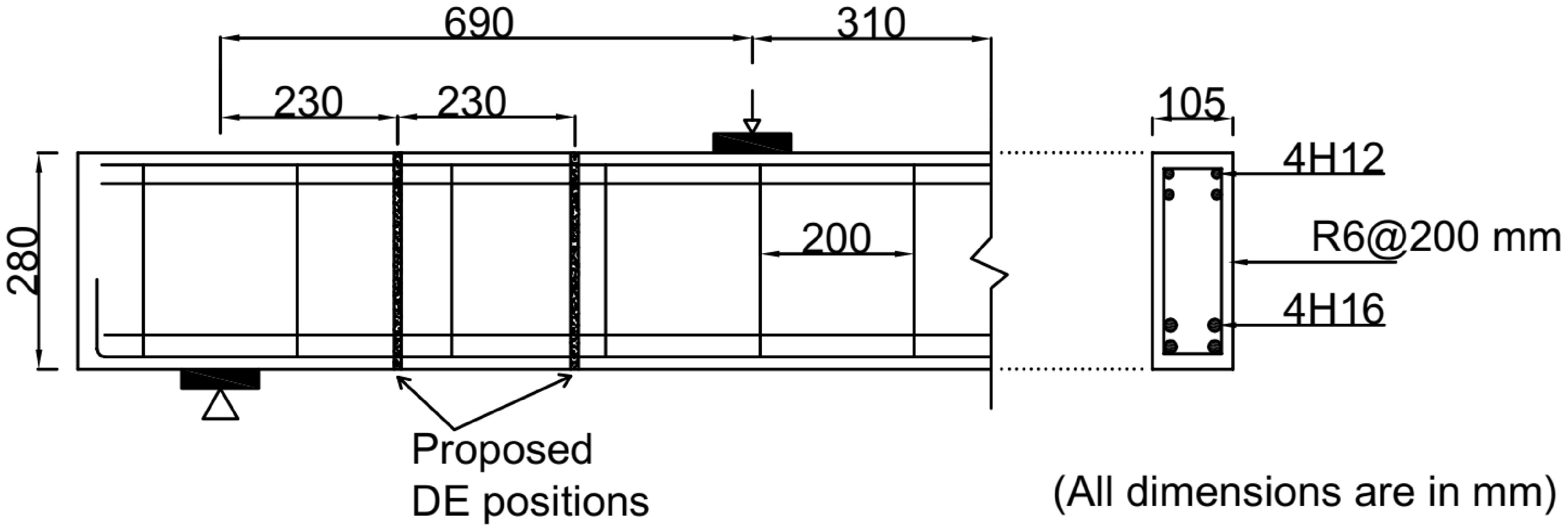
# Objective and scope

*Assess the potential of application of prestress to the DE shear retrofitting system via numerical analysis*

29

# Numerical investigation

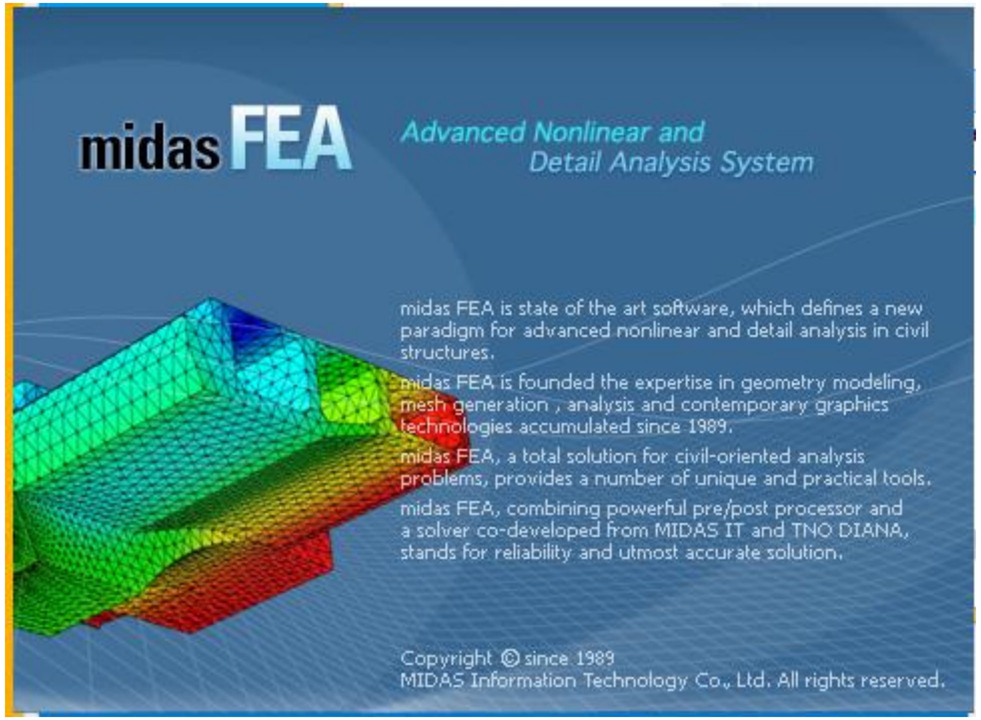
# Geometrical parameters



# Material parameters

| | | | |
|---|---|---|---|
| Concrete | C32/40 | | |
| Steel | Tensile | H16 | fy = 500 MPa |
| | Compression | H12 | fy = 500 MPa |
| | Shear | R6 | fy = 250 MPa |
| DE | CFRP | 7.5 mm | fy = 2000 MPa |
| | | | E = 120 GPa |

# MIDAS FEA

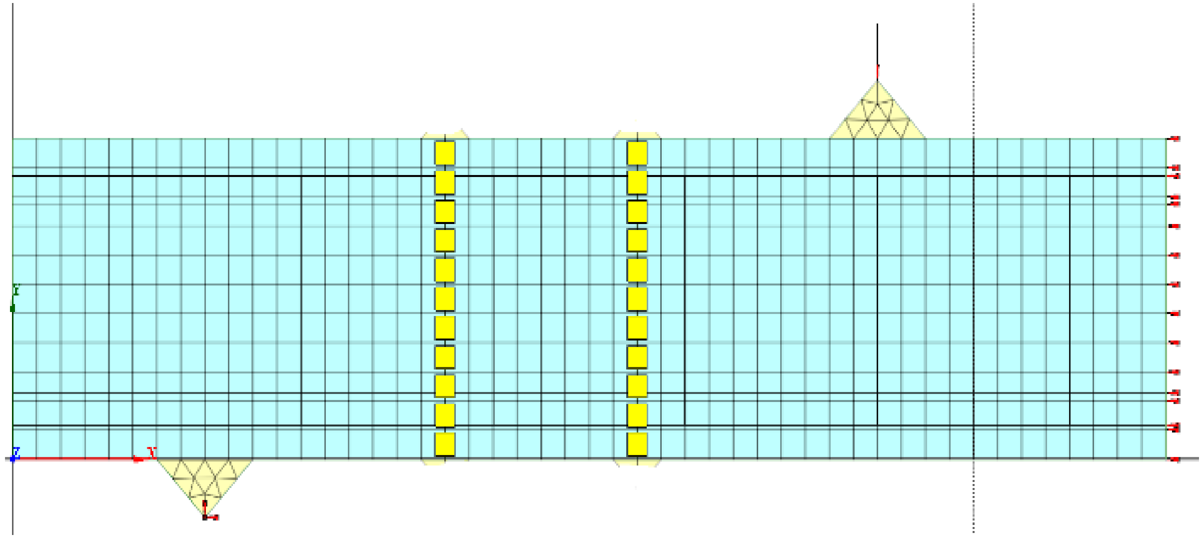



**Attributes**

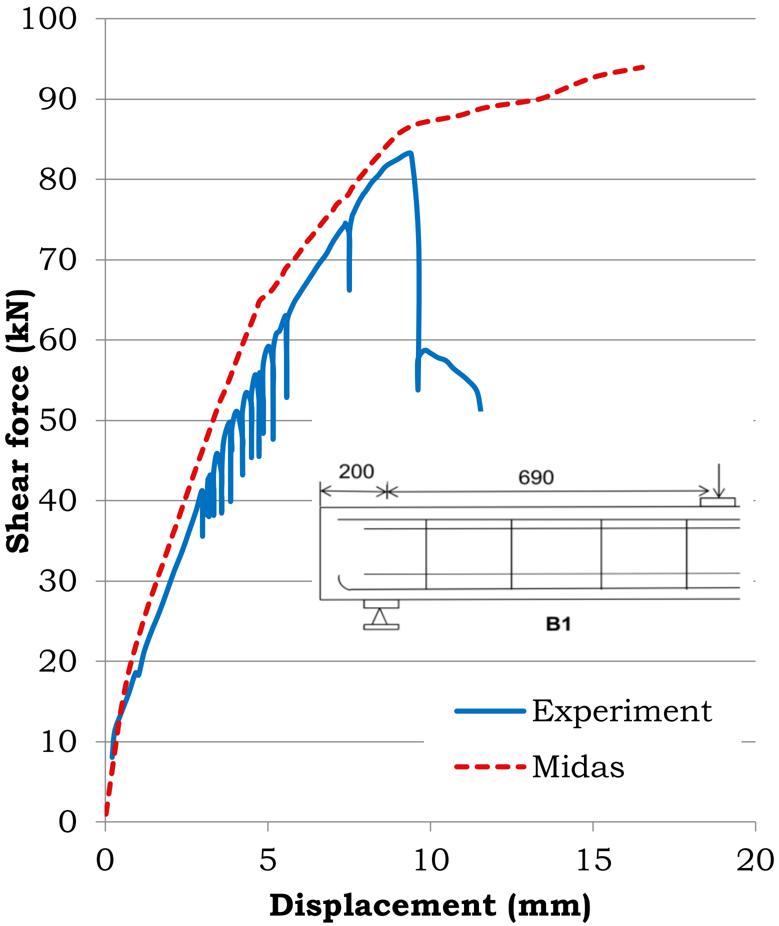
- Non-linear modelling
- Total strain crack model
- Construction stage analysis
- Bonded reinforcement element
- Availability of latest material models

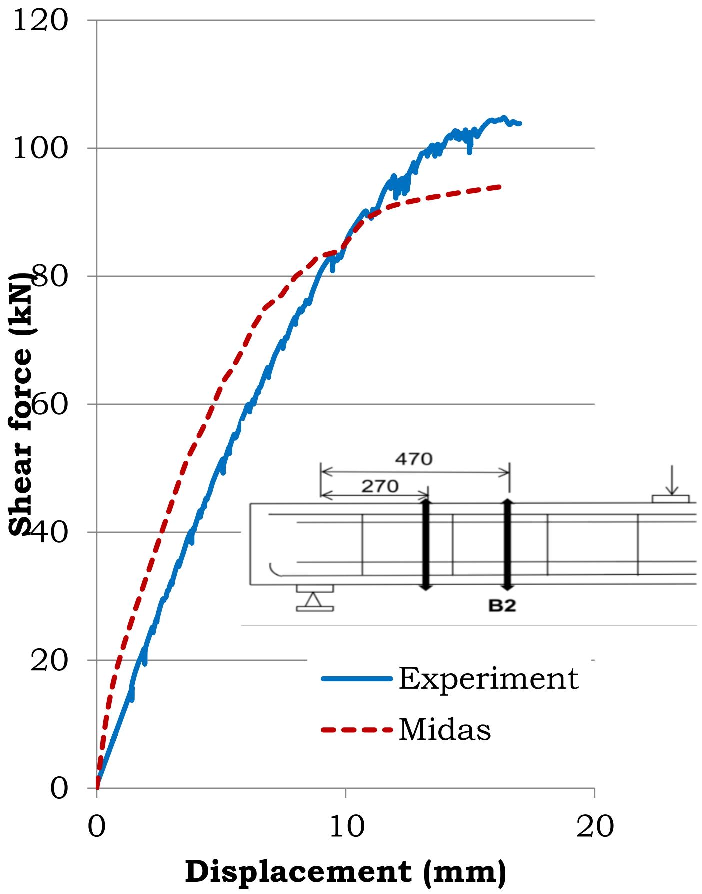
# Mesh parameters

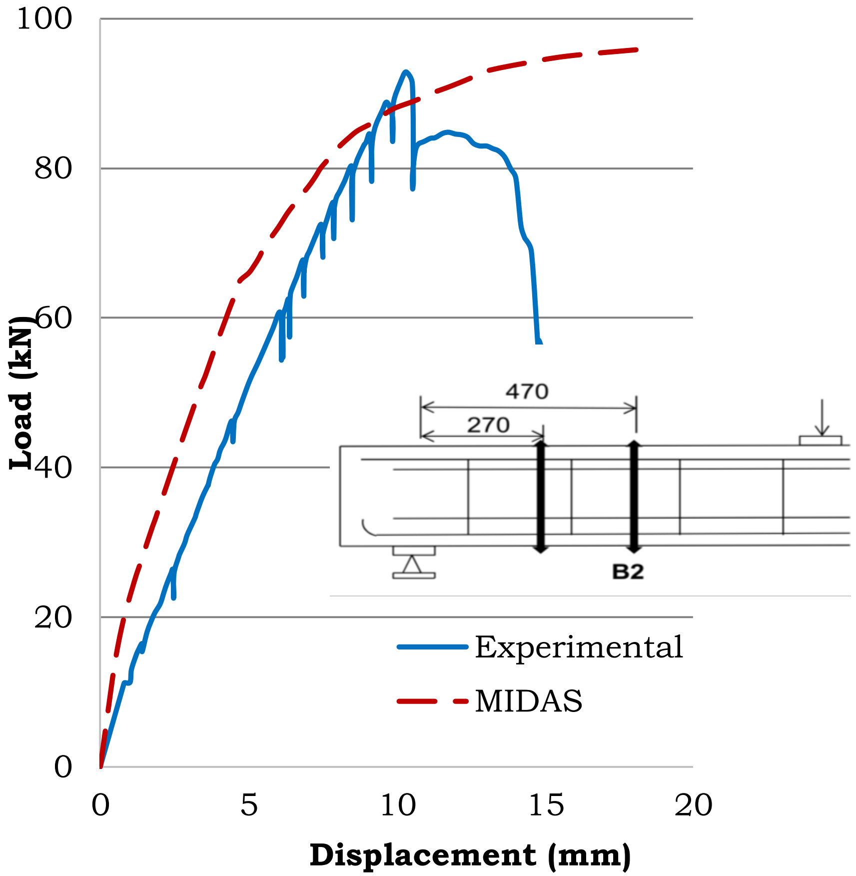
- Beams
  - 2D isotropic plane-stress elements
  - Element size: 25 mm square
- Steel bearing plates
  - Triangular plane- stress elements
  - Elastic
- Reinforcement
  - Embedded 1D elements
- CFRP DE bars
  - 1D isotropic truss elements
- Bond - rigid



# Model validation (by Kurukulasuriya et al. 2017)



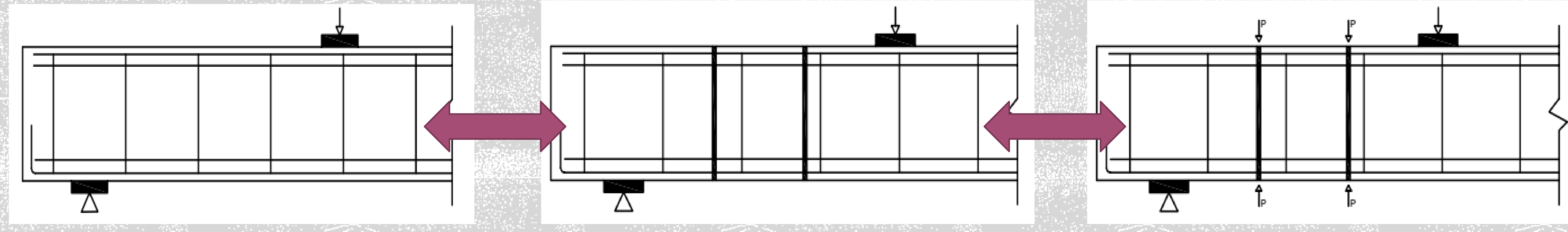



# Material model selection

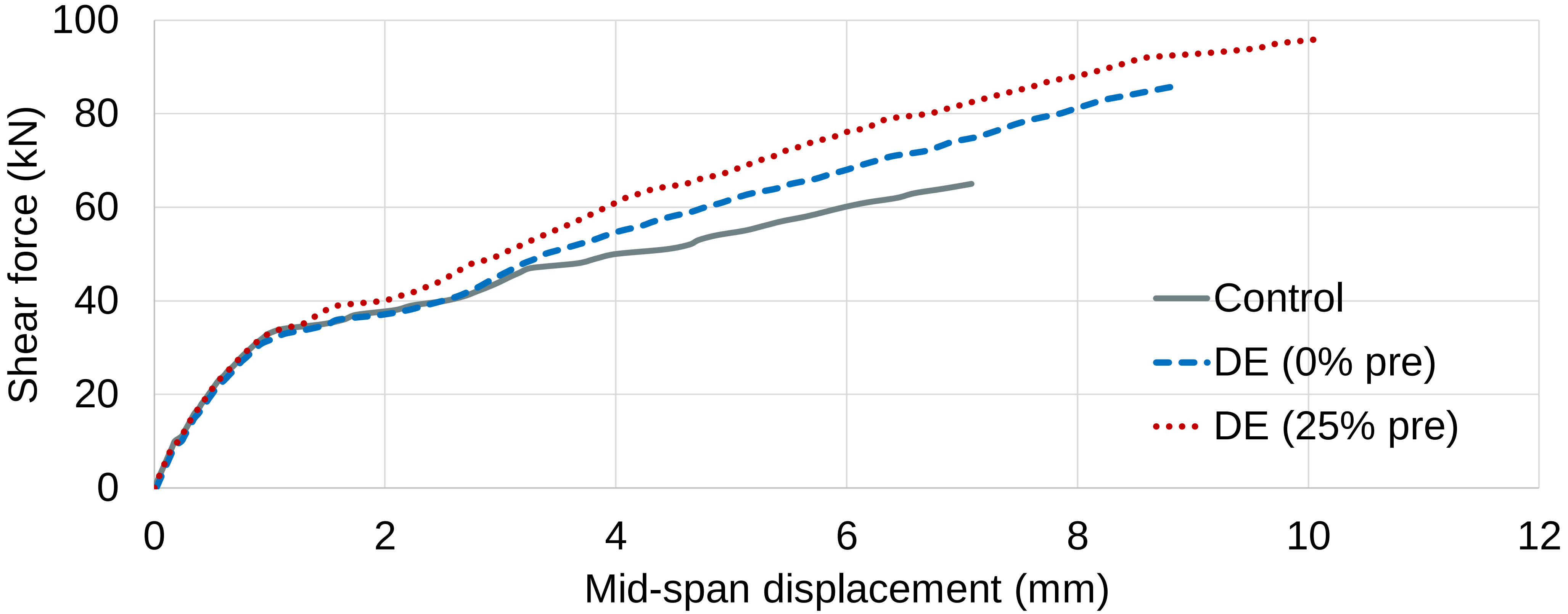
- Concrete compression: Thorenfeldt
- Concrete tension: Exponential
- Concrete crack model: Total strain crack model – fixed
- Shear model: Constant shear retention ($\beta = 0.1$)
- Steel reinforcement - Von Mises yield criterion
- CFRP DE bar – linear

# FE simulation results

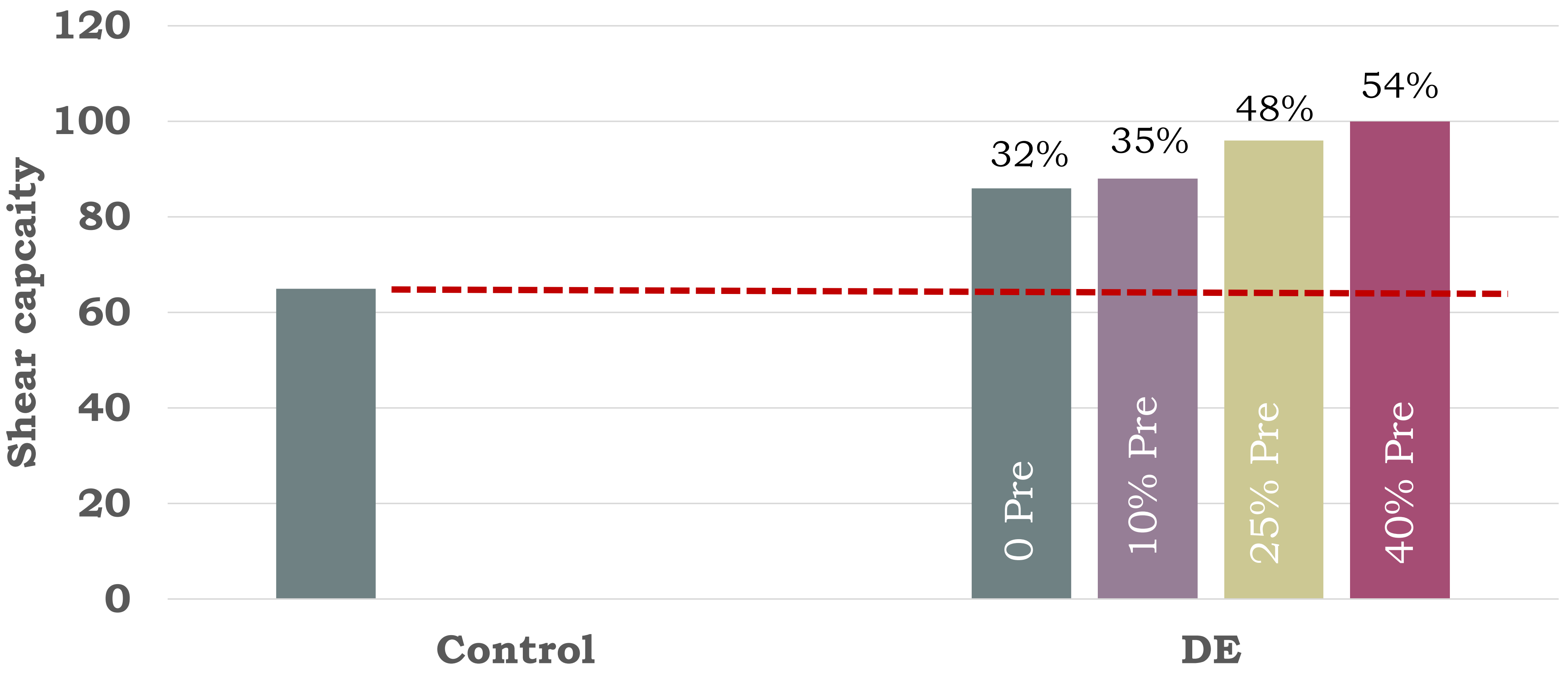




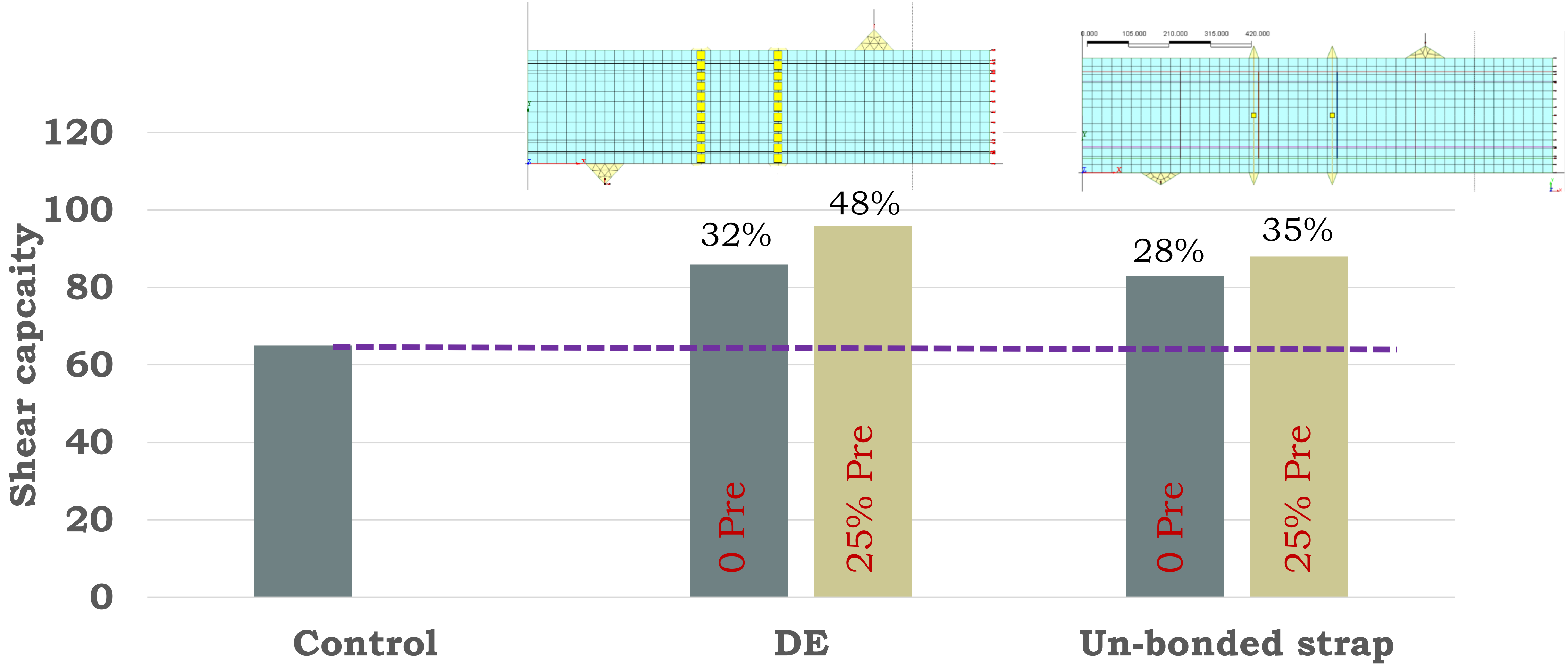
# Load-displacement profile



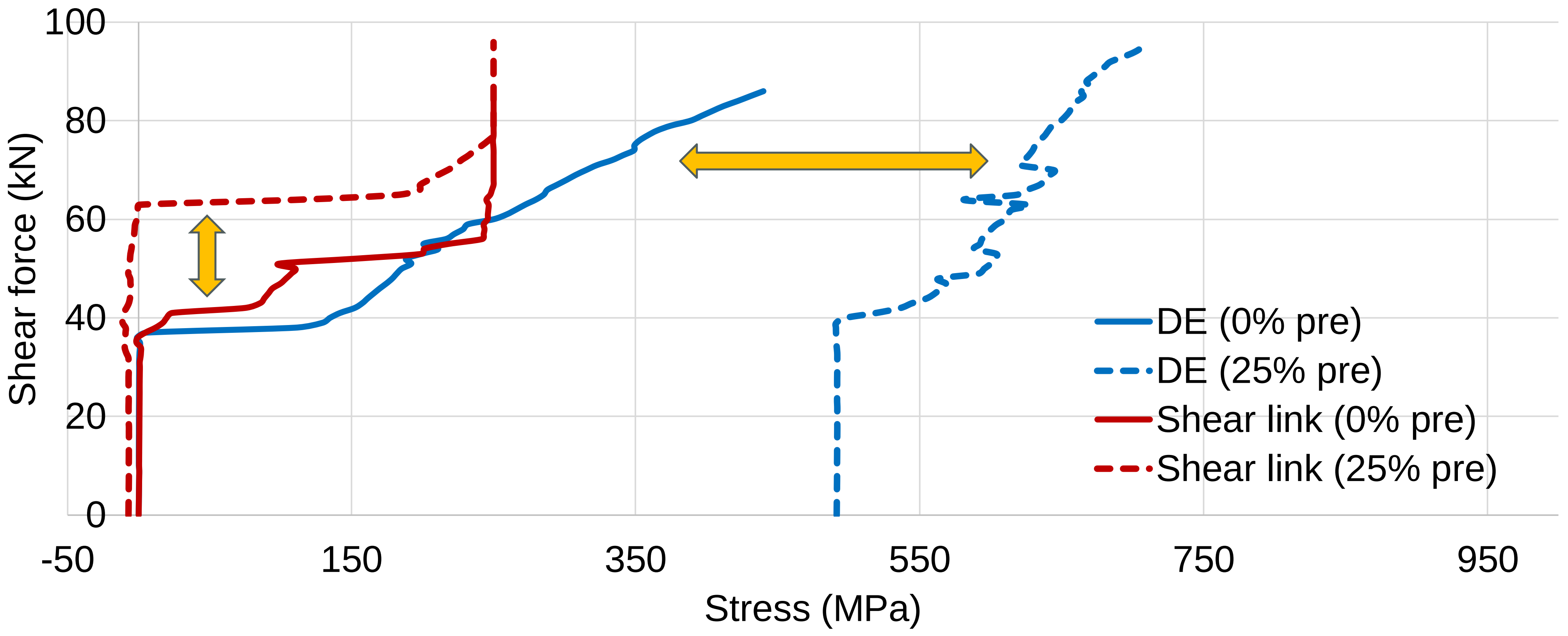
# Shear Capacity



# Comparison with the strap system

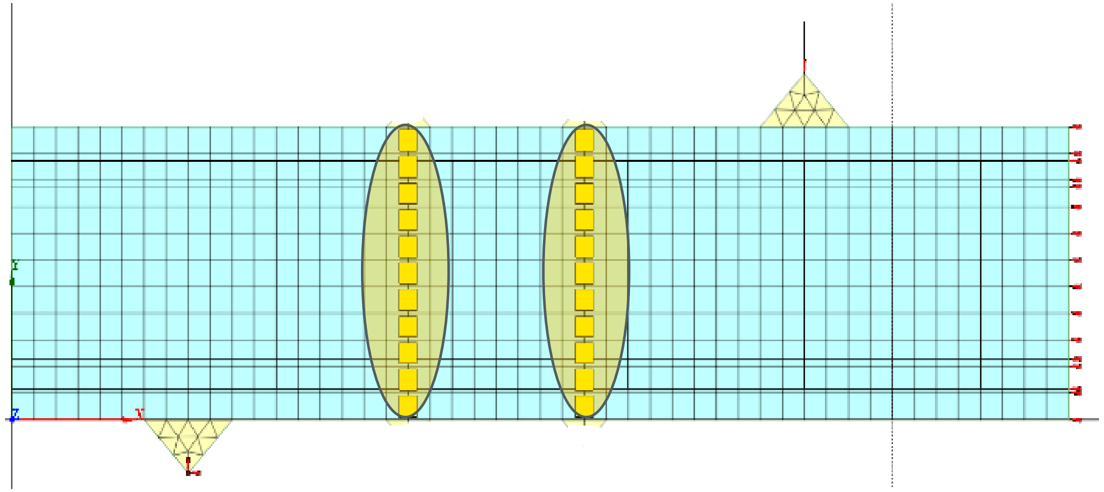


# DE & shear r/f stresses

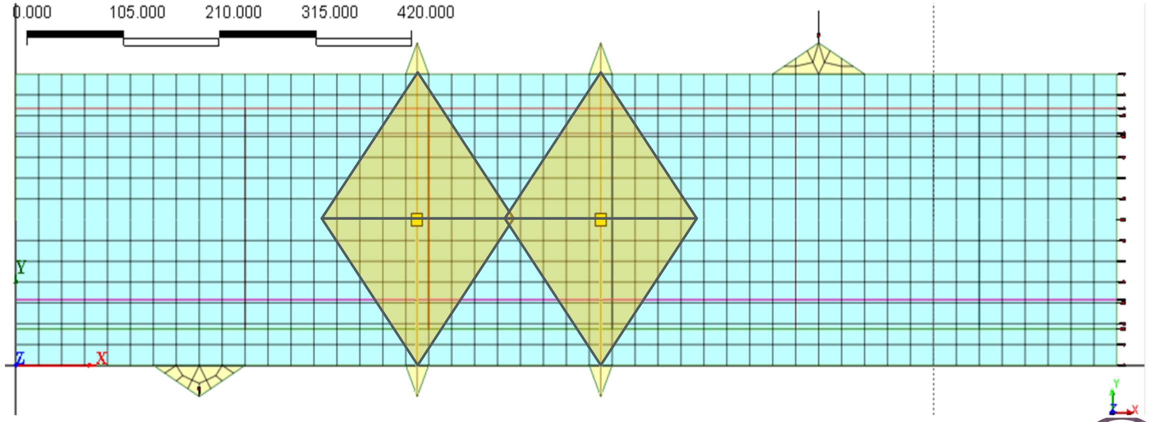


# How does prestress support?

DE



Prestressed CFRP strap

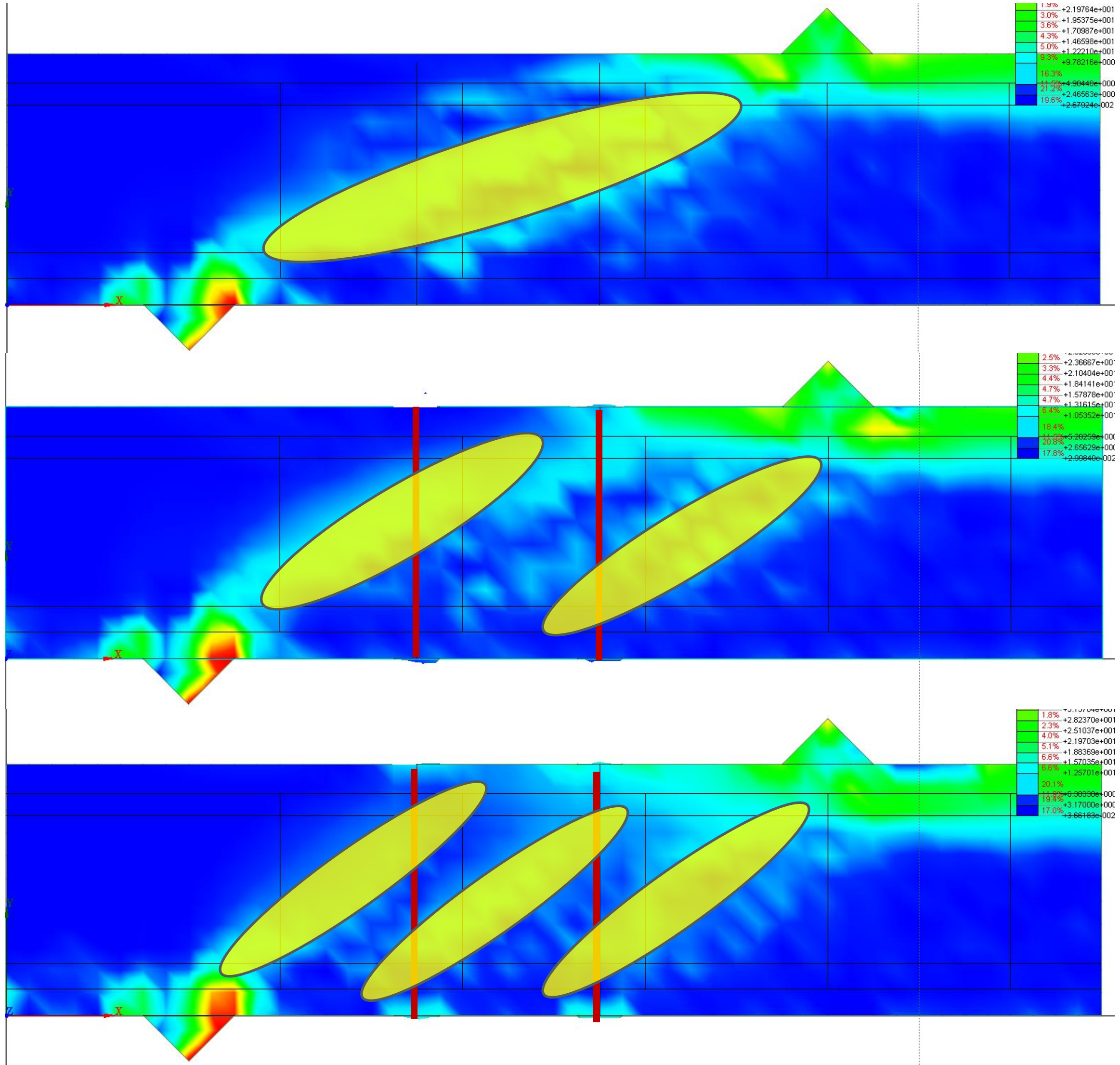


# Cracking…

Control

DE

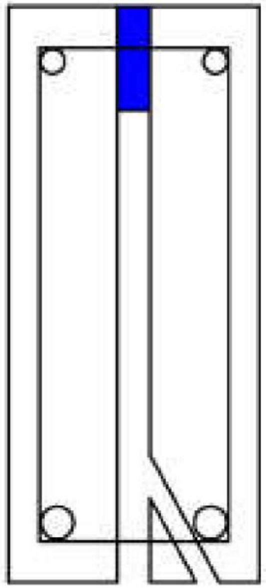
DE + prestress



Crack angle

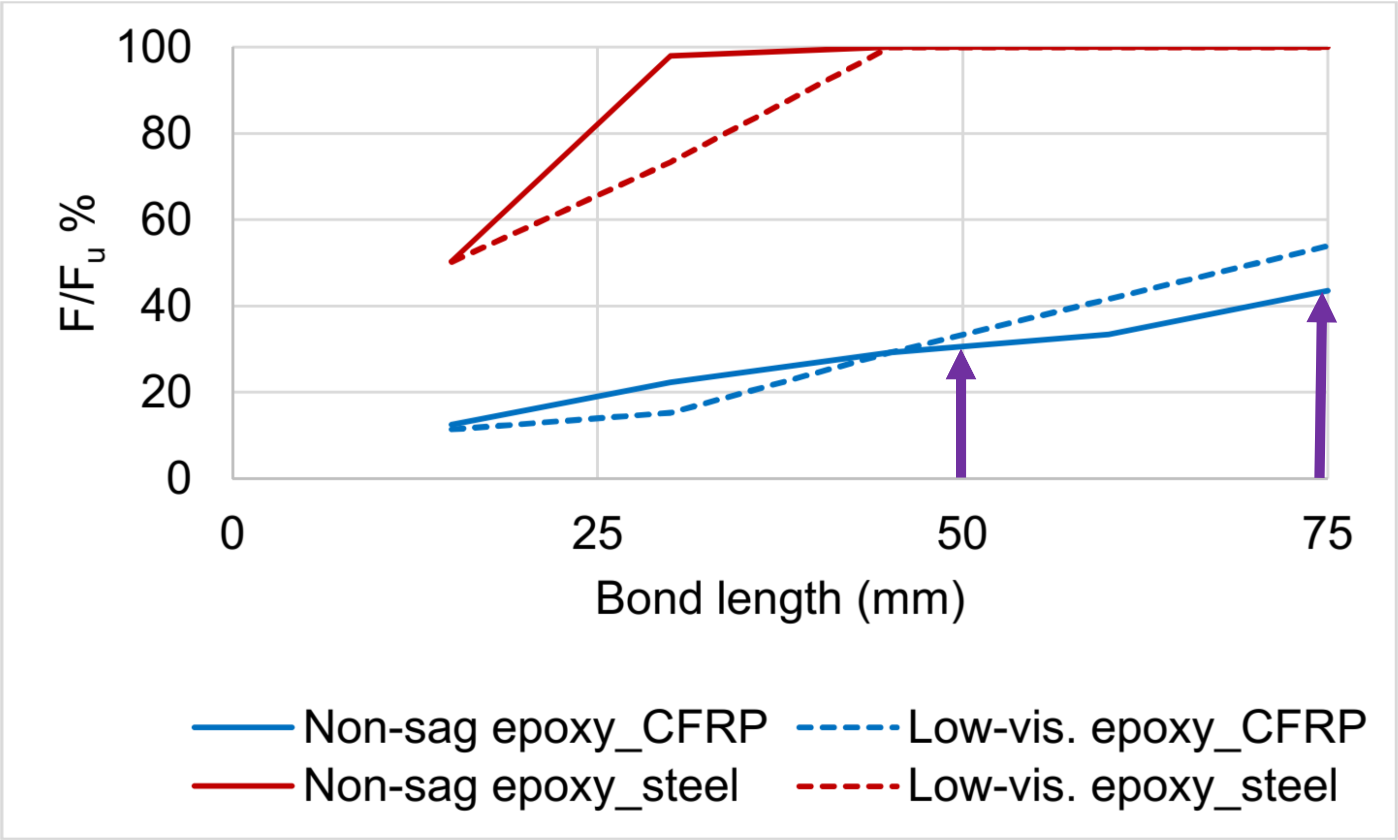
Crack distribution

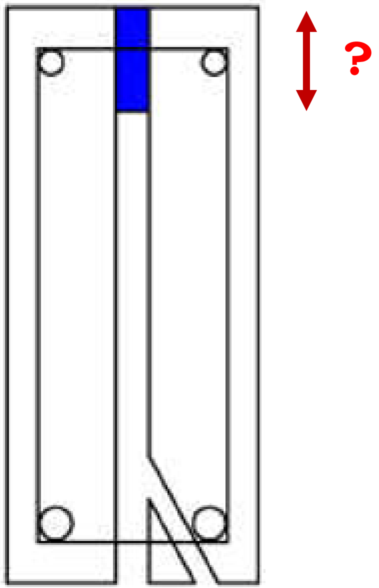
# Prestressed DE system implementation



(a)

# How much bond length?



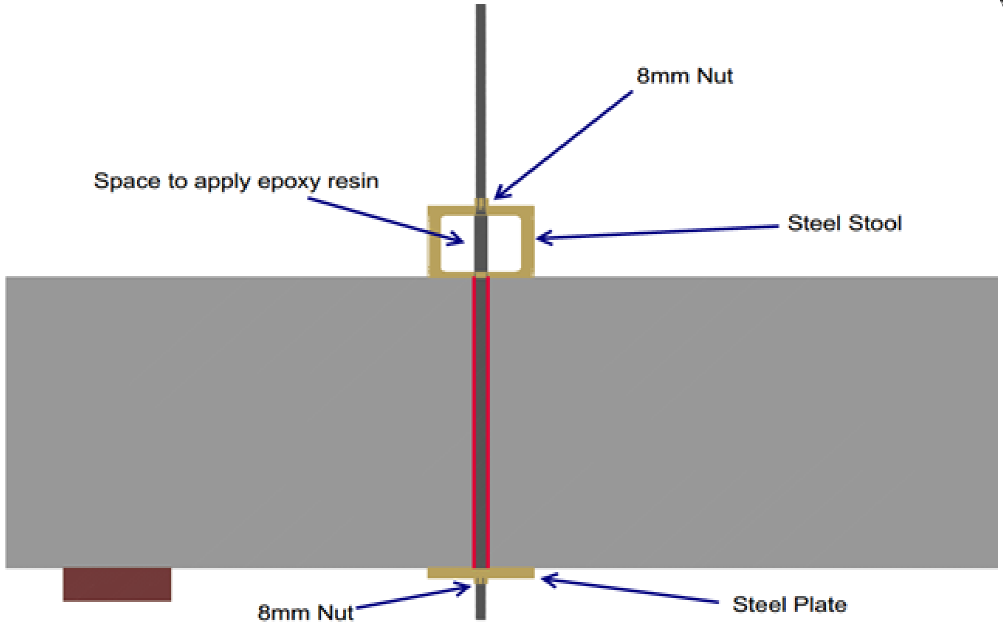
# Conclusions

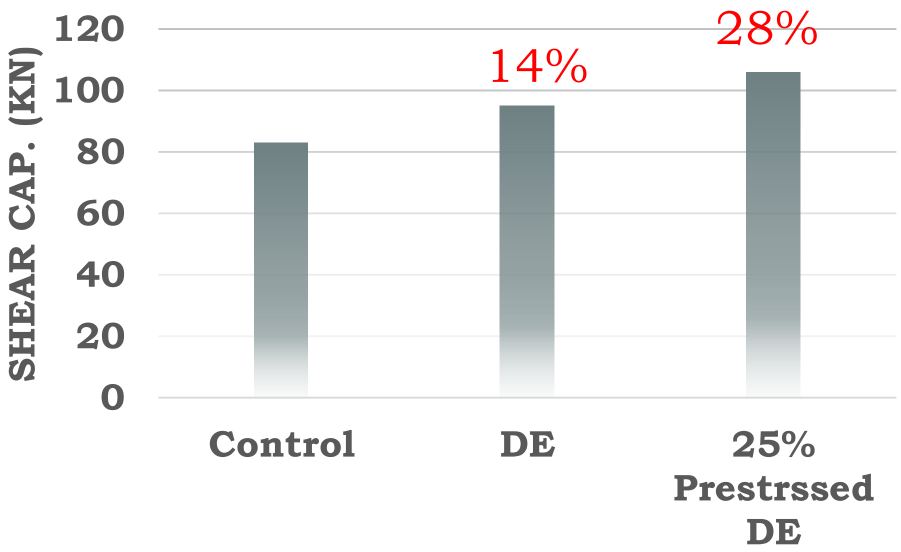
1. The FE simulations show that the prestress application to the DE system was impressive and the load capacity, ductility and stiffness of the retrofitted RC beams were increased
2. The shear enhancement in the DE system could be escalated by 16% and by 22% when the DE element was subjected to 25% and 40% prestress, respectively
3. Considering the requirements on the bond and on the residual capacity of the retrofitting element, 25% prestress was deemed as a recommendable prestress level
4. The CFRP contribution towards the beam load capacity was more efficient in the prestressed beam than in the non-prestressed beam
5. The use of prestress in the DE system resulted also in better serviceability conditions for the beam.

# Challenges and future work

- Prestressing mechanism needs to be explored
- Experimental validation is essential
- Conduct mode precise FE simulations to master the sensitivity of the DE shear retrofitting parameters

# On-going experiment (with steel DE)




# Acknowledgements


- NRC 17-047 grant
- University of Peradeniya
- Co-authors M. Fatheen and S. Ahamed
- M. Bhanugopan

# Thank you!