

Aswan University & Ibaraki University



STRENGTHENING OF REINFORCED CONCRETE STRUCTURES WITH BASALT FRP GRIDS

Dr. Ahmed Monier

STRENGTHENING OF RC STRUCTURES

- **WHY** RC Structures are in need to strengthening?

to upgrade strength & carry higher loads or correct strength loss due to deterioration



Cairo - Egypt



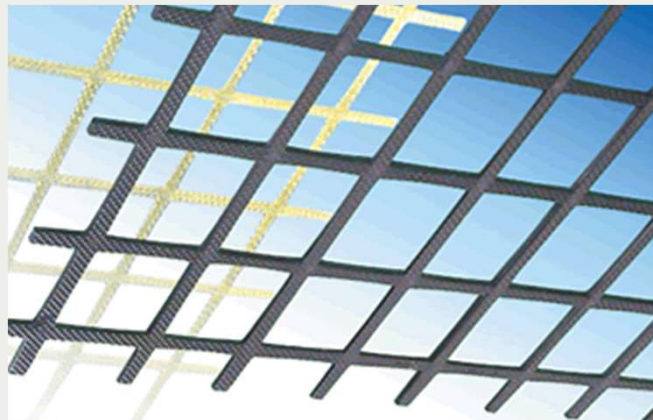
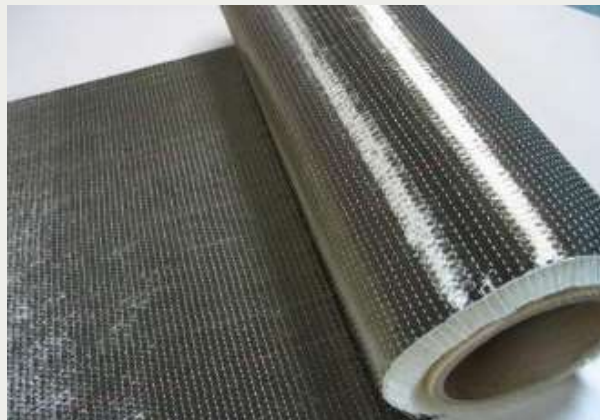
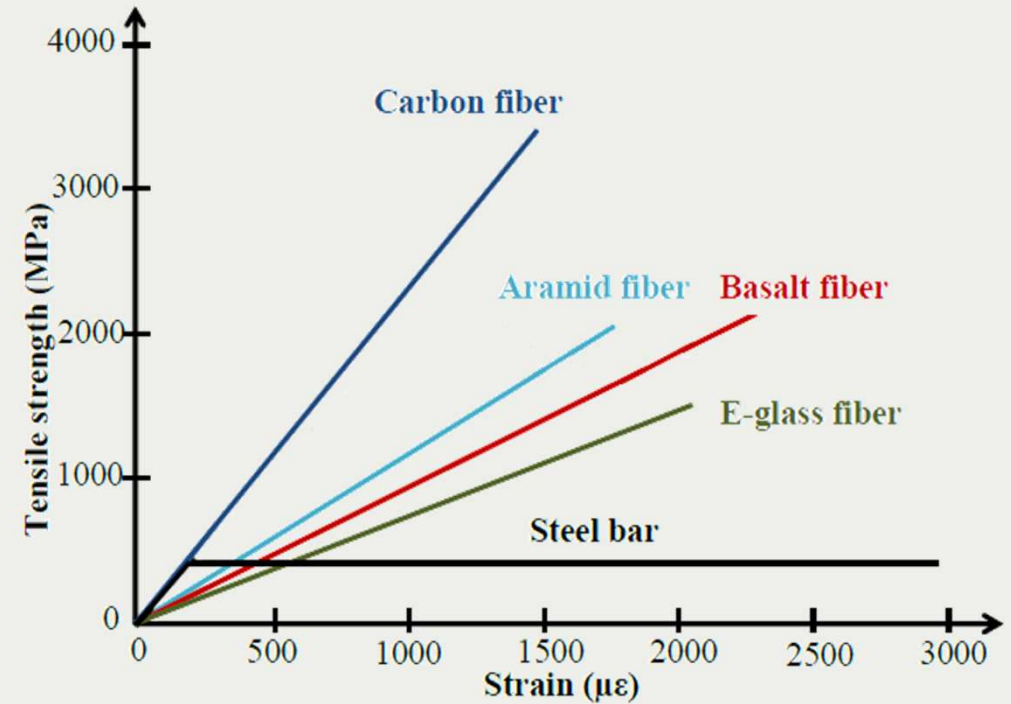
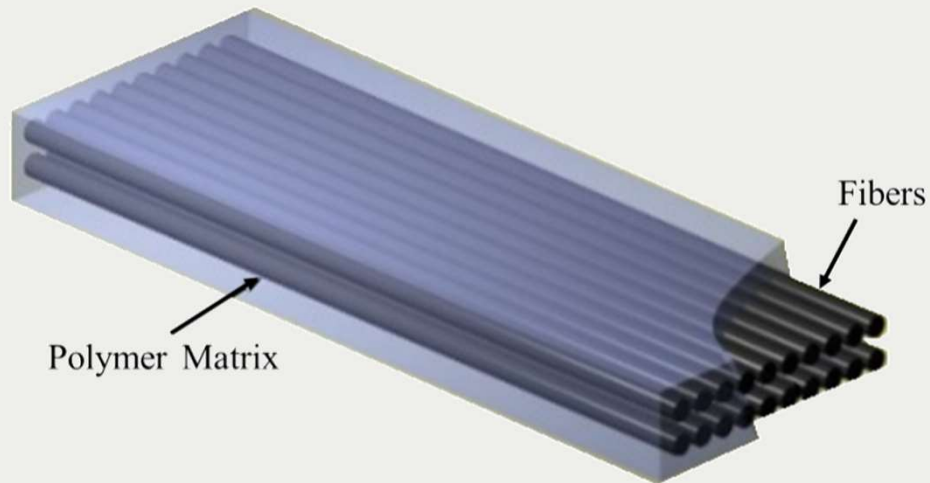
Oita prefecture - Japan

- **HOW TO** strengthen RC Structures?

Strengthening manufactured from *the traditional techniques* such as external bonded steel plates or concrete jacketing, by utilising *fiber reinforced polymer (FRP) composites.*

STRENGTHENING OF RC STRUCTURES

- *Fiber Reinforced Polymer (FRP) composites:*



STRENGTHENING OF RC STRUCTURES

- **Epoxy-Bonded FRP Sheet Strengthening Systems:**

This strengthening system may be defined as one in which *FRP sheets* are bonded, in most cases, to a concrete structure with *an epoxy adhesive* to improve its structural behavior and strength. Those strengthening systems have been proven as an effective method in repairing and strengthening concrete structures.



Flexural strengthening



Shear strengthening



Confinement

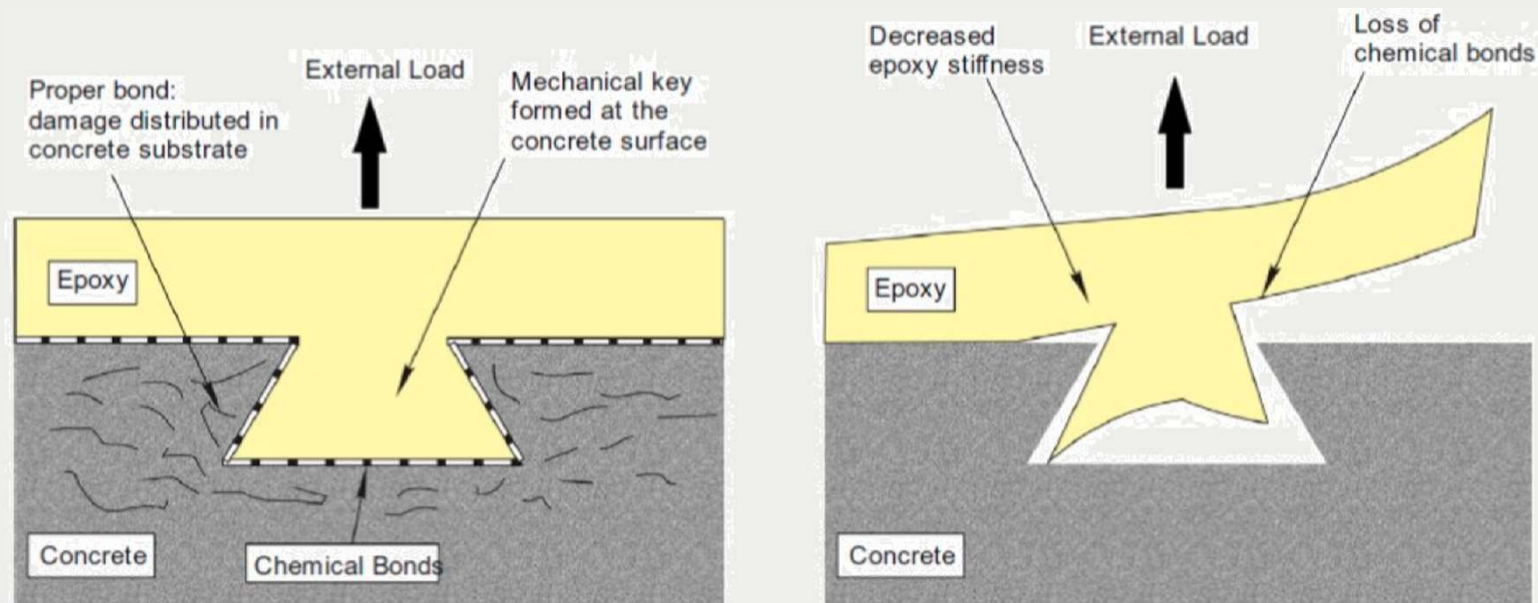
STRENGTHENING OF RC STRUCTURES

- **Epoxy-Bonded FRP Sheet Strengthening Systems:**

Epoxies providing excellent force transfer between FRP composites and concrete surface.

However, those bonding agent have some disadvantages.

1. Organic resins create a hazardous working environment for the workers causing eczema.
2. Organic resins lack fire resistance and have low compatibility with concrete surface.
3. The recommended minimum application temperature often above **10°C**.
4. In addition, a substantial slip took place when temperature exceeded **40°C**.

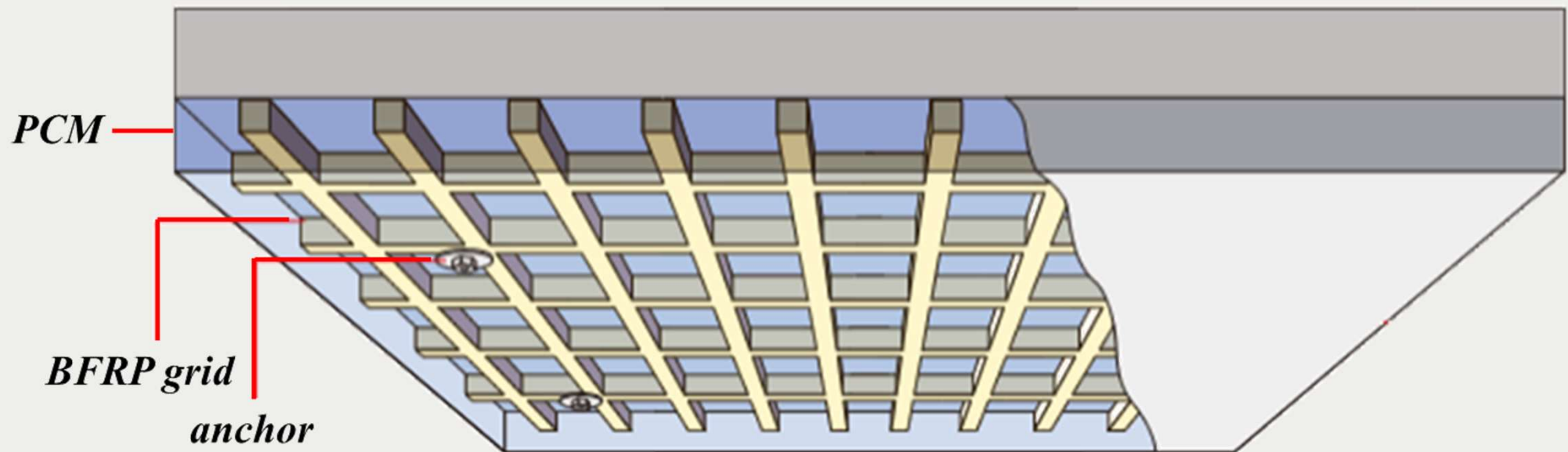


STRENGTHENING OF RC STRUCTURES

This thesis presents a *mineral-based composites (MBC)* strengthening technique for RC structures contains of *Basalt FRP grids bonded with Polymer Cement Mortar (PCM)*.

The main objectives of this research are:

- a) *Check the efficiency of BFRP grid in external strengthening of RC beams.*
- b) *Propose design guidelines for BFRP grid strengthened RC beams.*

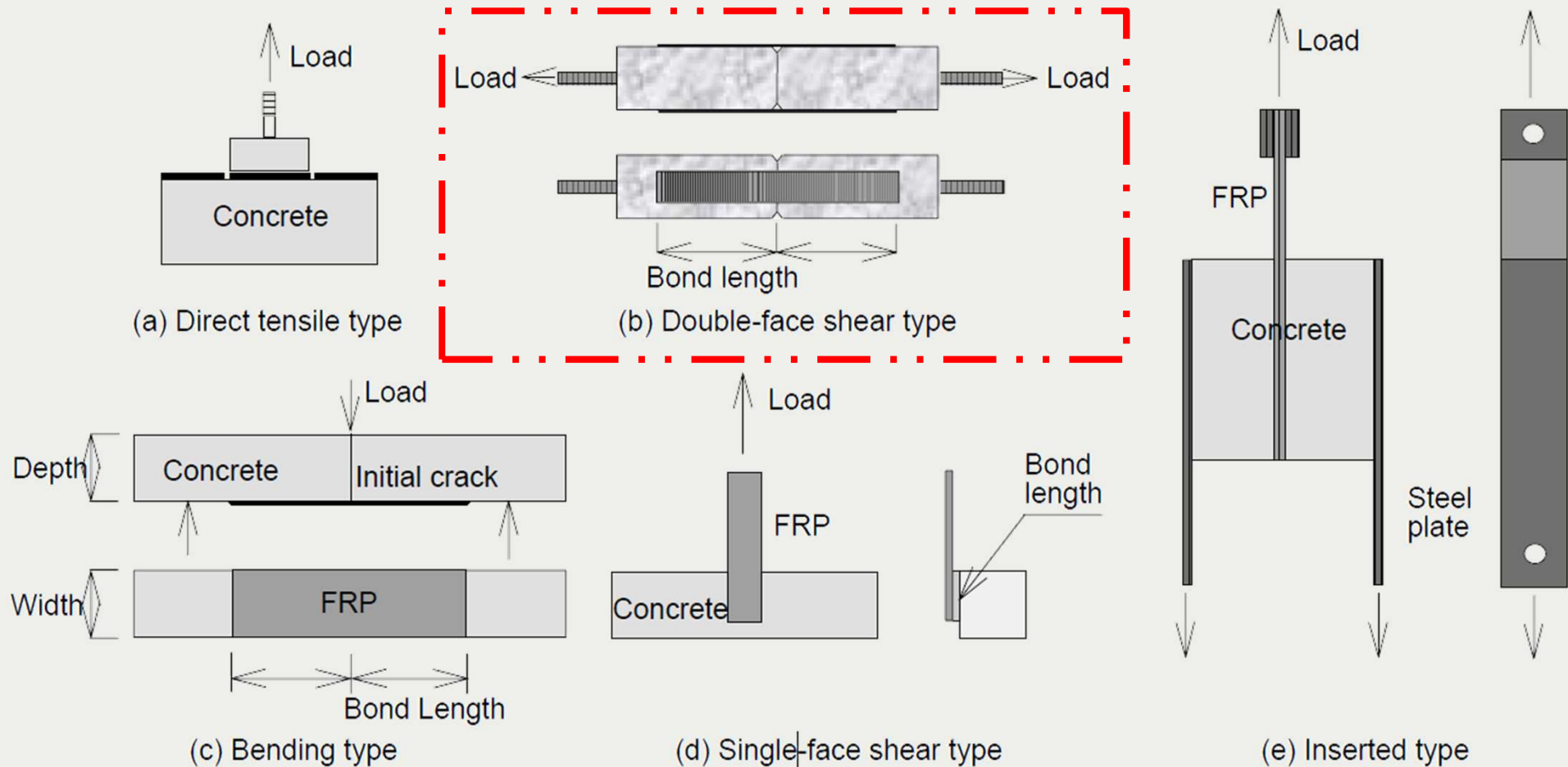


Contents of thesis

- Strengthening of RC structures.
- **BOND-SLIP MODELS OF BFRP GRIDS.**
- FLEXURAL STRENGTHENING.
- SHEAR STRENGTHENING.
- CONCLUSION AND RECOMMENDATION.

BOND-SLIP MODELS OF BFRP GRIDS

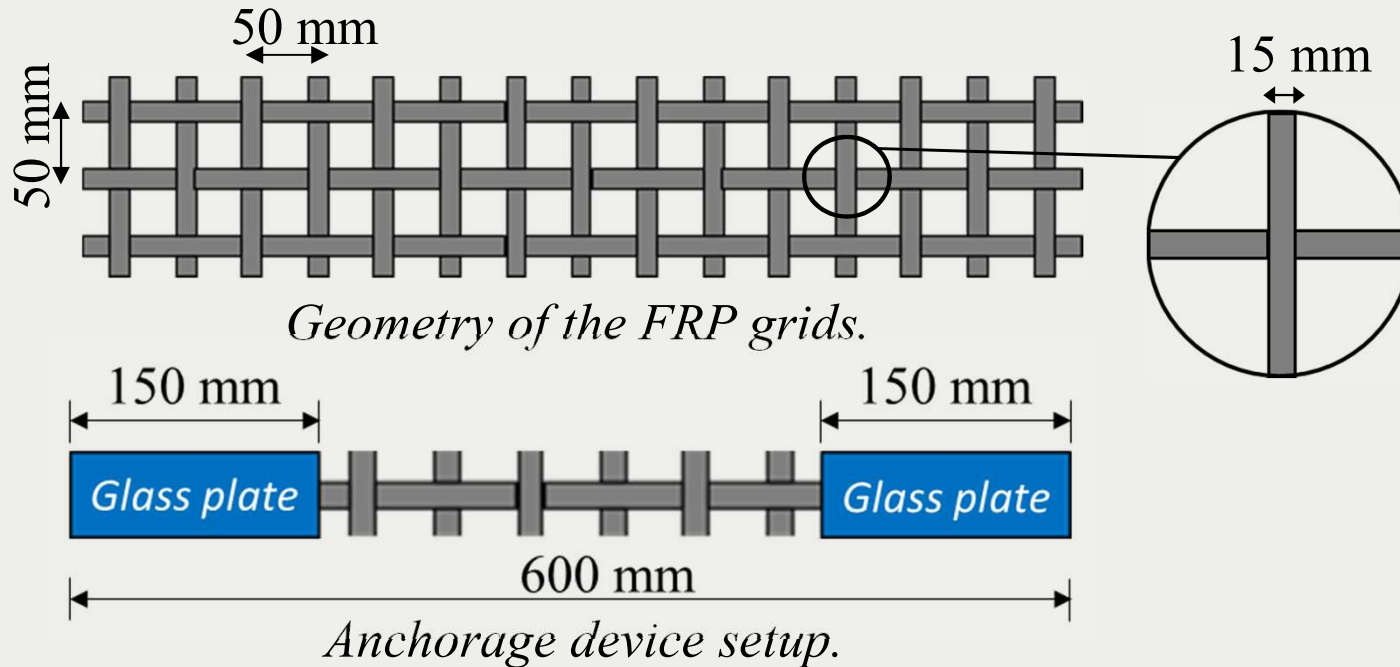
Interfacial bond between external bonded FRP composites and concrete surface plays a significant role in controlling the structural behaviour of the strengthened structures.



BOND-SLIP MODELS OF BFRP GRIDS

- Mechanical Properties of BFRP Grids:**

Three different BFRP grids were used to investigate the effect of different fiber content on the bond behavior between the bonded grids and the concrete surface. *ASTM D7205/D7205M*.



Test setup of BFRP grid.

| ID | Th. (mm) | $P_{Ult.}$ (kN) | ϵ (%) | σ (MPa) | E_F (GPa) |
|--------|----------|-----------------|----------------|----------------|-------------|
| BG - L | 3 | 20.50 | 2.62 | 455.6 | 17.4 |
| BG - M | 4 | 24.60 | 2.52 | 410.0 | 16.3 |
| BG - H | 5 | 28.70 | 2.49 | 382.7 | 15.4 |

BOND-SLIP MODELS OF BFRP GRIDS

- **Bonding agents:**

Two bonding agents were used in this study to bond the BFRP grids to the concrete surface;

A. Polymer Cement Mortar (PCM) was produced by *StoCretec Japan*, under name of *TS100*.

B. Epoxy Putty produced by *Nippon Steel & Sumikin Materials Co., Ltd.* under name of *FE-ZWL*.

❑ Mechanical properties of **PCM**

| Criteria | Value |
|--|-----------------------|
| Apparent density of fresh mortar | 2.1 kg/m ³ |
| Tensile strength (28 days) | > 2.0 MPa |
| Flexural Strength (28 days) | 10 – 12 MPa |
| Compressive Strength (28 days) | 60 - 70 MPa |
| Static modulus of elasticity (28 days) | 23.0 GPa |

❑ Mechanical properties of **Epoxy Putty**

| Criteria | Value |
|--|------------------------|
| Specific gravity | 1.56 kg/m ³ |
| Bond strength (Pull-off) | 2.4 MPa |
| Tensile lap-shear strength | 13 MPa |
| Compressive Strength | 72 MPa |
| Static modulus of elasticity (compressive) | 1863 MPa |

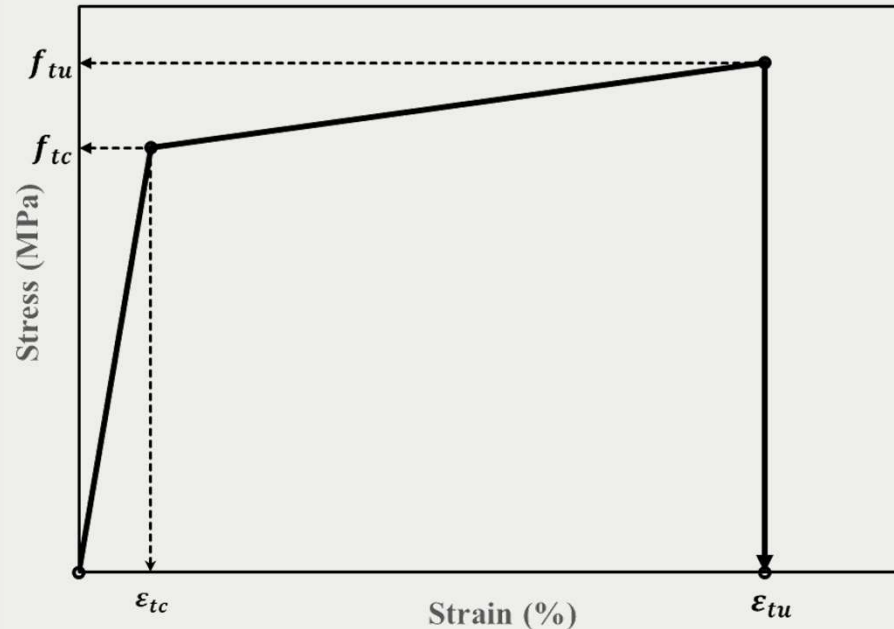
BOND-SLIP MODELS OF BFRP GRIDS

- **Bonding agents:**

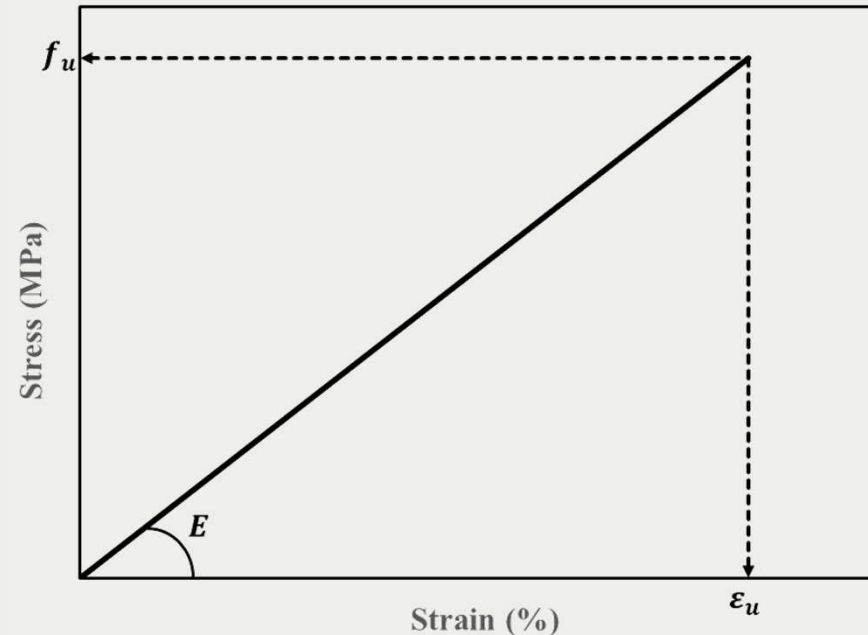
Two bonding agents were used in this study to bond the BFRP grids to the concrete surface;

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*Tensile stress-strain curve of **PCM**.*



*Tensile stress-strain curve of **Epoxy Putty**.*

BOND-SLIP MODELS OF BFRP GRIDS

- **Bonding Procedures of PCM:**



1. Surface preparation.



2. Spraying the PCM into the wood frame.



3. Adjusting the final level.



4. Covering with plastic sheets.

BOND-SLIP MODELS OF BFRP GRIDS

- Bonding Procedures of Epoxy Putty :



1. Apply the primer layer



2. Apply the epoxy putty

The double shear bond test specimens



1. Apply the primer layer



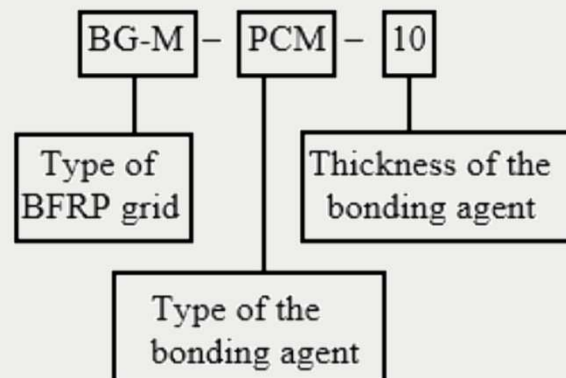
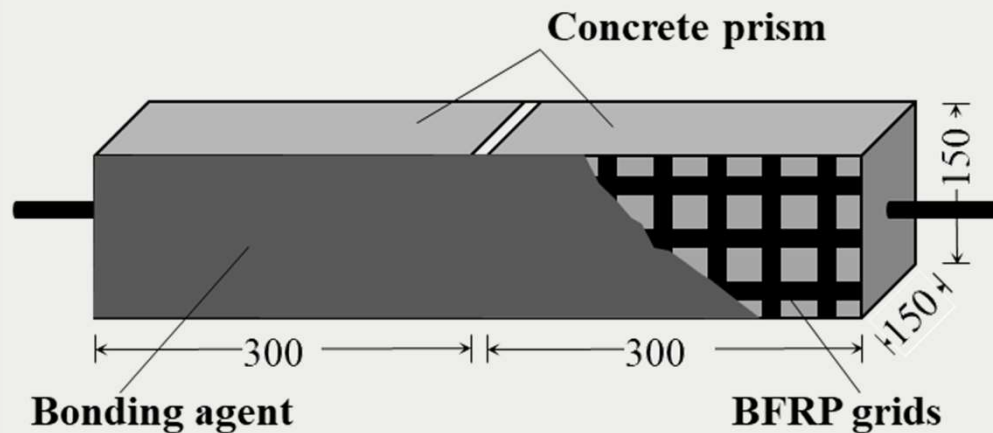
2. Apply the epoxy putty

Flexural strengthened RC beams specimens

BOND-SLIP MODELS OF BFRP GRIDS

- **Experimental Double Shear Bond Tests:**

A total of 24 specimens of double shear test were prepared and tested. Three parameters were studied; the fiber content of the BFRP grids, the type of the bonding agents, and the thickness of the bonding agent PCM; three specimens for each test.



Name convention for specimens.



Test setup of double shear test.

BOND-SLIP MODELS OF BFRP GRIDS

- The interfacial fracture energy (G_f):

Wu and Yin 2002 defined the interfacial fracture energy as a key parameter to describe the shear strength of the bond interface between the FRP composites and the concrete surface.

Täljsten 1996 derived the following simple equation to express the interfacial fracture.

$$G_f = \frac{P_{max}^2}{2b_f^2 \cdot E_f \cdot t_f}$$

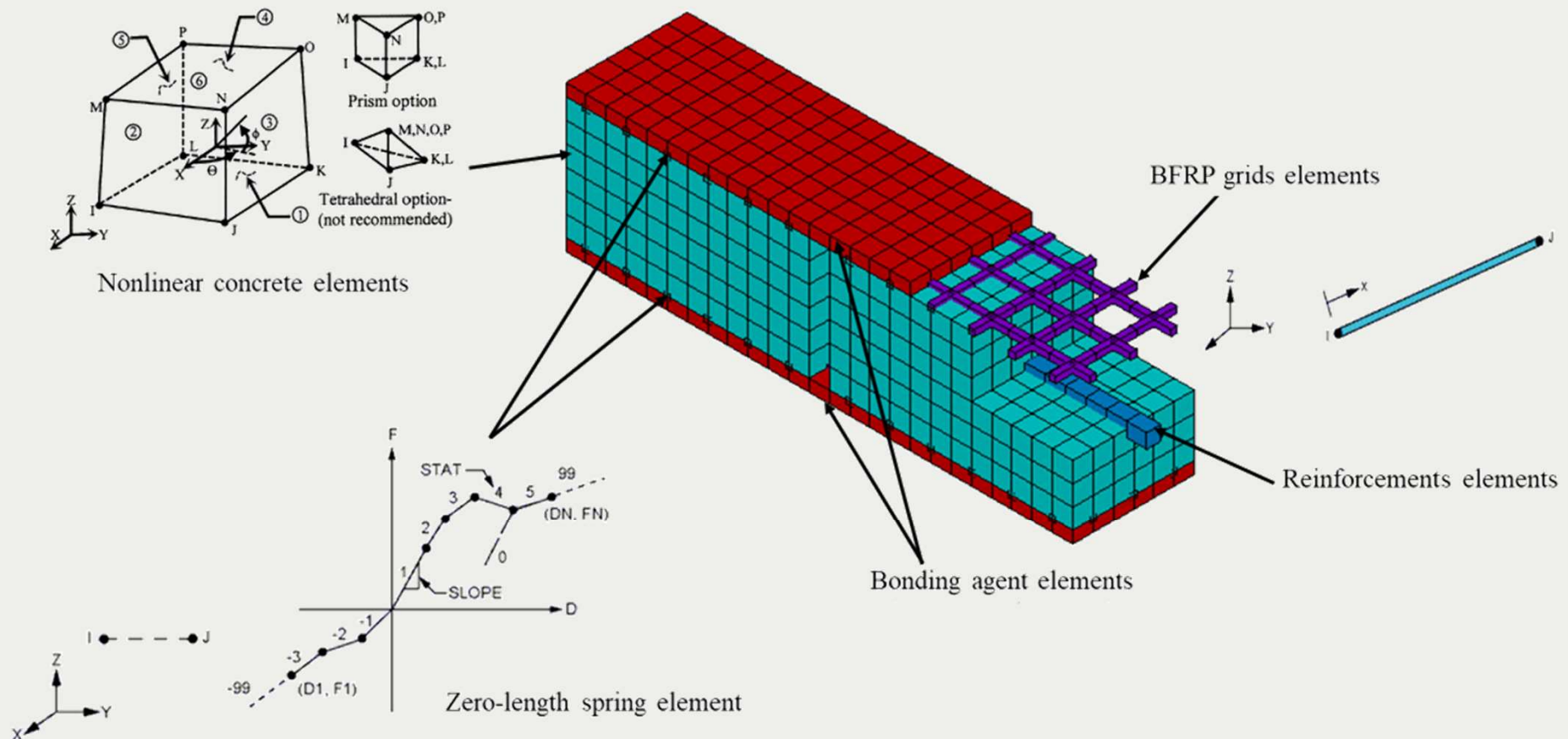
| ID | P_{max} (kN) | b_f (mm) | $E_f \cdot t_f$ (kN/mm) | G_f (N/mm) |
|-------------|-------------------|---------------|----------------------------|-----------------|
| C5-SCFH | 25.63 | 50 | 87.19 | 1.51 |
| BG-M-PCM-15 | 39.65 | 150 | 26.10 | 1.34 |

The maximum interfacial fracture energy of FRP sheets tested by *Nakaba et al. 2001* was 1.50 N/mm, with almost double concrete compressive strength of the prisms.

BOND-SLIP MODELS OF BFRP GRIDS

- Numerical Simulations of Double Shear Bond Tests:**

The double shear bond tests were modeled using finite element method to identify the local bond-slip model of the BFRP grid and concrete surface.

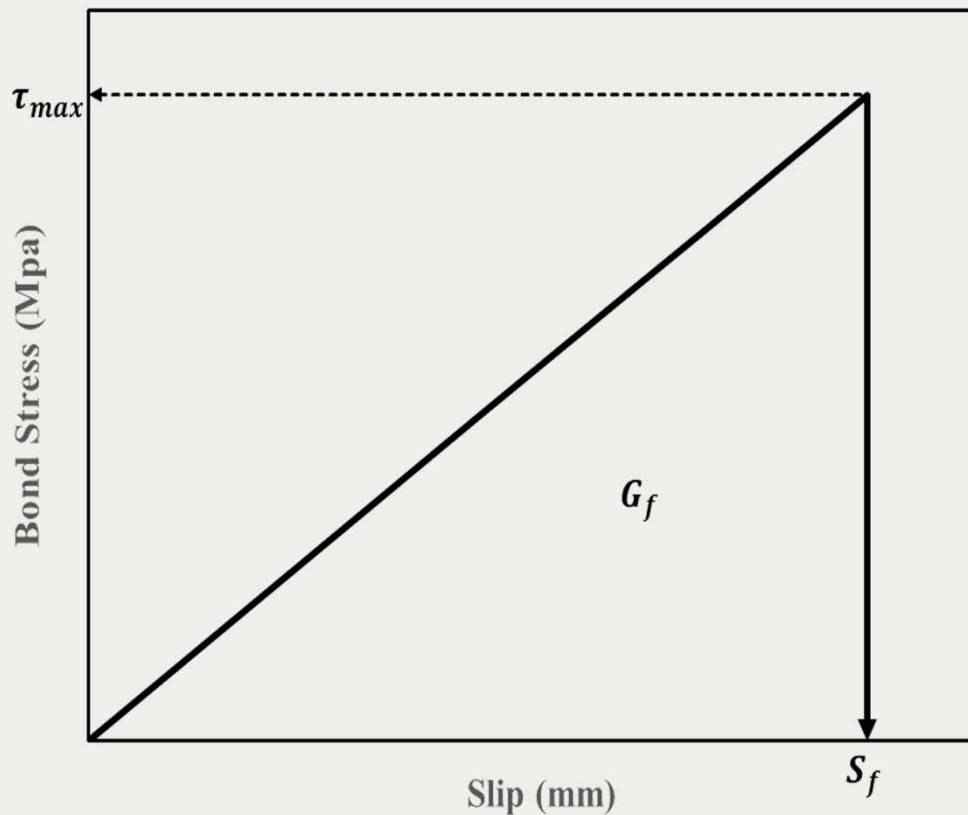


Typical 3D FEM of simulated double shear test specimens.

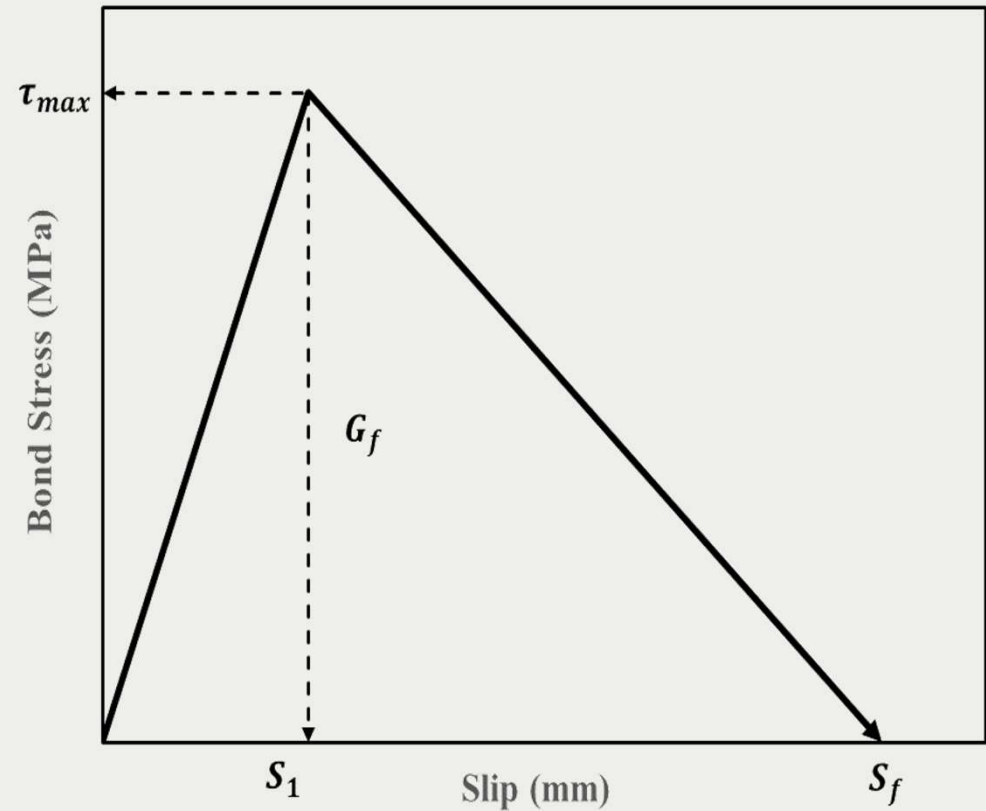
BOND-SLIP MODELS OF BFRP GRIDS

- **Numerical Simulations of Double Shear Bond Tests:**

Wu et al. 2002 described two models for the bond stress–slip relationship (τ - s), to represent the nonlinear interfacial stress transfer of adhesive joints in FRP strengthened concrete structures.



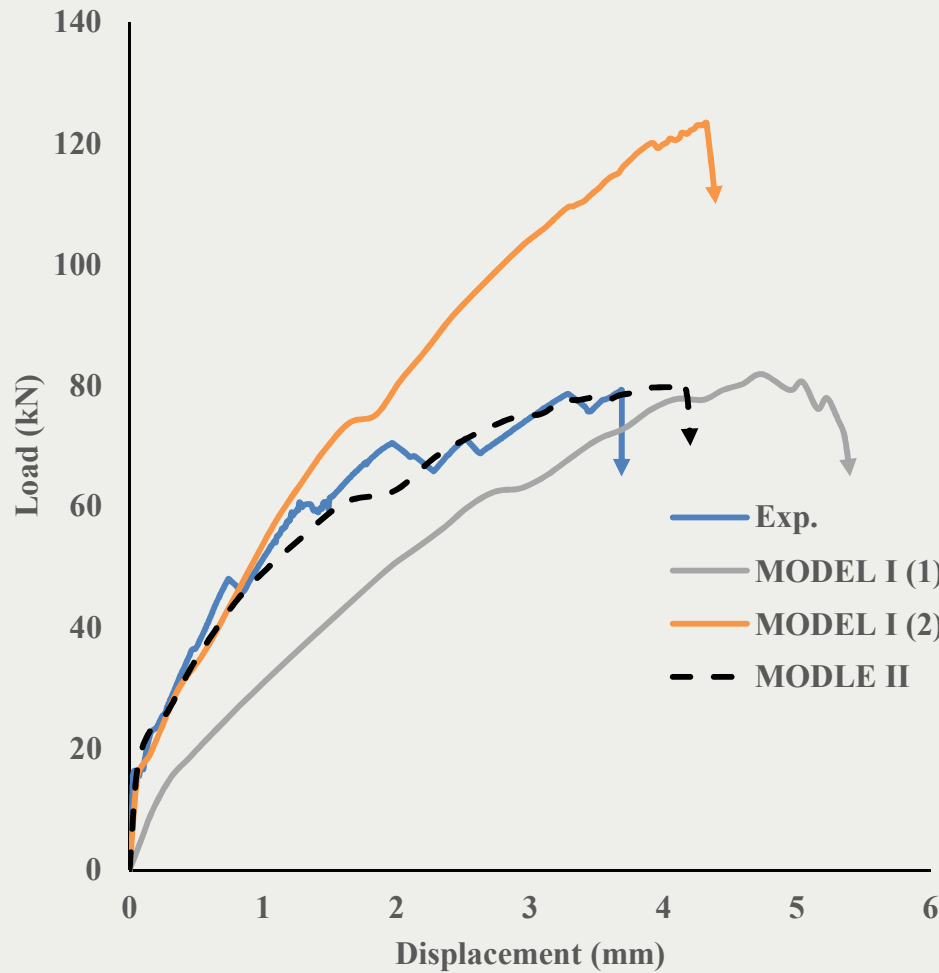
Simplified shapes of τ - S (MODEL I).



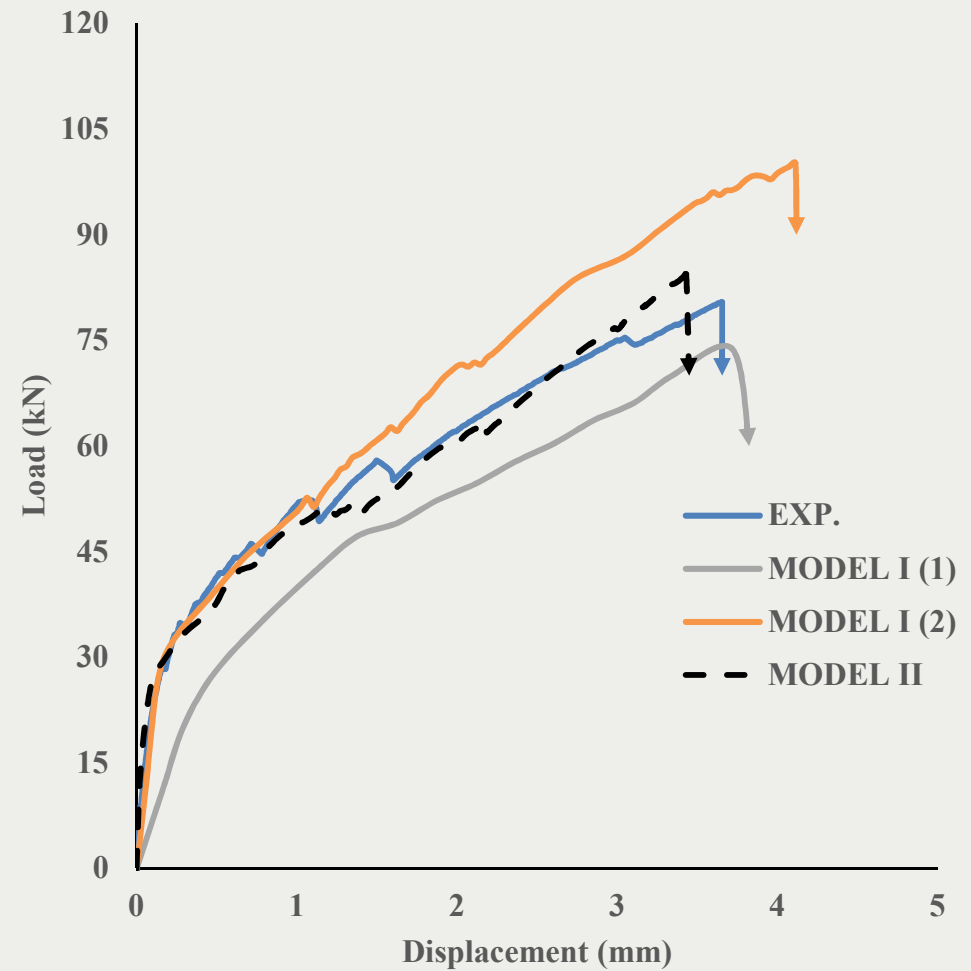
Simplified shapes of τ - S (MODEL II).

BOND-SLIP MODELS OF BFRP GRIDS

- Load-displacement Curves from Numerical Simulation:



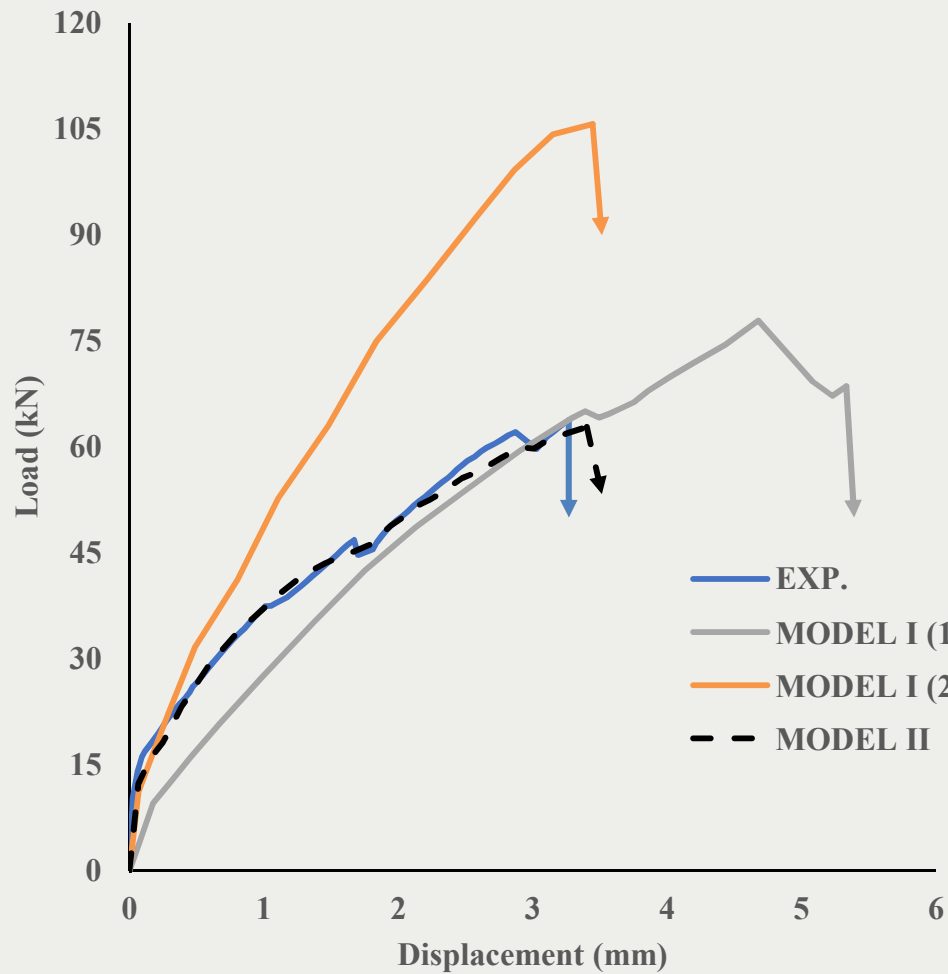
Load-displacement curves of [BG-M-PCM-15].



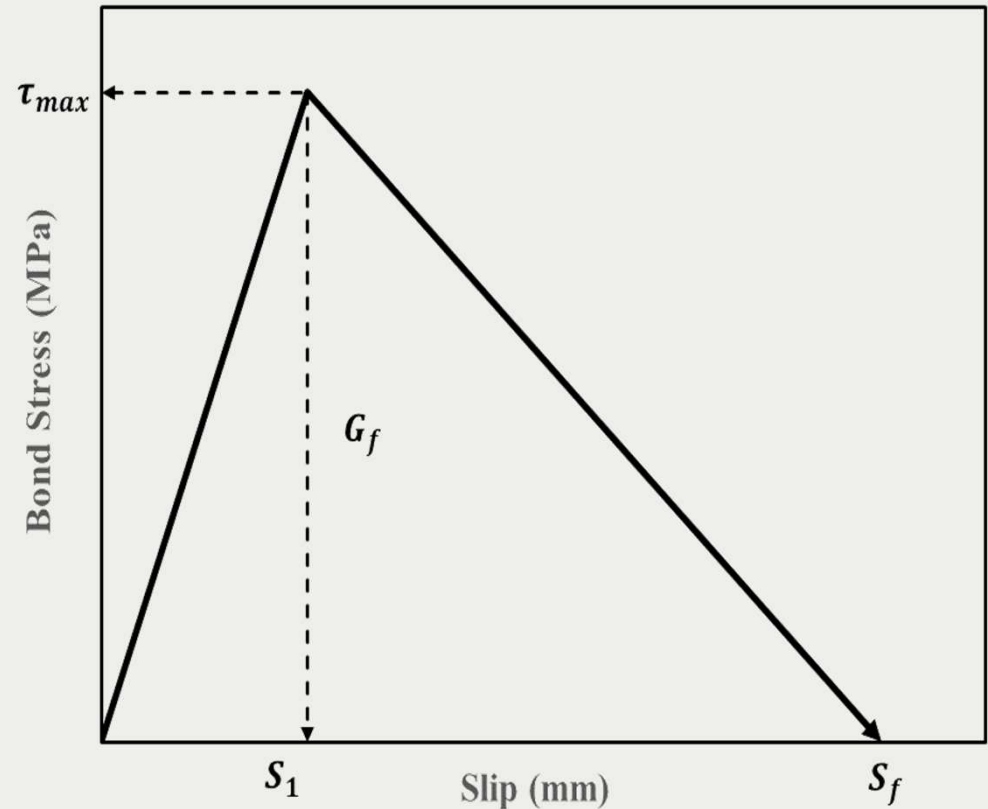
Load-displacement curves of [BG-M-PUTTY-5].

BOND-SLIP MODELS OF BFRP GRIDS

- Load-displacement Curves from Numerical Simulation:



Load-displacement curves of [BG-M-PCM-10].



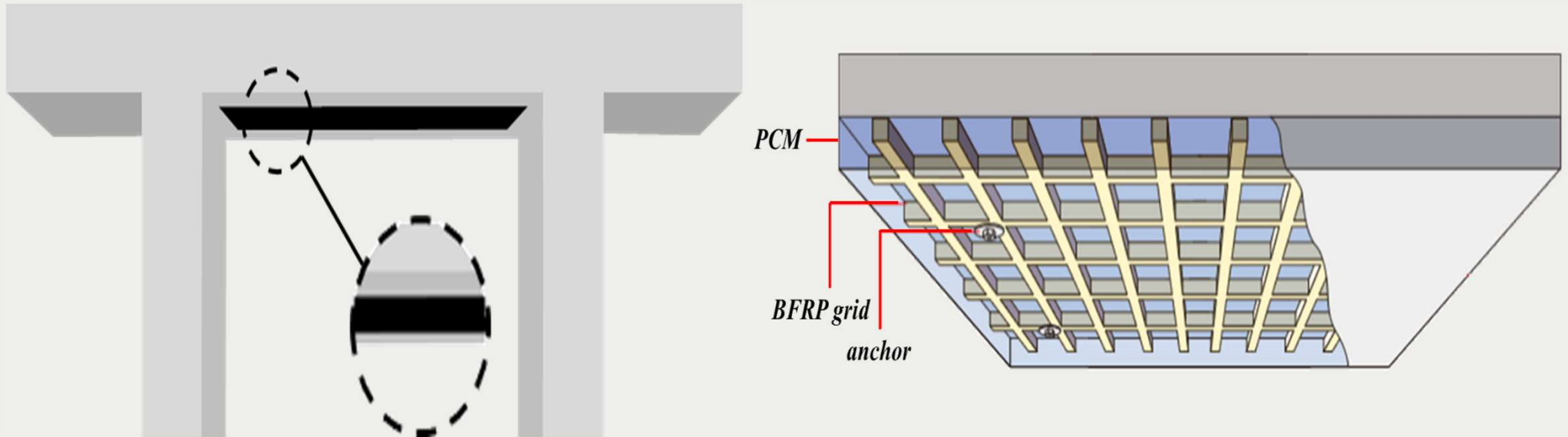
| Bonding agent | τ_{max} (MPa) | S_1 (mm) | S_f (mm) |
|---------------|--------------------|------------|------------|
| PCM | 3.00 | 0.07 | 0.40 |
| EPOXY PUTTY | 3.00 | 0.07 | 0.25 |

Contents of thesis

- **Strengthening of RC structures.**
- **BOND-SLIP MODELS OF BFRP GRIDS.**
- **FLEXURAL STRENGTHENING.**
- **SHEAR STRENGTHENING.**
- **CONCLUSION AND RECOMMENDATION.**

FLEXURAL STRENGTHENING OF RC BEAMS

One of the primary applications of FRP composites in construction field was flexural strengthening of RC beams with externally epoxy-bonded FRP sheets.

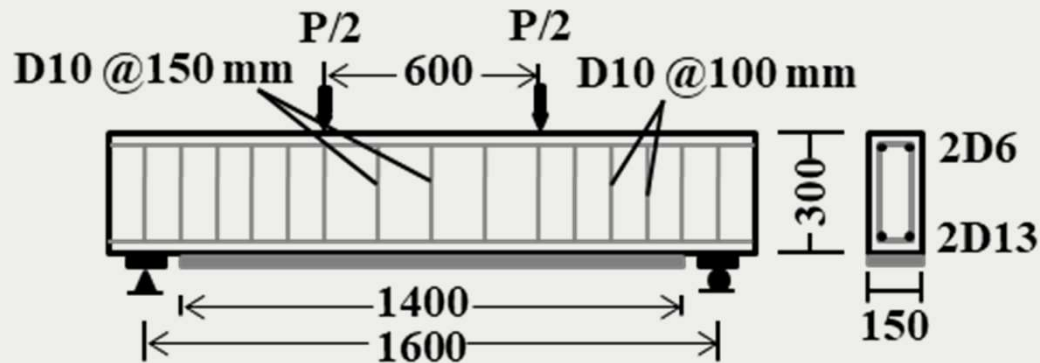


First, experimental bending tests on the flexural strengthened beams were prepared and tested. Then, the design guidelines in [ACI 440.2R](#) were followed and modified to calculate the flexural contribution of the FRP grids. Finally, numerical simulations of the flexural strengthened beams were done to highlight the flexural strengthening mechanism.

FLEXURAL STRENGTHENING OF RC BEAMS

- **Experimental bending tests of flexural strengthened RC beam:**

A total of nine simply supported rectangular RC beams were constructed and tested to study the flexural strengthening efficiency of using external bonded BFRP grids.



Geometry of the RC beams.



Internal steel reinforcement of RC beams.

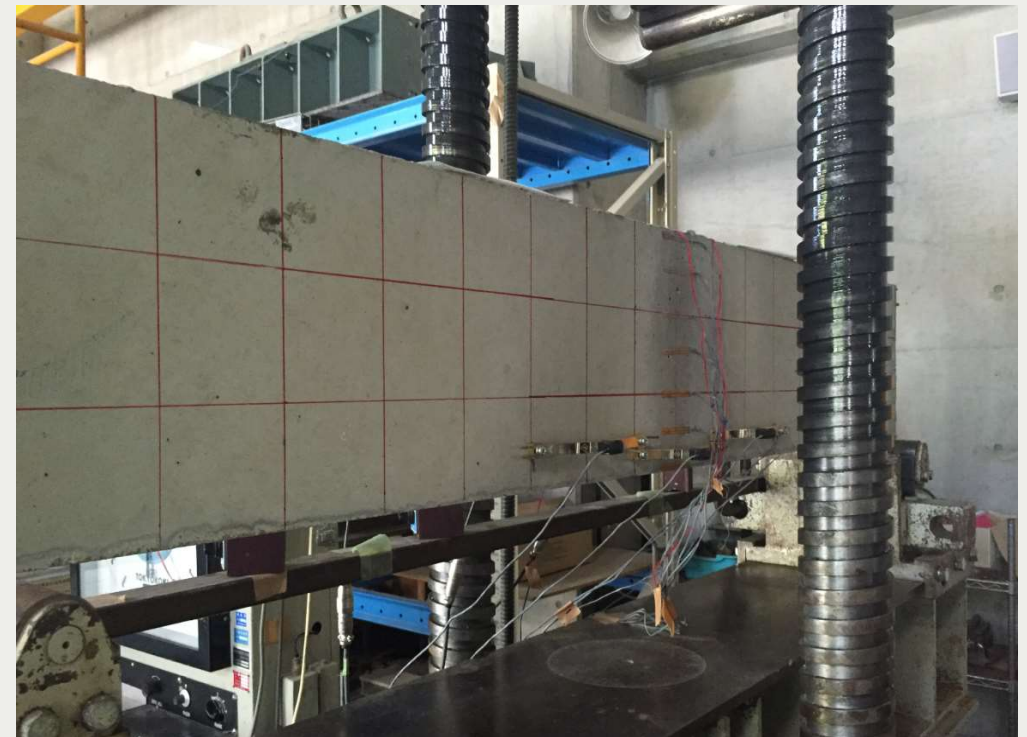


Work frame of RC beams.

FLEXURAL STRENGTHENING OF RC BEAMS

- **Experimental bending tests of flexural strengthened RC beam:**

A total of nine simply supported rectangular RC beams were constructed and tested to study the flexural strengthening efficiency of using external bonded BFRP grids.



Setup of bending tests of RC beams.

FLEXURAL STRENGTHENING OF RC BEAMS

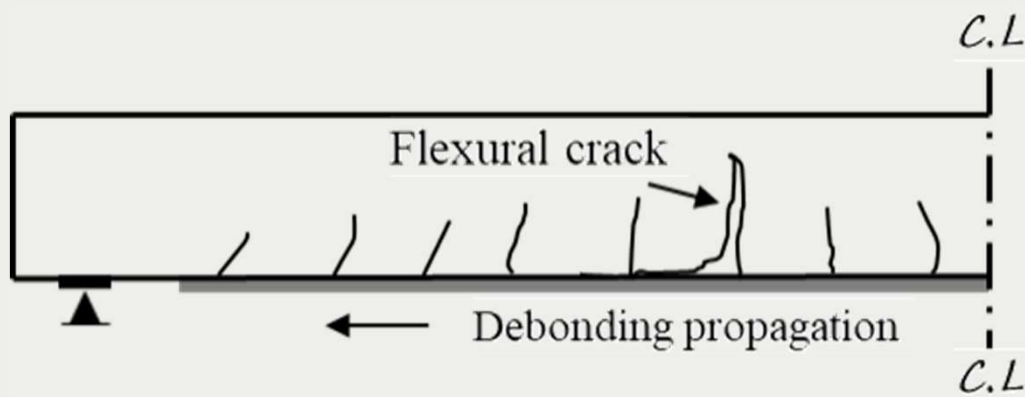
- Failure mode of the tested flexural strengthened RC beam:



Concrete compressive crushing of [B0]



Failure mode of beam [BG-L-PCM-15].



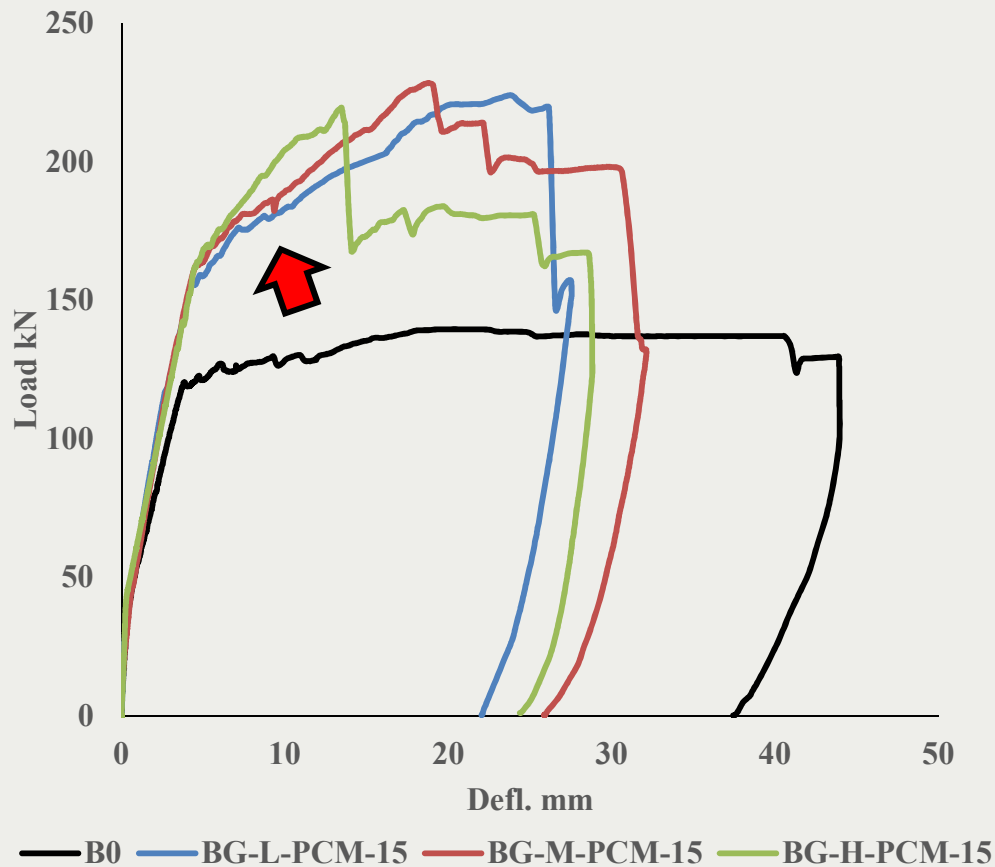
IC debonding failure of strengthened beams



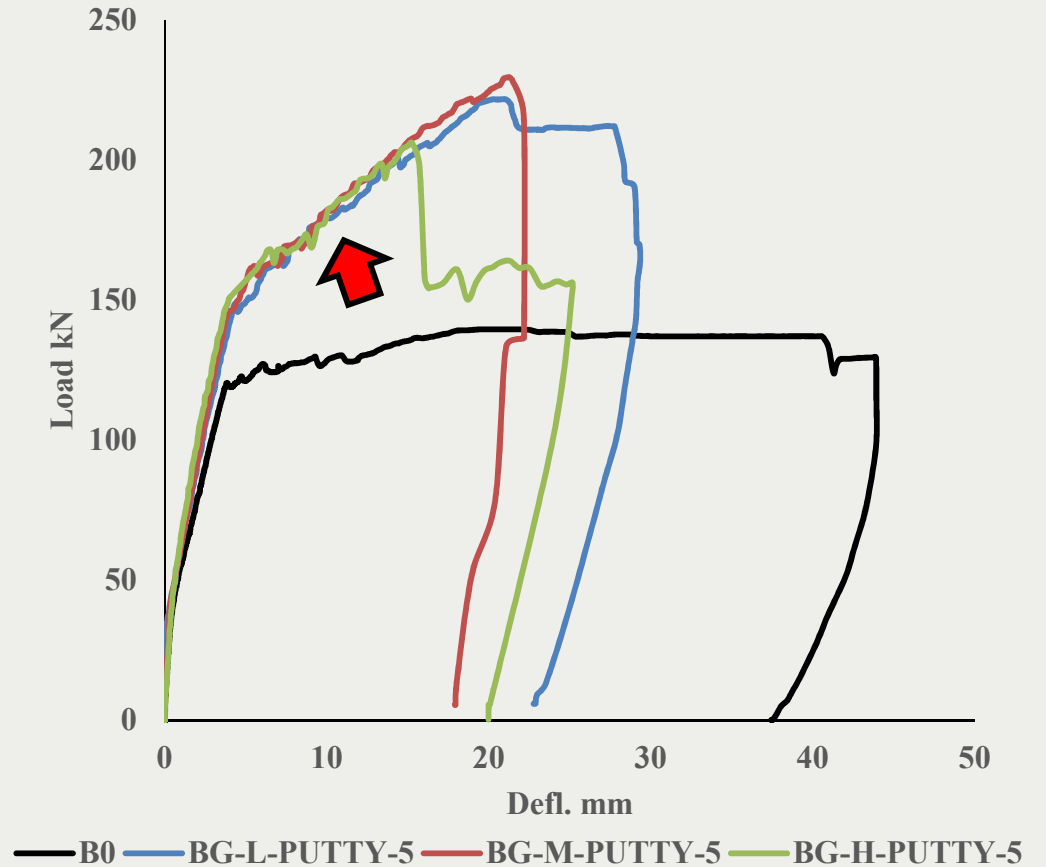
Failure mode of beam [BG-M-PUTTY-5].

FLEXURAL STRENGTHENING OF RC BEAMS

- Load-deflection relationship of tested RC beam:



Load-deflection curve for strengthened beam with BFRP grids and PCM.

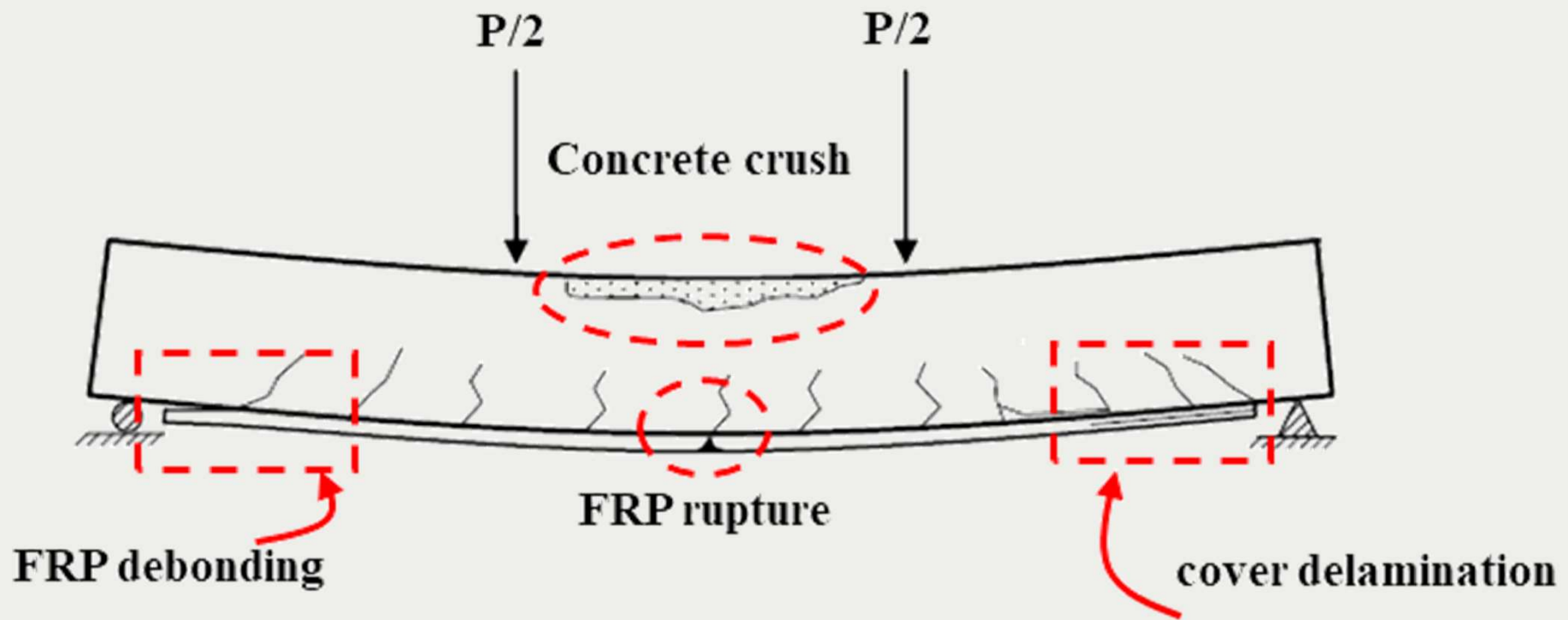


Load-deflection curve for strengthened beam with BFRP grids and epoxy putty.

FLEXURAL STRENGTHENING OF RC BEAMS

- **Flexural contribution of externally bonded FRP grids:**

The flexural strength of a section depends on the controlling failure mode. There are several possible failure modes for externally bonded FRP strengthened beams that can take place in the ultimate limit state as mention in *ACI 440.2R*.



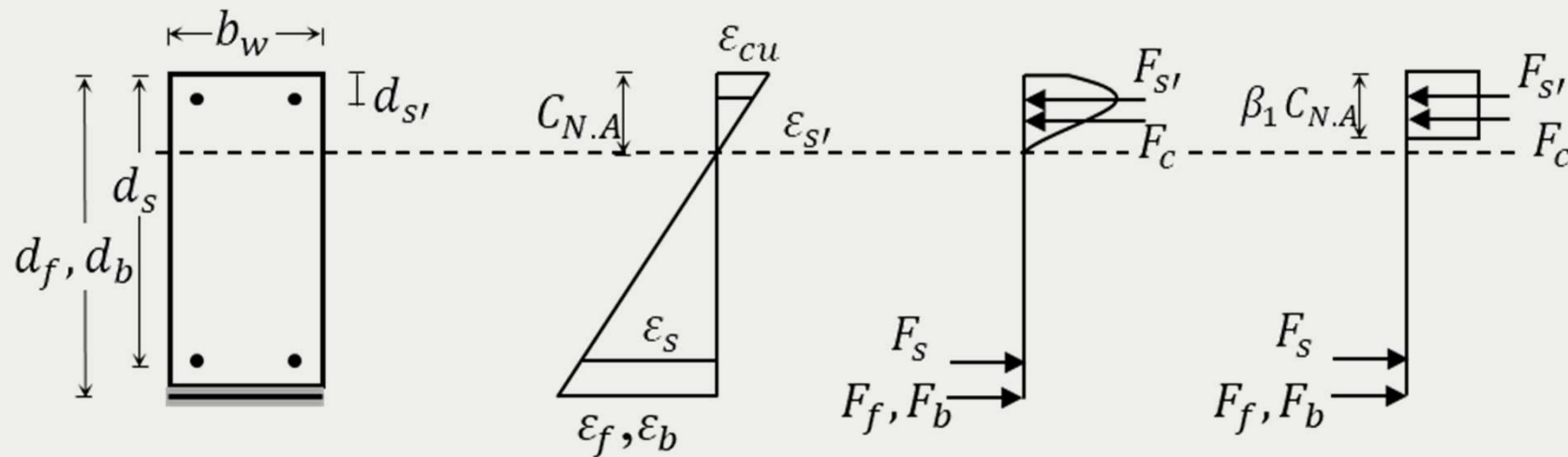
Possible failure modes for externally bonded FRP strengthened RC beam.

FLEXURAL STRENGTHENING OF RC BEAMS

- **Flexural contribution of externally bonded FRP grids:**

The effective strain in FRP composites at which debonding may occur, ϵ_{fd} , is defined as following,

$$\epsilon_{fd} = 0.45 (f'_c)^{0.2} / (E_f t_f)^{0.35}$$



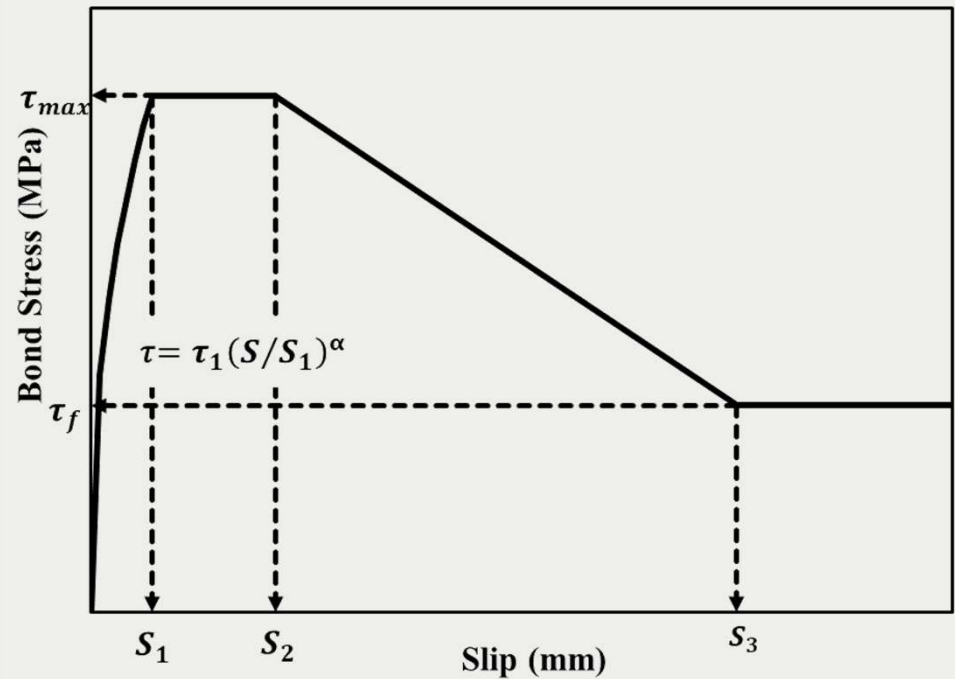
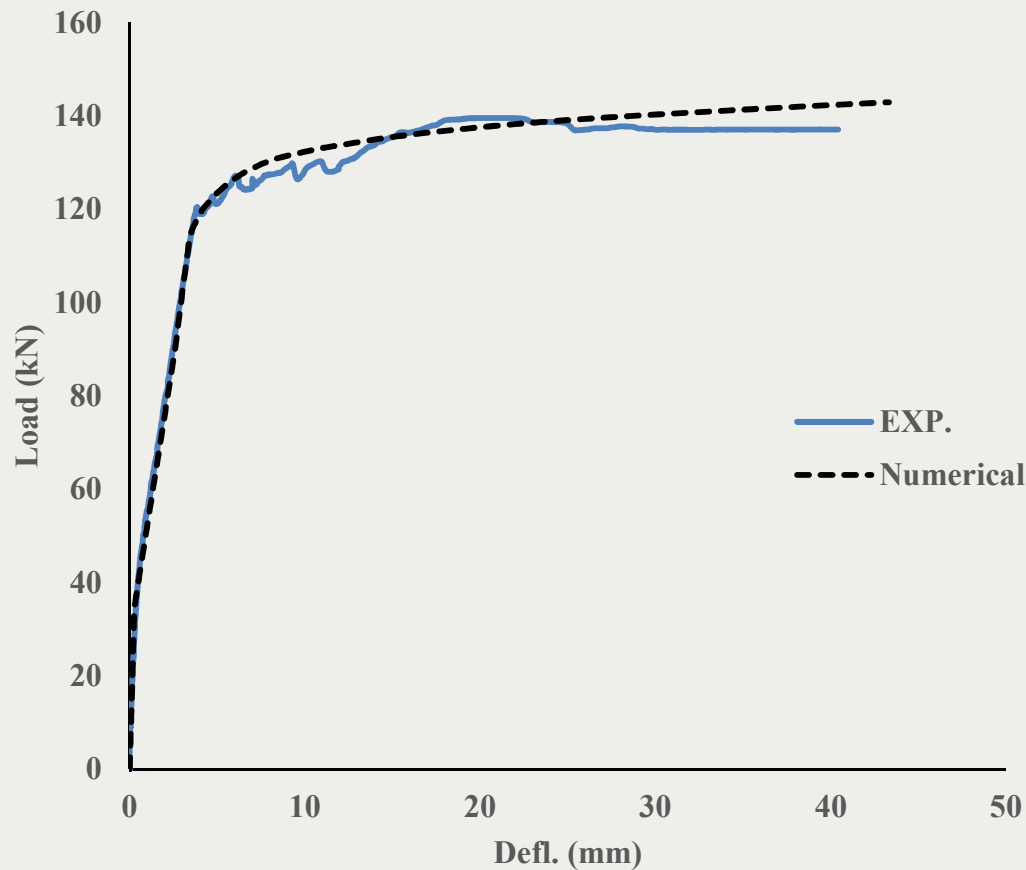
Stress-strain relationship for a RC beam.

$$M_n = A_{s'} F_{s'} \left(\frac{\beta_1 c_{N.A}}{2} - d_{s'} \right) + A_s F_s \left(d_s - \frac{\beta_1 c_{N.A}}{2} \right) + \psi_f A_f F_f \left(d_f - \frac{\beta_1 c_{N.A}}{2} \right) + \psi_b A_b F_b \left(d_b - \frac{\beta_1 c_{N.A}}{2} \right)$$

FLEXURAL STRENGTHENING OF RC BEAMS

- Numerical Simulations of Strengthened RC Beams:**

The FEM was first validated with the experimental data of the control beam to ensure the accuracy of the material properties and steel bond–slip model (*CEB-FIP Model code 1990*).



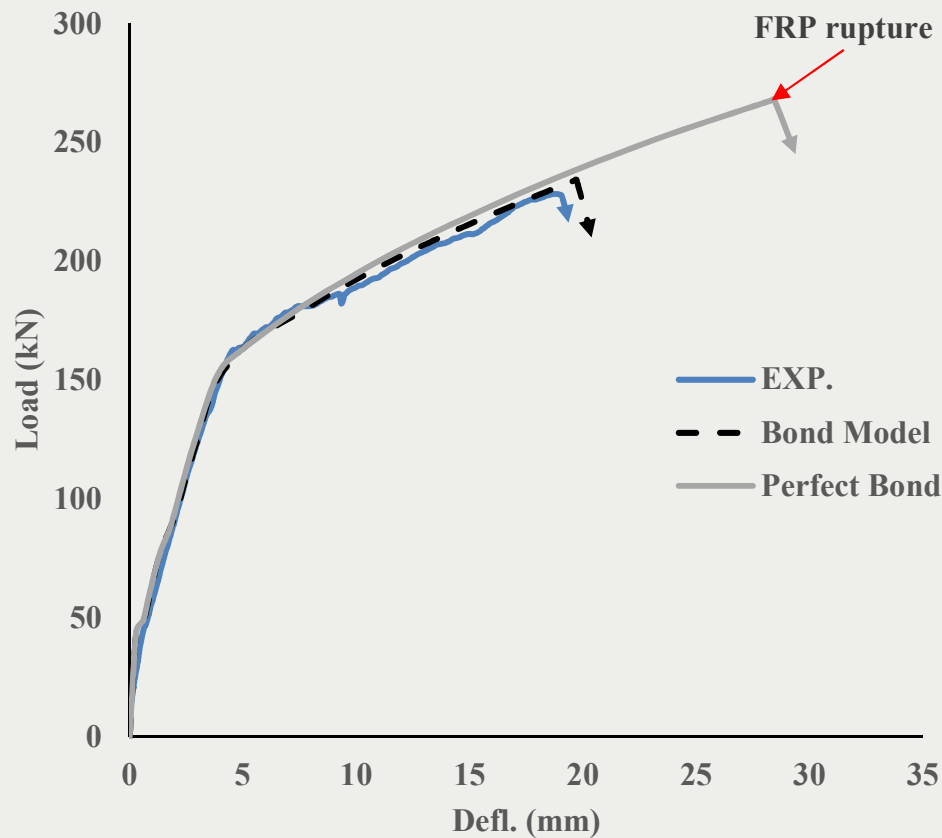
Local bond–slip model for steel bars.

Load–deflection curve of the control beam.

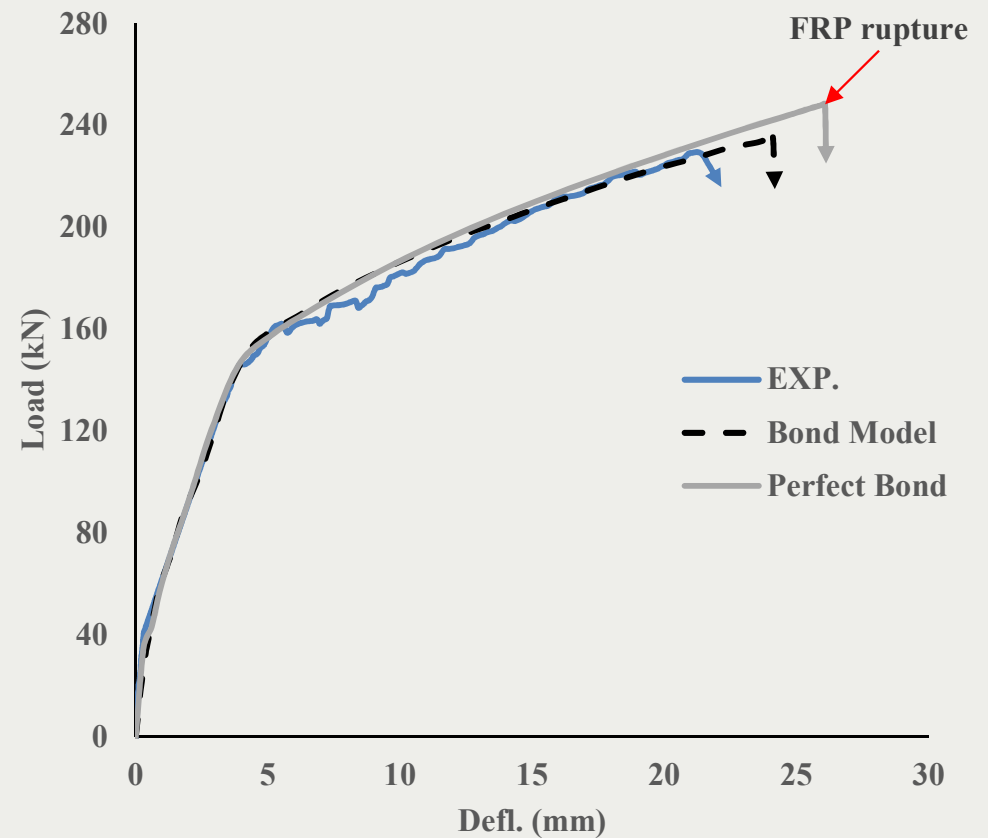
FLEXURAL STRENGTHENING OF RC BEAMS

- Numerical Simulations of Strengthened RC Beams:**

Two cases of the interfacial bond between the external BFRP grid and concrete surface were studied.



Load-deflection curves of [BG-M-PCM-15].

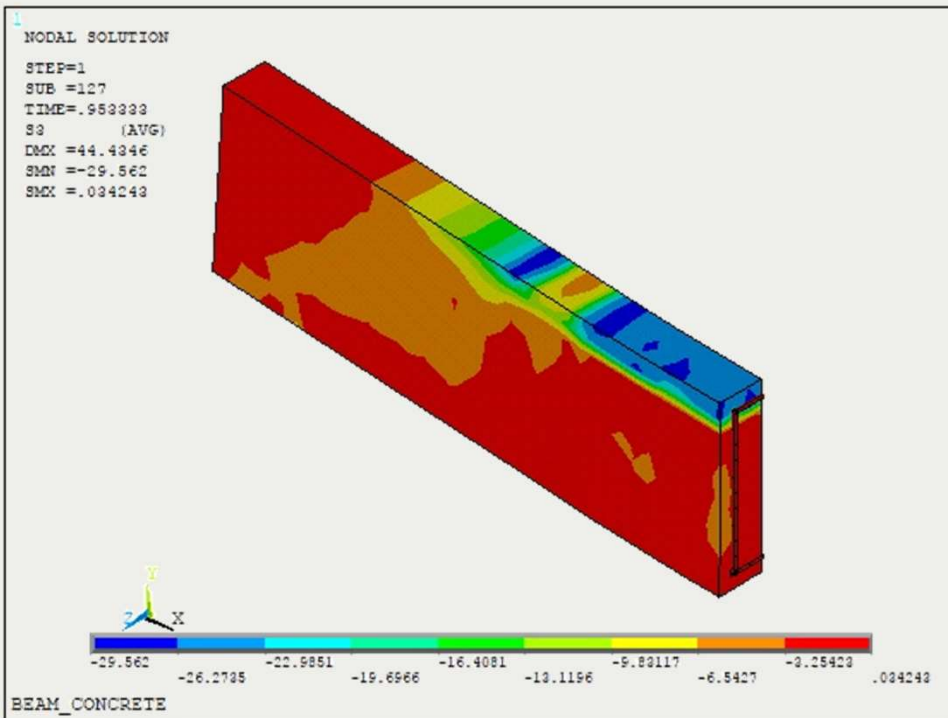


Load-deflection curves of [BG-M-PUTTY-5].

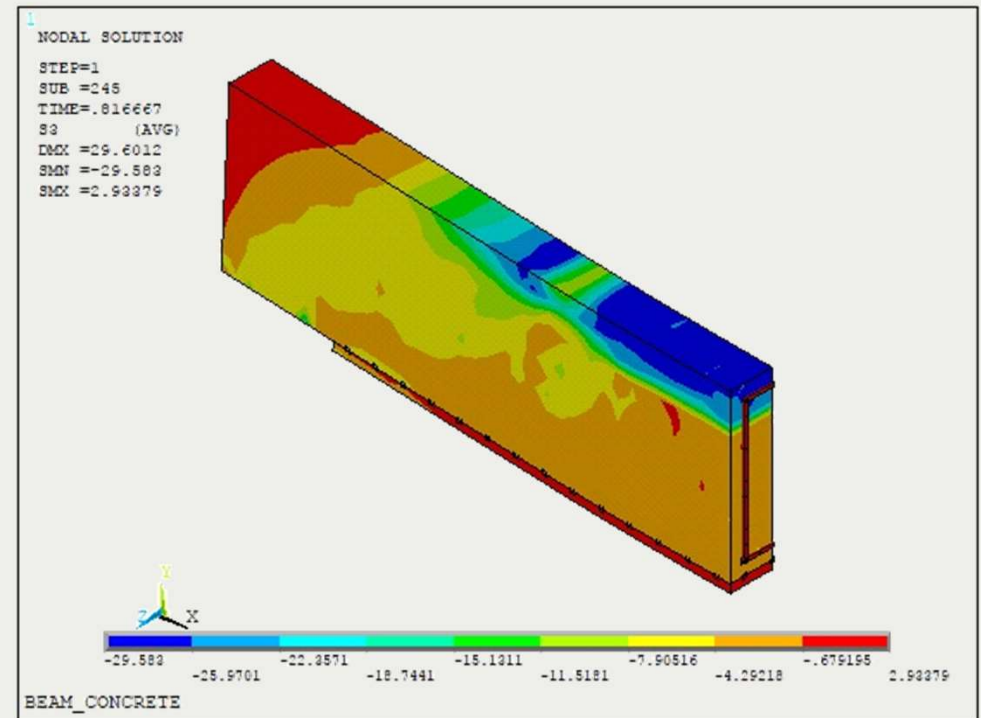
FLEXURAL STRENGTHENING OF RC BEAMS

- **Contour Plots of flexural stress:**

It approves that the flexural stresses of the strengthened beams with BGRP grids increased comparing to the control beam.



Flexural stress of the beam [B0].



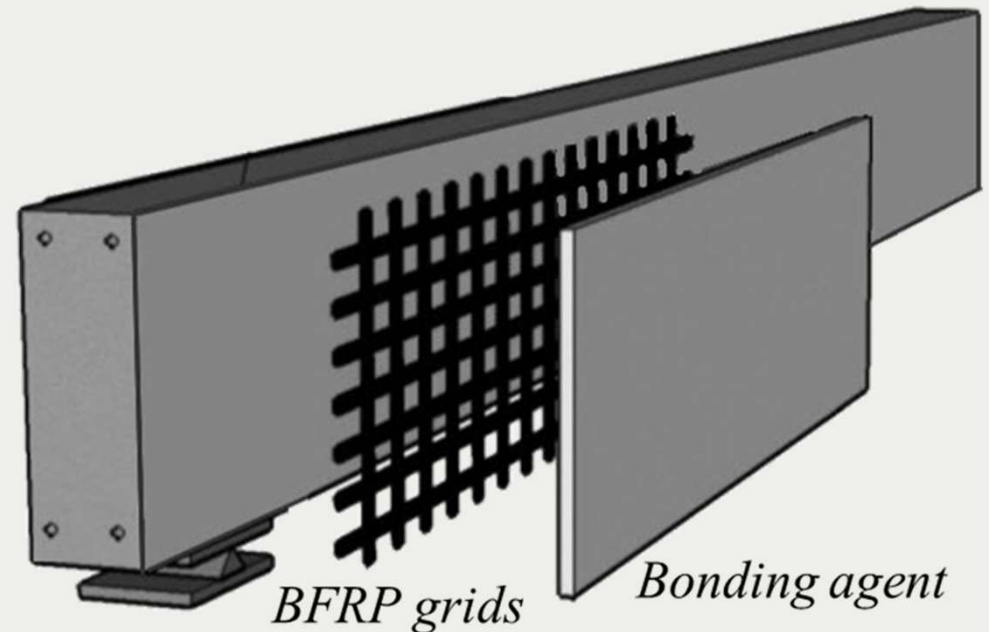
Flexural stress of the beam [BG-M-PCM-15].

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- **CONCLUSION AND RECOMMENDATION.**

SHEAR STRENGTHENING OF RC BEAMS

One of the most common shear-strengthening techniques of RC members includes epoxy bonded FRP sheets to the concrete surface with the fiber oriented as parallel as practically possible to that of maximum principal stress trajectories in the shear critical zones.

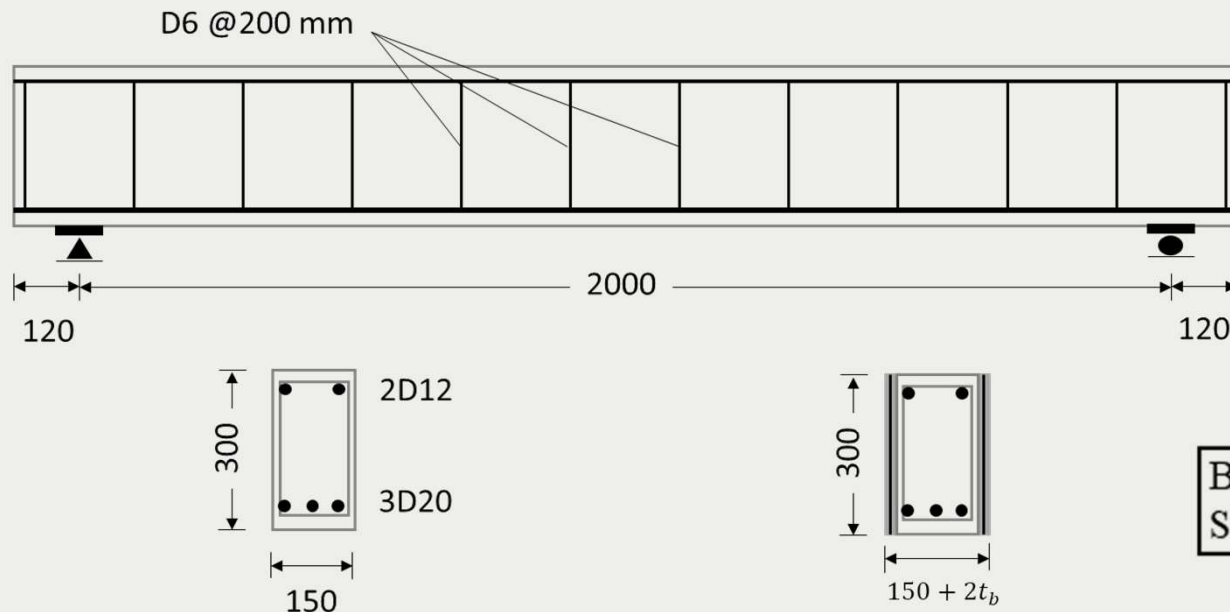


First experimental bending tests on the shear strengthened beams were prepared and tested. Then, the design guidelines in [ACI 440.2R](#) were followed to calculate the flexural contribution of the externally bonded FRP grids. Finally, numerical simulations of the shear strengthened beams were done to illustrate the shear contribution of the BFRP grids.

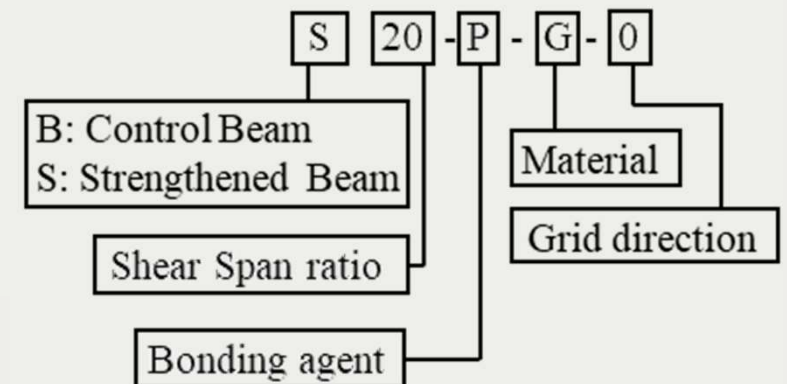
SHEAR STRENGTHENING OF RC BEAMS

- Experimental bending tests of shear strengthened RC beam:**

A total of nine simply supported rectangular RC beams were constructed and tested to study the shear strengthening efficiency of using external bonded BFRP grids.



Geometry of the RC beams.

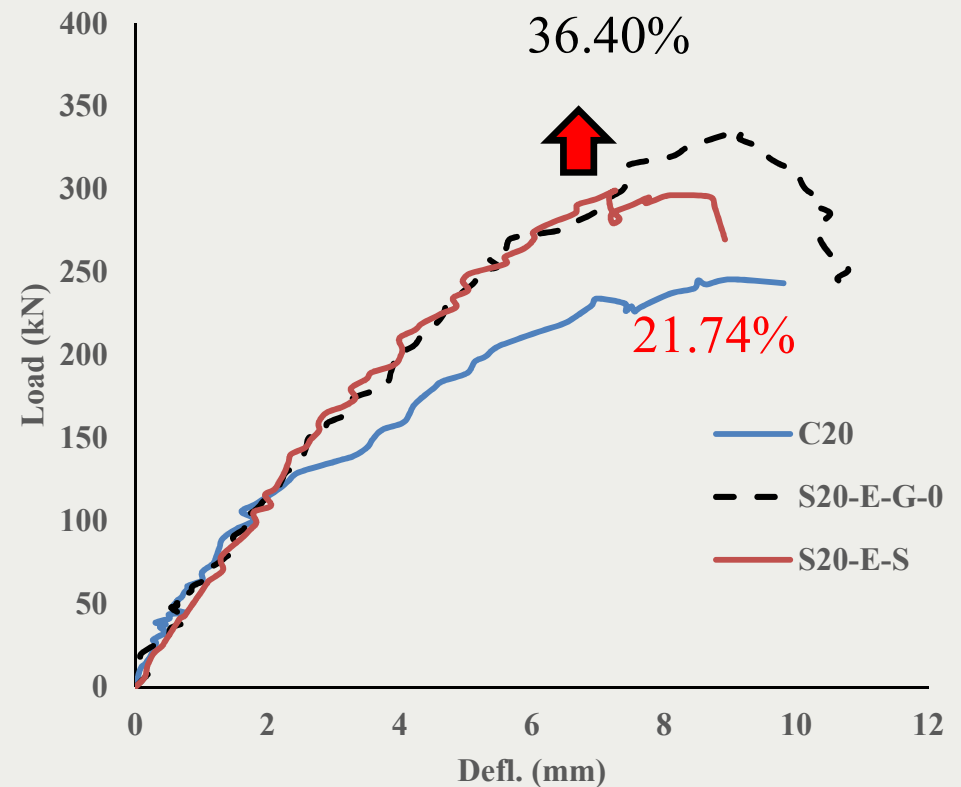
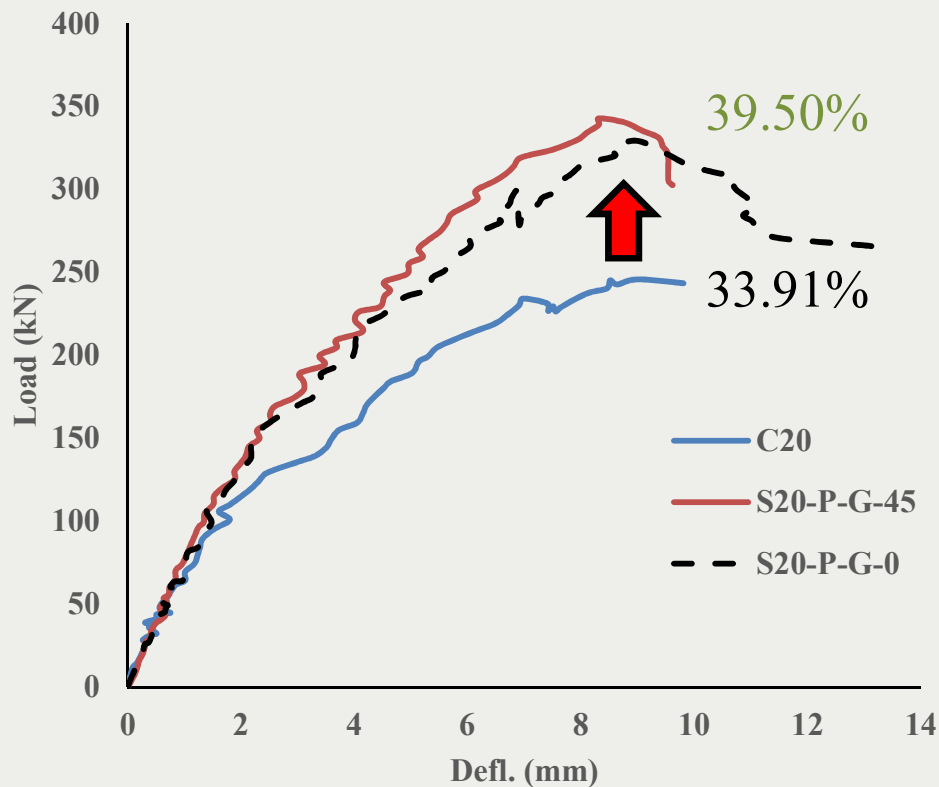


Name convention for specimens.

SHEAR STRENGTHENING OF RC BEAMS

- **Load-deflection relationship of the tested RC beam:**

The external shear strengthened layer is effective in controlling the diagonal shear cracks width.



Load-deflection curves of strengthened beam with BFRP grid in PCM for shear span 2.0.

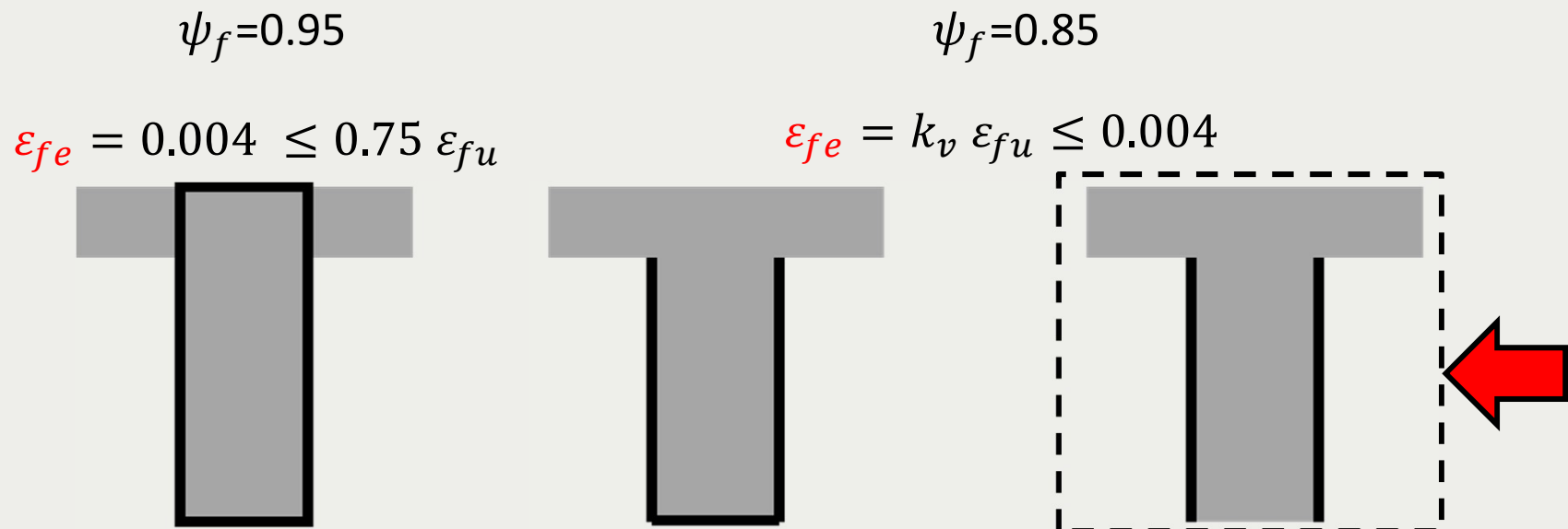
SHEAR STRENGTHENING OF RC BEAMS

- **Shear contribution of externally bonded FRP grids:**

The nominal shear strength of an FRP strengthened concrete member can be determined by adding the contribution of the FRP external shear reinforcement to the contributions from the reinforcement steel stirrups and the concrete, *ACI 318* and *ACI 440.2R*.

$$\Phi V_n = \Phi(V_c + V_s + \psi_f V_f)$$

$$V_f = A_{fv} E_f \epsilon_{fe} (\sin \alpha + \cos \alpha) d_{fv} / S_f$$



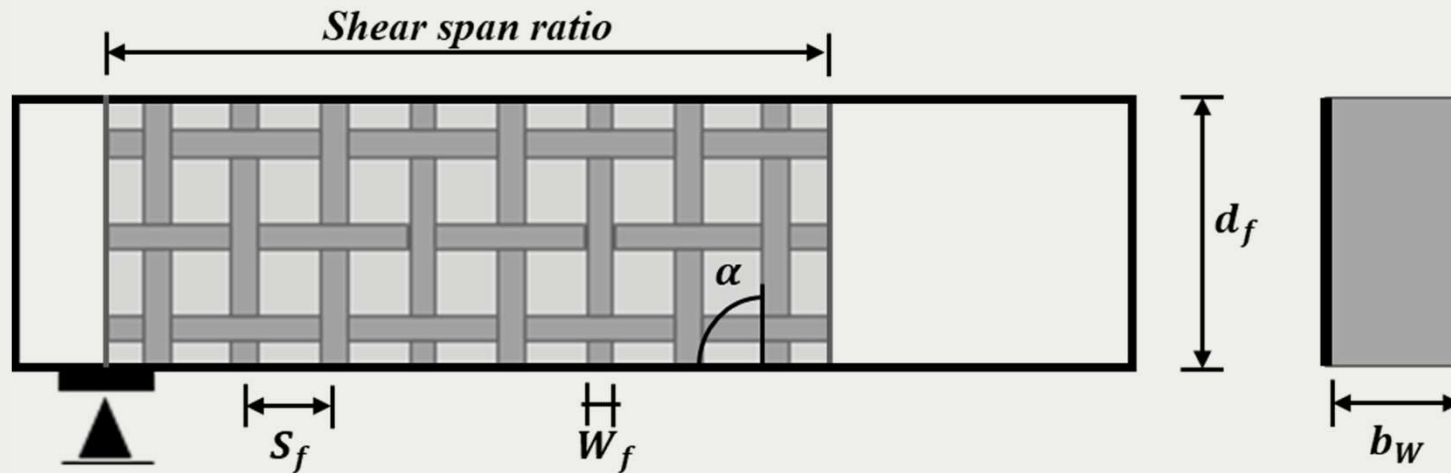
Typical wrapping schemes for shear strengthening using FRP composites.

SHEAR STRENGTHENING OF RC BEAMS

- Shear contribution of externally bonded FRP grids:

$$V_f = A_{fv} E_f \varepsilon_{fe} (\sin \alpha + \cos \alpha) d_{fv} / S_f$$

$$A_{fv} = 2nt_f w_f$$



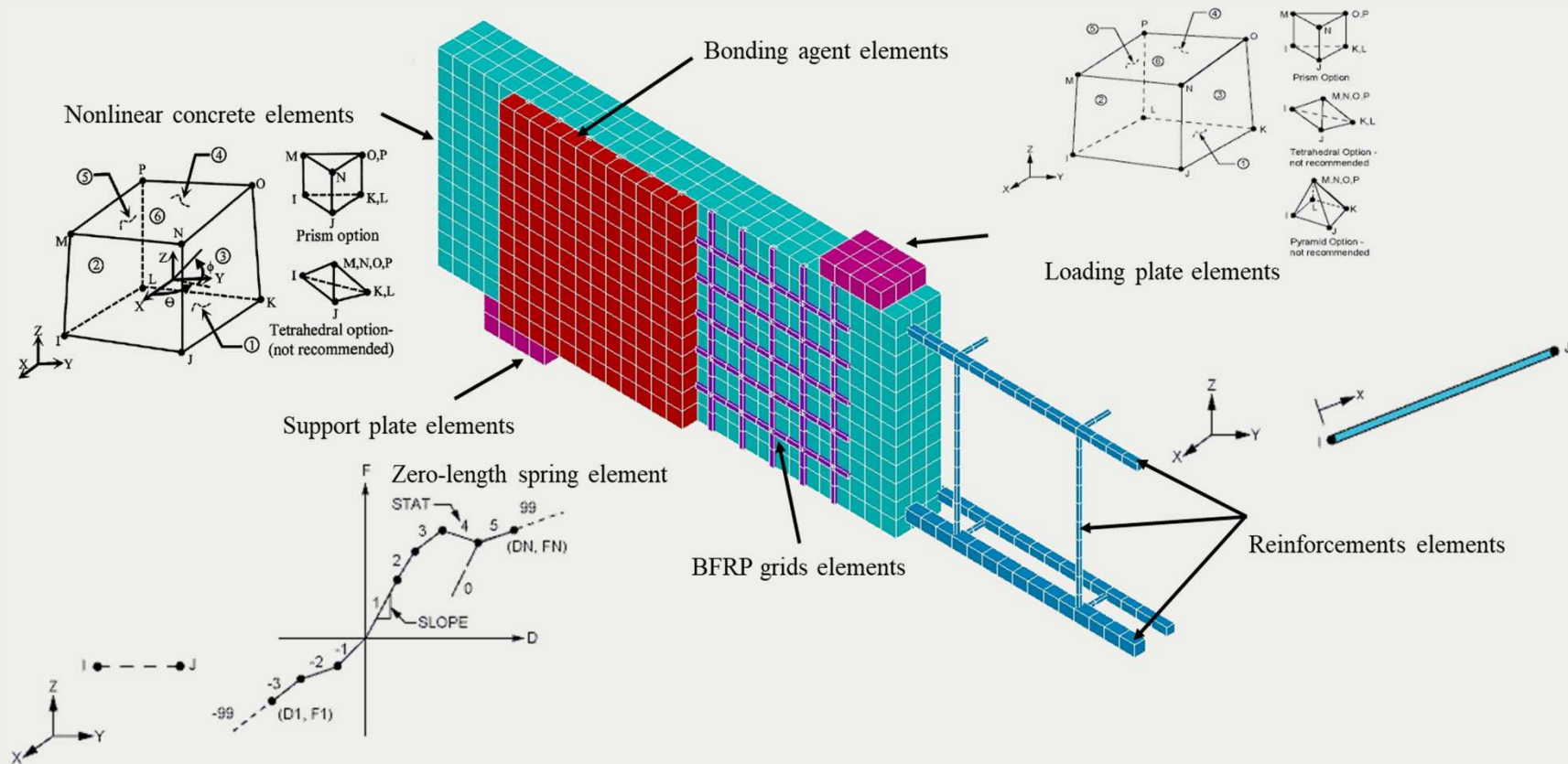
| FRP grid schemes | V_{fVL} (kN) | V_{fHL} (kN) | V_f (kN) | [Exp.] V_f (kN) |
|------------------|----------------|----------------|------------|-------------------|
| Parallel grids | 24.48 | 20.60 | 45.09 | 45.88 |
| 45° grids | 24.41 | 24.41 | 48.82 | 48.45 |

That indicates that horizontal ribs not only enhance the bond between FRP grids and concrete surface, but also has its contribution in the shear strength.

SHEAR STRENGTHENING OF RC BEAMS

- Numerical Simulations of Strengthened RC Beams:**

FEMs with quarter size of [1120 mm × 300 mm × 75 mm] were modeled with same procedures in the previous double shear simulations and using the identified local bond-slip models.

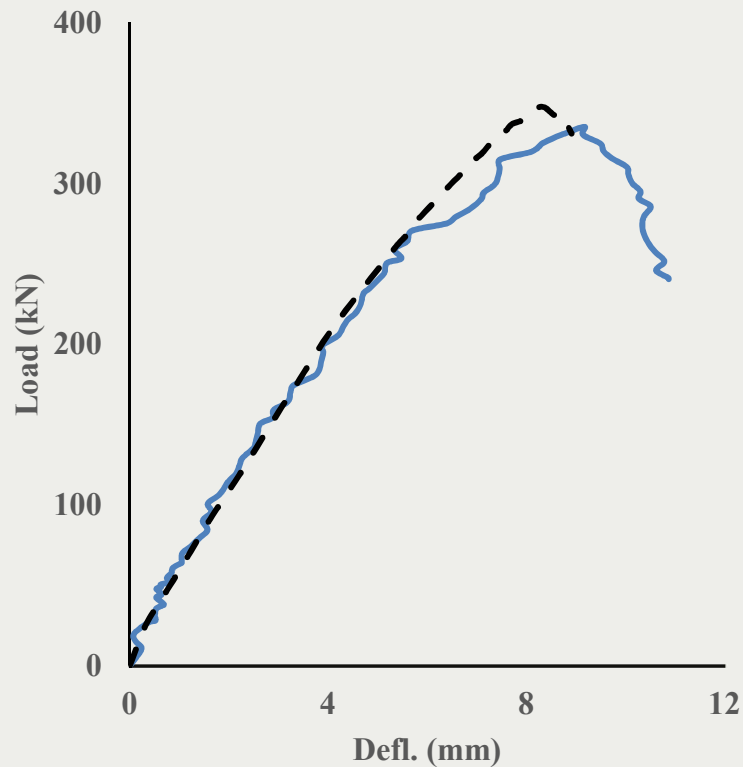


Typical 3D FEM for simulating the shear strengthened RC beam specimens.

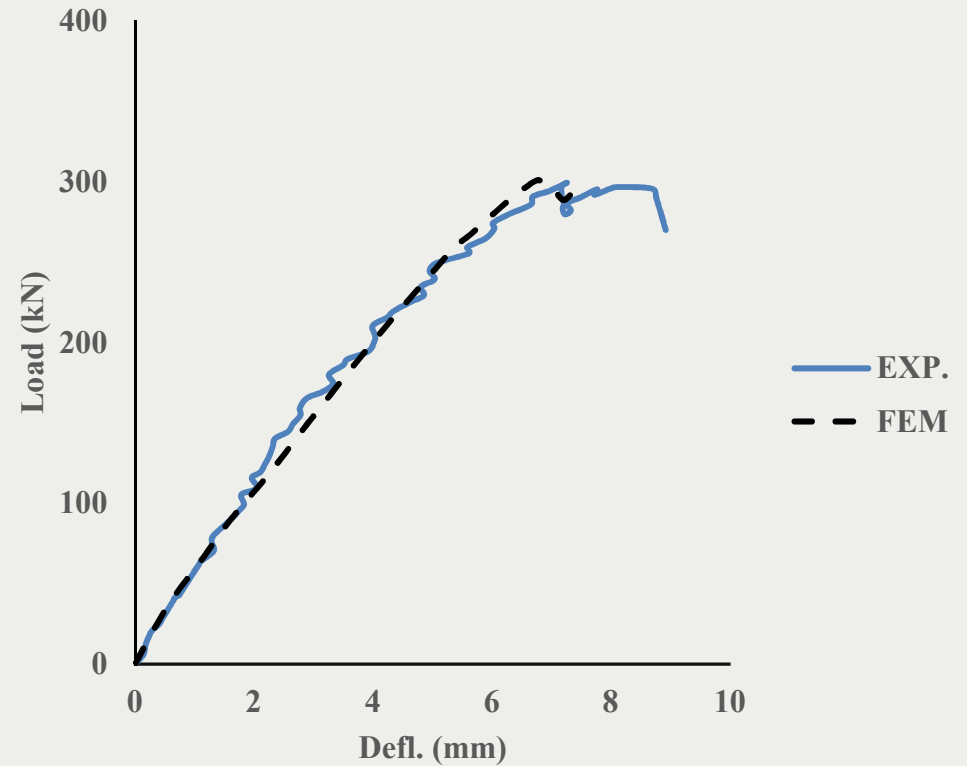
SHEAR STRENGTHENING OF RC BEAMS

- Numerical Simulations of Strengthened RC Beams:**

A link element was adopted to represent a 25 mm wide of the BFRP sheets, the bond between the BFRP sheets and the adjacent concrete surface was assumed perfect (*Sato and Ko, 2008; Ibrahim et al., 2016*).



Beam [S20-E-G-0].



Beam [S20-E-S].

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CONCLUSION AND RECOMMENDATION

- **The efficiency of BFRP grid in external strengthening of RC beams:**

The bond behavior of the BFRP grids strengthened system is highly competitive compare to epoxy-bonded FRP sheets. This appears to be primarily due to the better bond performance between the longitudinal ribs of the grids and concrete surface by the anchorage provided by the orthogonal (transverse) ribs of the grids.

The flexural strengthened beams with BFRP grids exhibited a hardening behavior after steel yielding, that refers to the efficiency of this system in flexural strengthening. Furthermore, the strengthened beams bonded with PCM obtain higher load bearing capacities to epoxy-bonded system, which indicates the contribution of the PCM to the flexural capacity of the strengthened beams.

From the shear strengthening investigations, BFRP grids bonded with PCM is more effective than epoxy-bonded FRP sheet systems in term of shear contribution per fiber content. In addition, the appearance and propagation of cracks in the bonding agent PCM gives an enough warning of the imminence failure.

CONCLUSION AND RECOMMENDATION

- The design guidelines for BFRP grid strengthened RC beams:

For flexural strengthening, the design guidelines based on the maximum effective strain in externally bonded FRP composites at which debond may occur, give an excellent prediction. A slight modified had done by taken the flexural contribution of the bonding agent into consider.

$$M_n = A_{s'}F_{s'} \left(\frac{\beta_1 c_{N.A}}{2} - d_{s'} \right) + A_s F_s \left(d_s - \frac{\beta_1 c_{N.A}}{2} \right) + \psi_f A_f F_f \left(d_f - \frac{\beta_1 c_{N.A}}{2} \right) + \psi_b A_b F_b \left(d_b - \frac{\beta_1 c_{N.A}}{2} \right)$$

For shear strengthening, the design guidelines stated in *ACI 318* and *ACI 440.2R* gives an excellent prediction of the shear contribution of the external FRP grids and the shear capacity of the strengthened beams.

$$V_f = A_{fv} E_f \epsilon_{fe} (\sin \alpha + \cos \alpha) d_{fv} / S_f$$

الْحَمْدُ لِلَّهِ الَّذِي بِنِعْمَتِهِ تَتِمُّ الصَّالِحَاتُ

Thank you
Very much