Strengthening of Bridge Components Using Epoxy-bonded Fiber Reinforced Polymers (FRP) and Health Monitoring using Non-Destructive Evaluation (NDE) Techniques

By

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Part 1-Introduction

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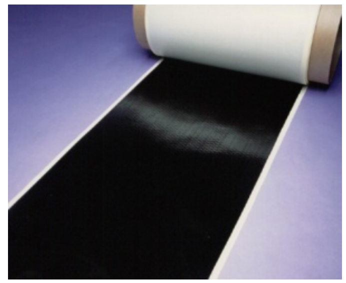
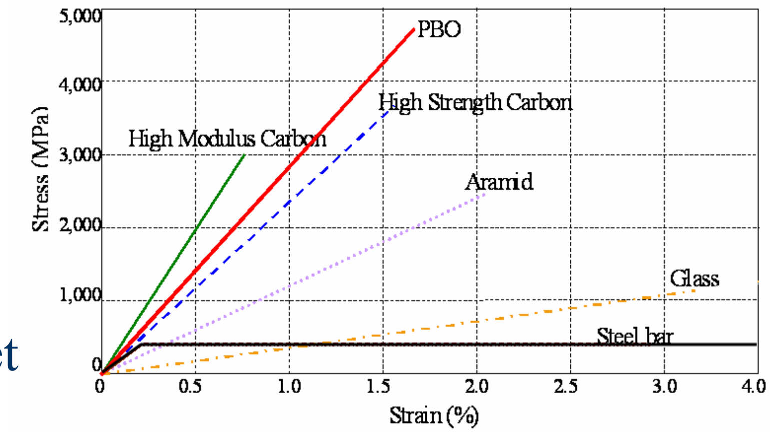
Fibers



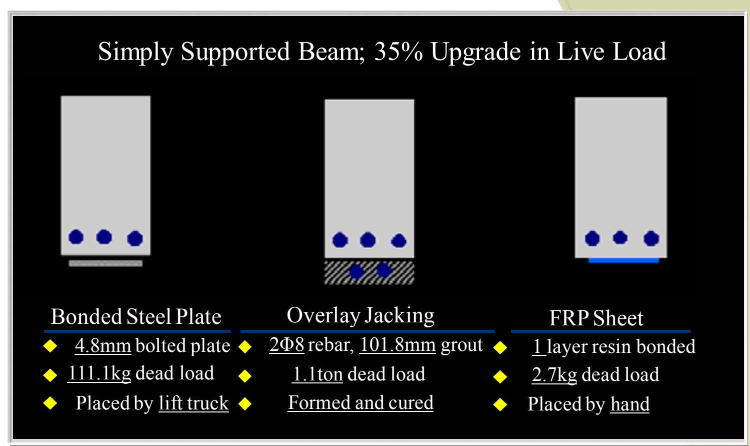
Carbon Fiber Sheet



- **Externally bonded *Fiber Reinforced Polymer (FRP) composites* used for strengthening of deficient RC structural components**

Advantages in using composites for structural rehabilitation

- **Reduced weight**
- **High stiffness/weight, strength/weight ratio**
- **Corrosion resistance**
- **Significant enhancements in strength and ductility**
- **Limited disruption of traffic**



Part1- Field applications

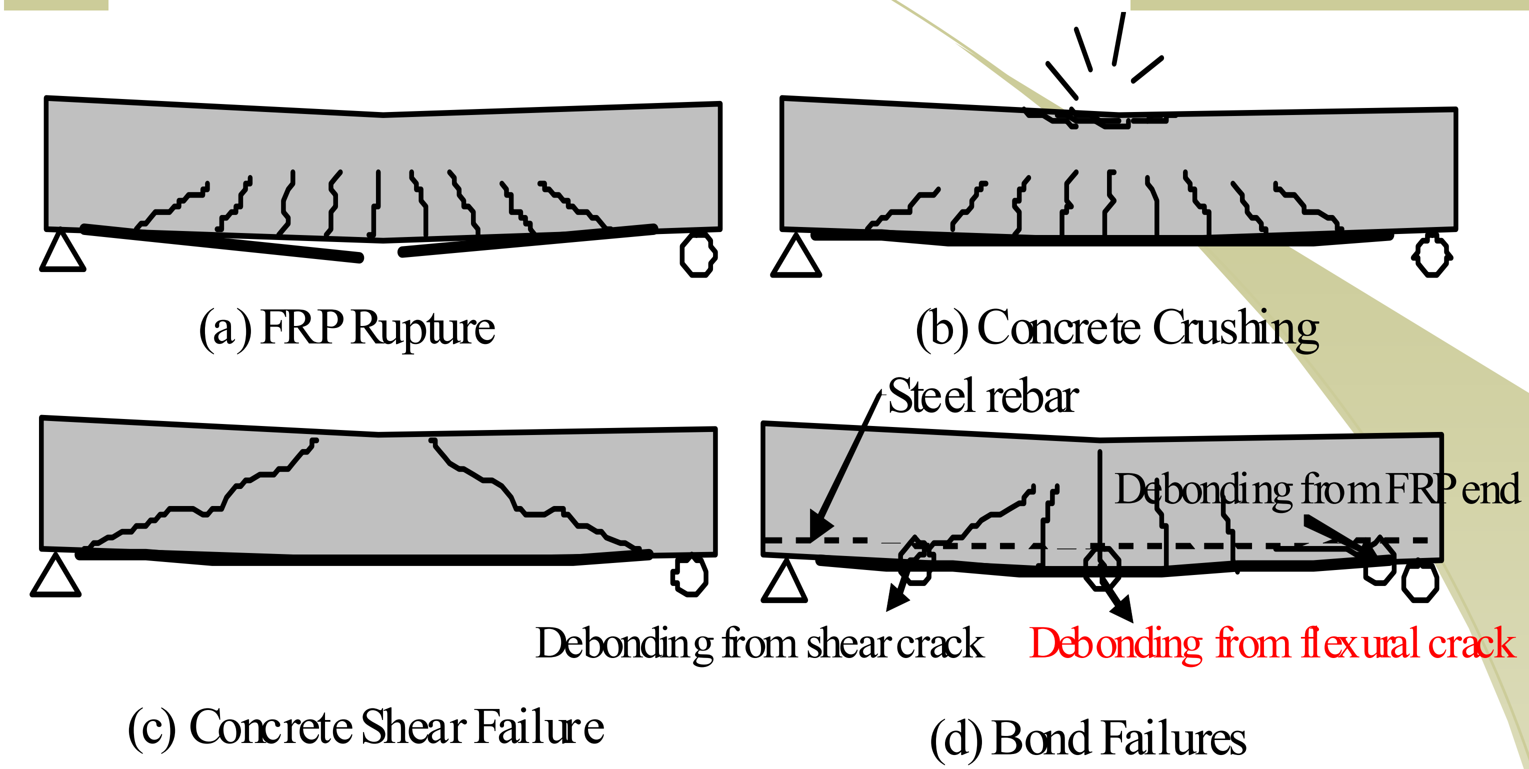
Bridge pier- confinement

Girder Strengthening

Tunnel lining

Deck Strengthening

Part1-Typical failure modes



FRP Flexural Strengthening of Structures

Intermediate crack-induced debonding failure is dominant and hard to predict

Part 1- ACI 440 procedure 1

- **ACI nominal capacity is limited by the effective FRP strain, governed by concrete crushing (ε_{cu} = 0.003) and debonding failure**

Strain in FRP at concrete crushing

Initial strain in FRP due to dead load

Ultimate strain of FRP factored by bond coefficient to prevent debonding failure

$$\varepsilon_{fe} = \varepsilon_{cu}\left(\frac{h-c}{c}\right) - \varepsilon_{bi} \le \kappa_m \varepsilon_{fu}$$

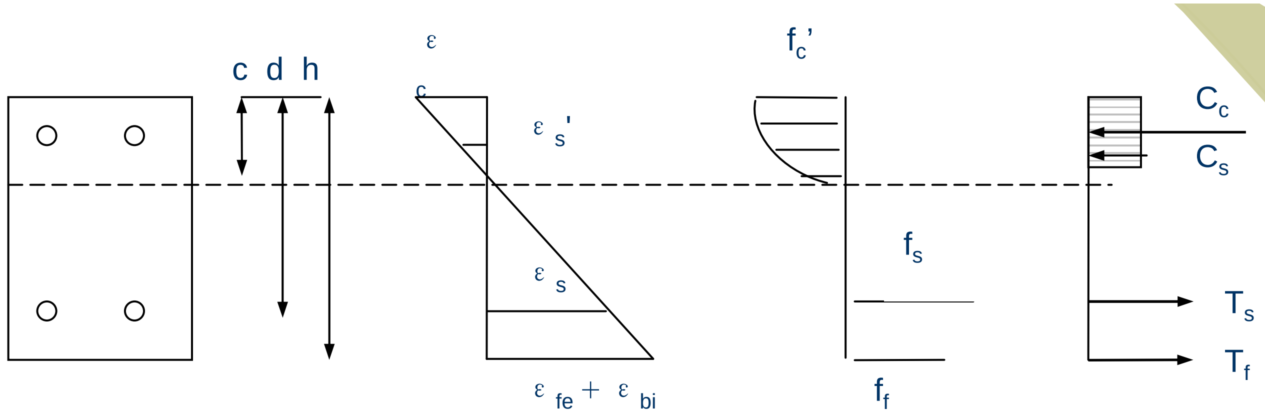
- **Ultimate strain of FRP is factored by bond coefficient in order to take into account premature debonding**

$$\kappa_m = \frac{1}{60\varepsilon_{fu}}\left(1 - \frac{nE_f t_f}{360{,}000}\right) \le 0.9 \;\; for \; nE_f t_f \le 180{,}000$$

$$\kappa_m = \frac{1}{60\varepsilon_{fu}}\left(\frac{90{,}000}{nE_f t_f}\right) \le 0.9 \;\; for \; nE_f t_f > 180{,}000$$

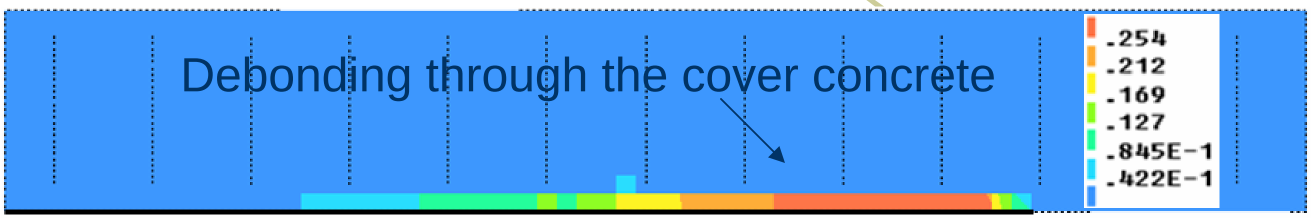
Part 1-ACI 440 procedure 2

$$M_n = A_s f_s\left(d - \frac{\beta_1 c}{2}\right) + \psi_f A_f f_{fe}\left(h - \frac{\beta_1 c}{2}\right) - A_s' f_s'\left(d' - \frac{\beta_1 c}{2}\right)$$

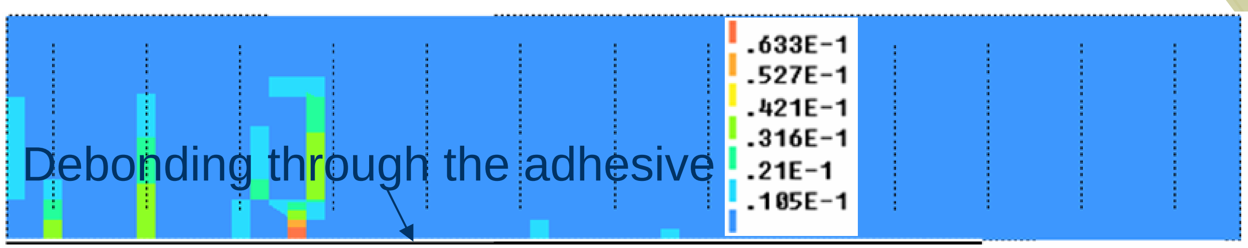


- **Nominal moment is calculated in the same way as conventional reinforced concrete, except there is an extra term for the FRP**
- **A reduction factor, ψ, is applied to the force in the composite, reducing its contribution to the nominal strength of the beam, in order to account for the uncertainty involved with FRP composites**

Part 1-Debonding failure mechanisms by FEM



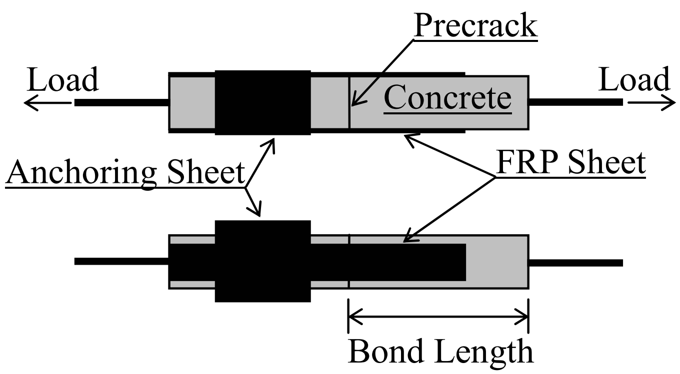
Low concrete strength



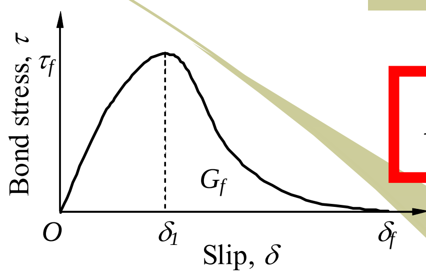
High concrete strength

<u>Debonding is an interface-related failure associated with properties of concrete, bond and FRP</u>

Part 1-Comparison of Loading Conditions



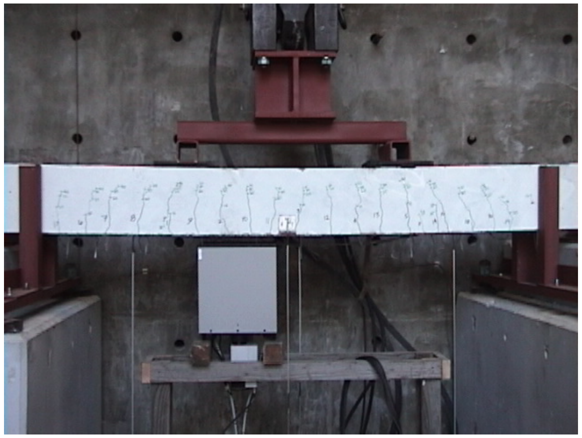
Simple bond test

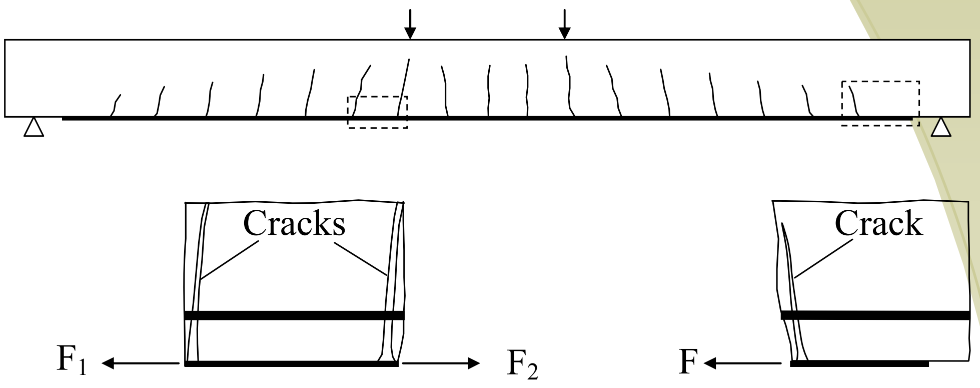


$$P_{\max} = b_{frp}\sqrt{2G_f E_{frp} t_{frp}}$$

where b_{frp}, E_{frp} and t_{frp} are width, modulus and thickness of FRP, respectively;

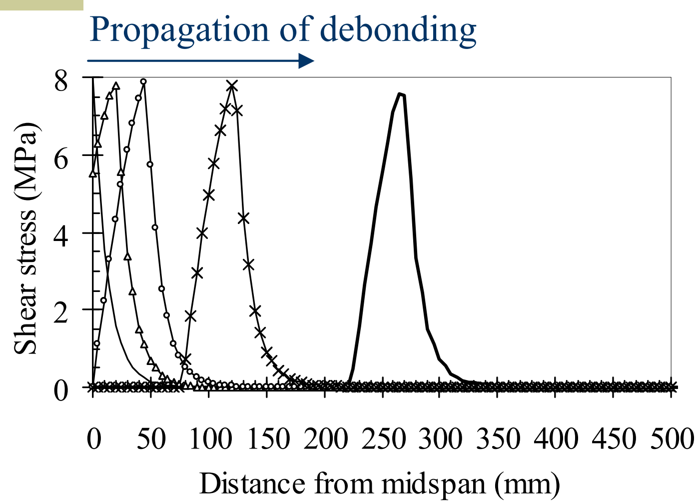
G_f=interfacial fracture energy consumed for debonding failure.



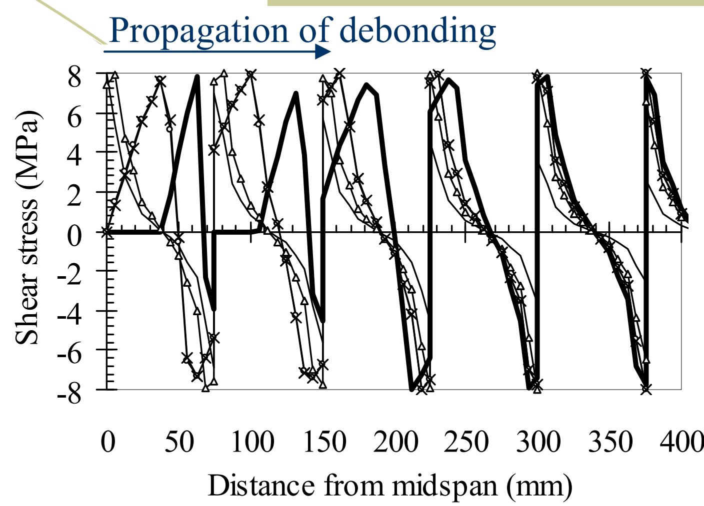


Debonding mechanisms in FRP-strengthened beams

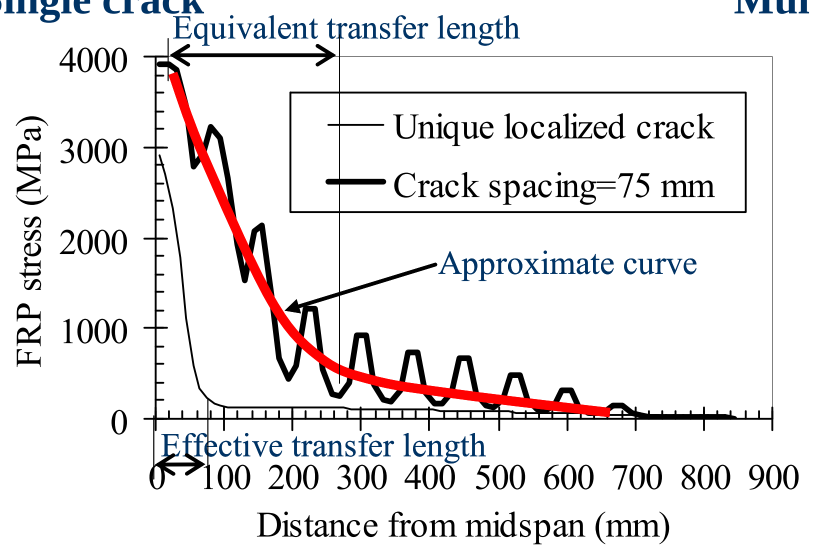
Part 1-Debonding behaviors by FEM



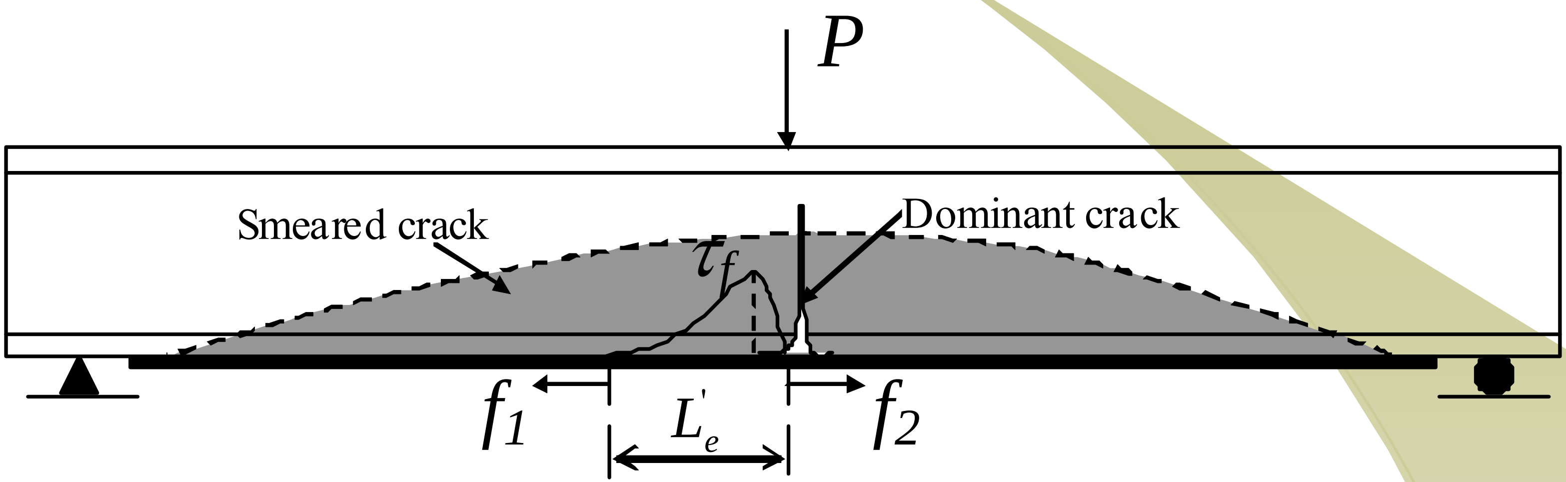
Simple bond test/ Single crack



Multiple cracks



Part 1-Prediction of debonding failure load

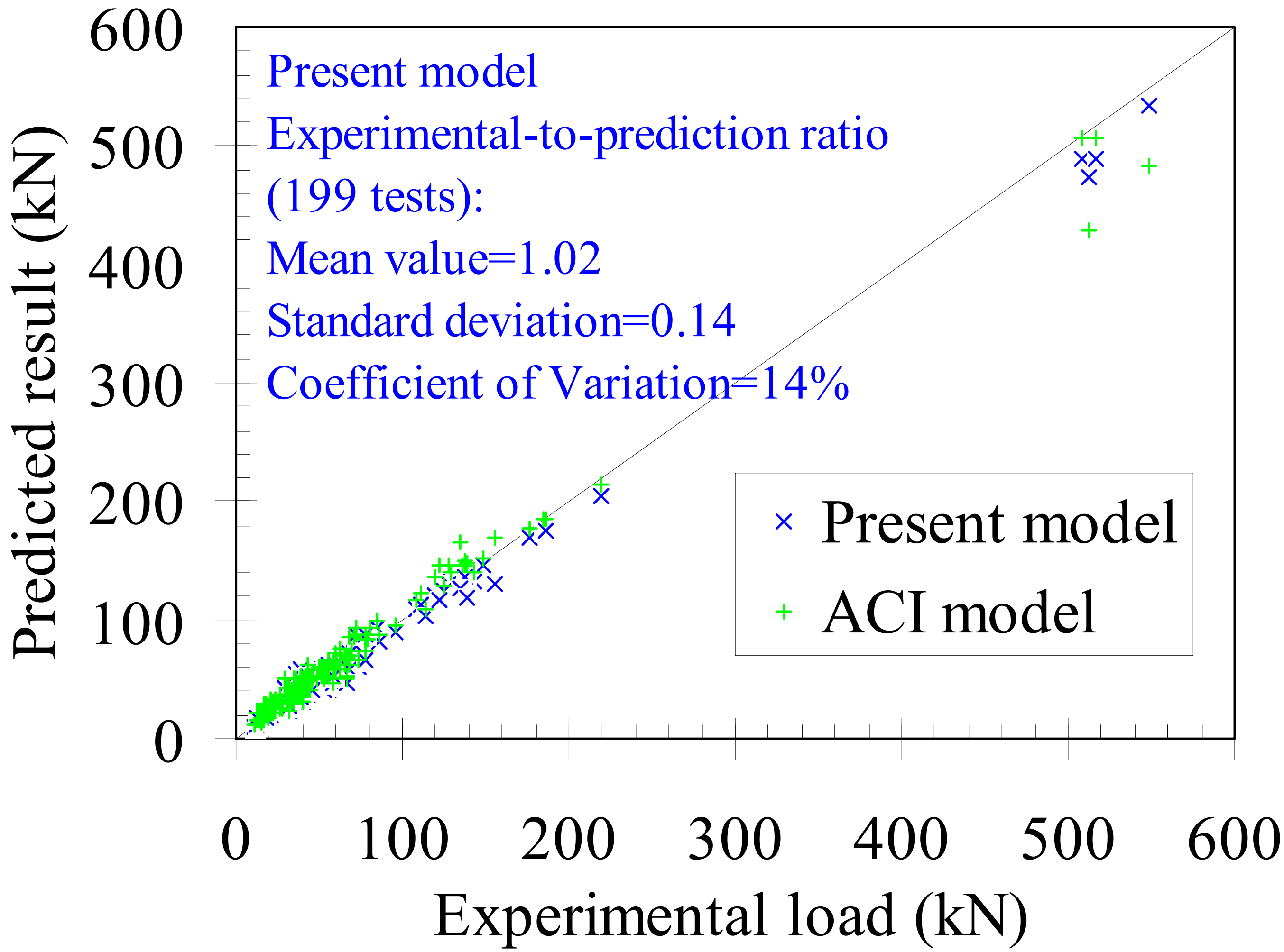


$$L_e' = \frac{1.3\sqrt{E_{frp} t_{frp}}}{f_c'^{0.095}} \quad \text{(mm, MPa)}$$

$$P_{deb} \Rightarrow (f_2 - f_1) \geq b_{frp}\sqrt{2G_f E_{frp} t_{frp}}$$

$$G_f = 0.644 f_c'^{0.19} \quad \text{(N/mm, MPa)}$$

Part 1-Validation of the proposed model



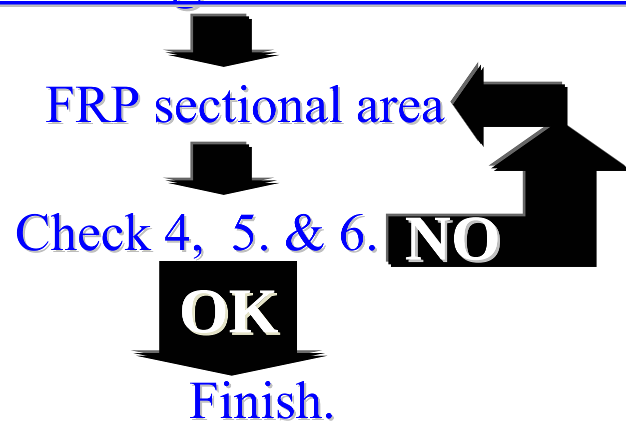
Simple model: $\varepsilon_{deb}=0.23(f_c')^{0.2}/(E_{frp}t_{frp})^{0.35}$ (Wu et al. 2008)

Part 1-Design considerations

1. Crushing of concrete before yielding of reinforcing steel
2. Yielding of reinforcing steel followed by rupture of FRP
3. Yielding of reinforcing steel followed by concrete crushing
4. Premature failure at ends of FRP laminate
5. Debonding of FRP due to flexural cracking
6. Peeling-off of FRP caused by shear cracking

Ductile & Preferable

3. Yielding of reinforcing steel followed by concrete crushing



Part 2-Non-destructive evaluation

- **To be used not only as a tool for periodic inspection and quality assessment but also to quantitatively monitor over time the appearance/progression of damage**

- **Should be rapid, cost-efficient and reliable**

- **Objective of NDE in FRP rehabilitated structures:**

  - **Quality Assurance / Data inventory**

  - **Local NDE**

    - **Evaluate performance level of FRP composite strengthening through detection of subsurface damage and deterioration at the composite-concrete or composite-composite interface**

  - **Global NDE**

    - **Health monitoring of overall structural performance over its life cycle in terms of damage appearance and/or progression**

Part 2-Case study overview

Systems level test of 3 girder-2 span slab-on-girder bridge segment

Modeling

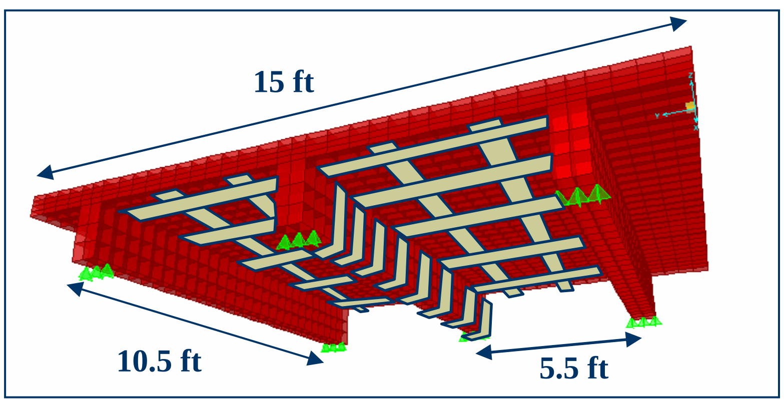
- Analytical and FE modeling – Capacity predictions

Testing

- Stage I: Damage in slabs followed by strengthening of slabs with FRP
- Stage II: Damage in girder followed by strengthening of girder with FRP
- Stage III: Failure of strengthened slabs and damage at slab-girder joint

Capacity estimation and monitoring damage progression through instrumentation and NDE

Comparison of analytical/FEM predictions with test results and correlating damage progression measured through NDE with visual observations and test results



Part 2-Composite strengthening

STRENGTHENING OF SLAB WITH COMPOSITE- Flexural strengthening


Resin impregnation of fabric


Adhesive application on concrete


Bonding fabric to concrete


Finished product

STRENGTHENING OF GIRDER WITH COMPOSITE- Shear strengthening

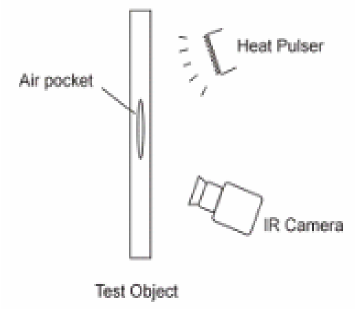

Application of primer coat

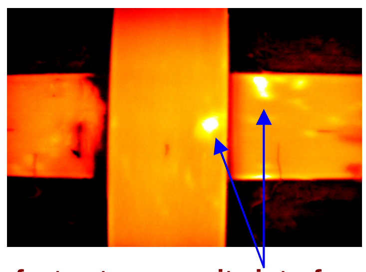

Bonding FRP to concrete


Finished product

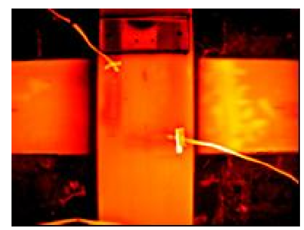
Part 2-Local NDE – IR thermography

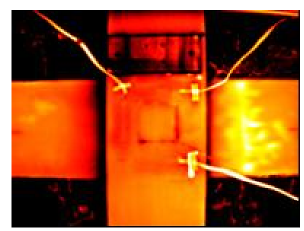
- **IR thermography as NDE tool for FRP Composite Defects:**
  - **Non-contact optical technique aimed at detection of subsurface defects with an infrared (IR) camera under relevant temperature differentials produced through ACTIVE (external source) or PASSIVE (natural source, e.g. the sun) heating**
    - **Defects cause interruption in heat flow resulting in hot / cold spots**



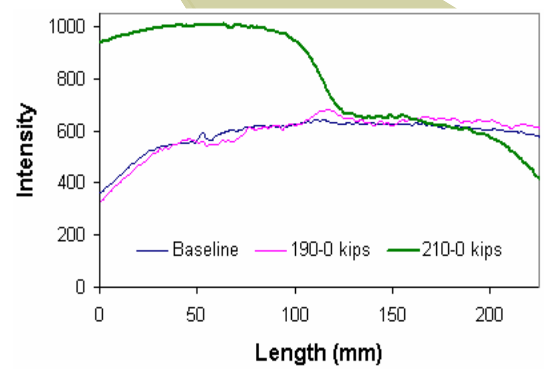


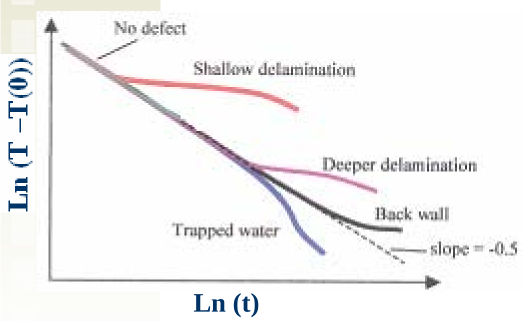
Defects at composite interface

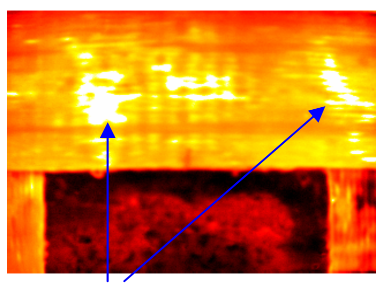




Damage progression at a crack



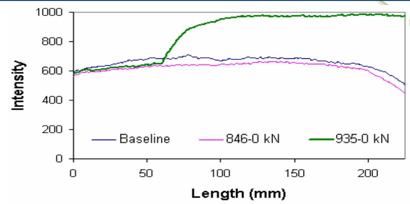
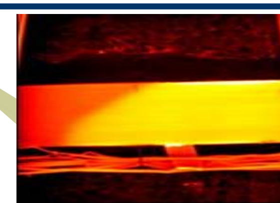
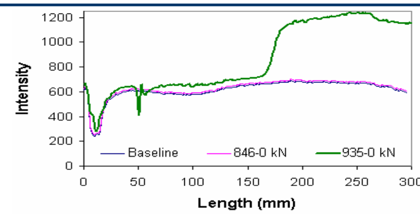
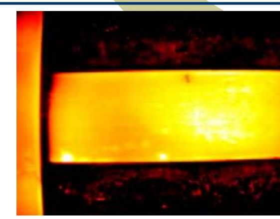
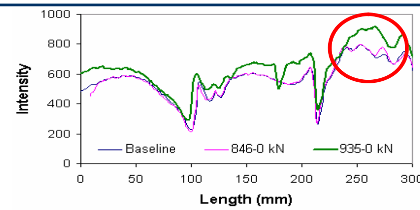
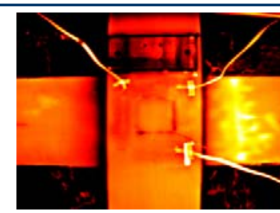
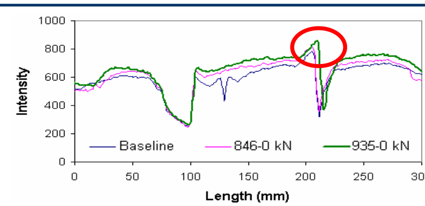
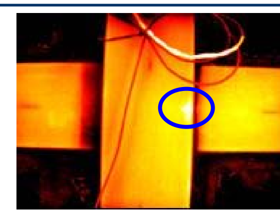
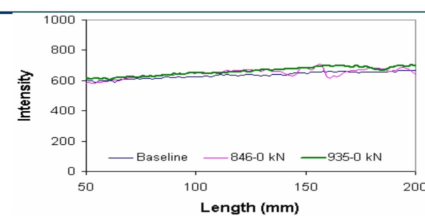
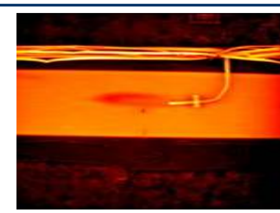




Defects at composite-concrete bond

- Real-time inspection and data interpretation allow instant assessment of integrity and serviceability

Part 2-Characterization of defects

1	**Debonding of composite at pultruded strip - concrete interface**		
2	**Interlaminar debonding in the pultruded strip due to separation between fibers and matrix of strip**		
3	**Debond at pultruded strip -concrete interface due to opening of cracks**		
4	**Air void defects produced during installation of the pultruded strip**		
5	**No damage/defects**		

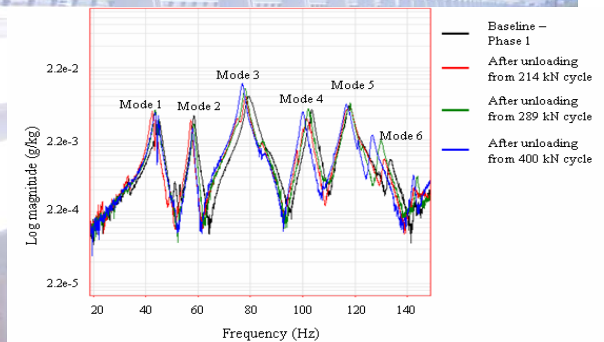
Part 2-Global NDE – modal testing

- **MODAL TESTING**
- **Obtain the dynamic signature of the structure (frequencies and mode shapes)**
  - **Related to mass and stiffness**

- **HEALTH MONITORING / MODEL UPDATING**
- **Monitor the health (in terms of stiffness) of structure by monitoring the frequencies and mode shapes**
- **Calibrate a baseline finite element model based on dynamic characteristics obtained from the baseline modal tests**
- **Use model updating over time to quantitatively determine the changes in stiffness parameters in localized regions of the model corresponding to the changes in the frequencies and mode shapes**
- **Localize the effects of damage progression and strengthening through quantification of the parameter changes**

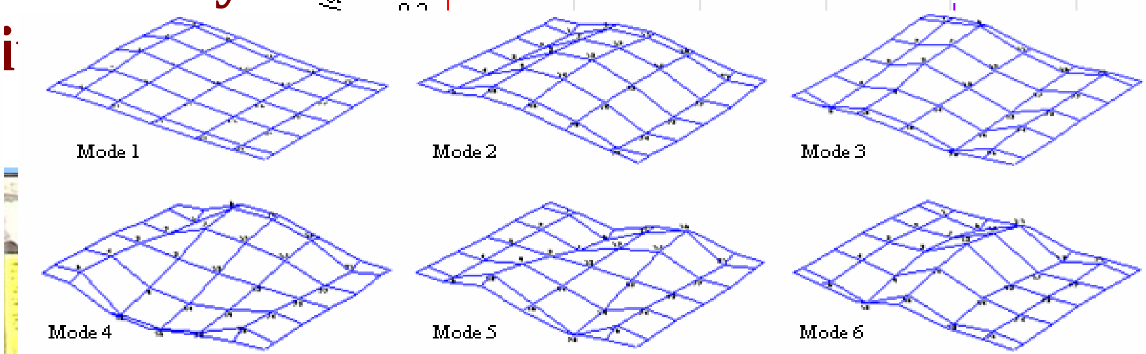
Part 2-Modal testing

Data Analysis

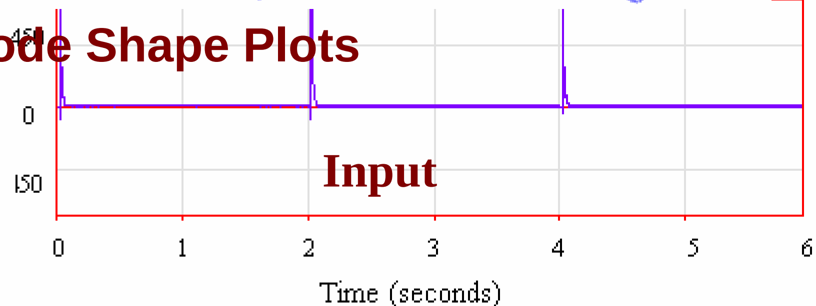


Spectral Density Plot

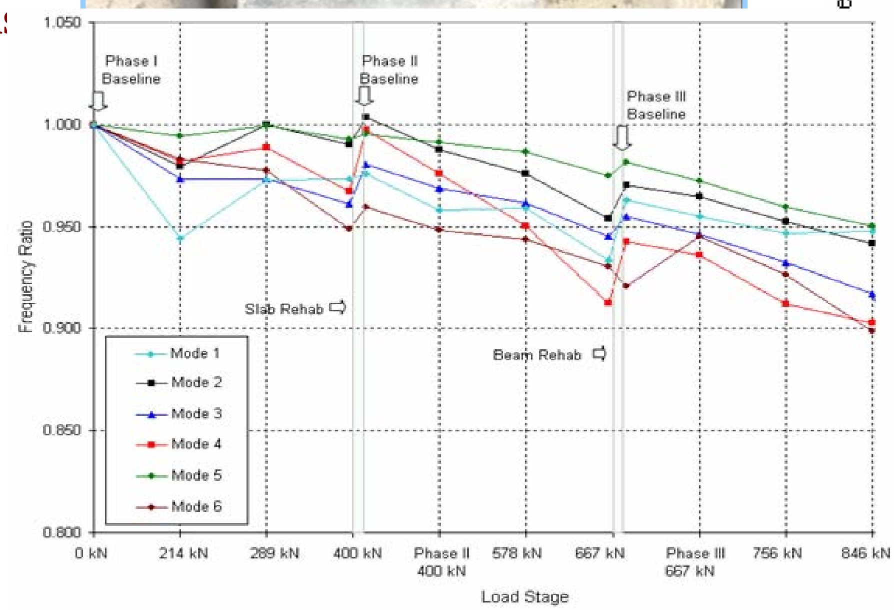
Visual Ins



Mode Shape Plots

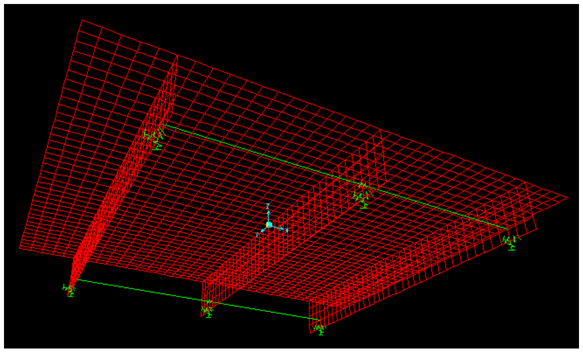


Input

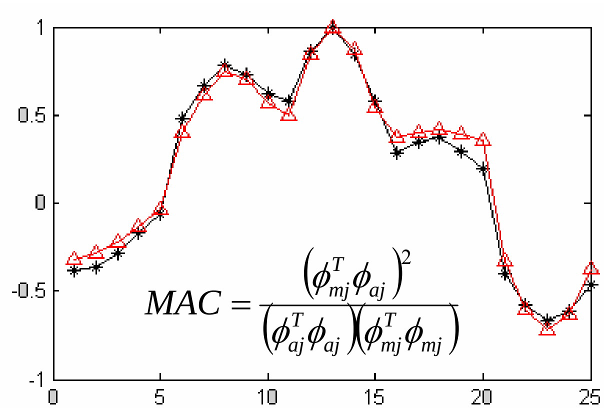


Natural Frequency Trend

Part 2-Model updating – damage localization



FE Model



Match between Experiment and FEM Modal Amplitudes for 1st longitudinal Bending

FUNDAMENTAL SYSTEM ID EQUATION

$$\mathbf{Z = F\alpha} \qquad k_j^* = k_j(1+\alpha_j)$$

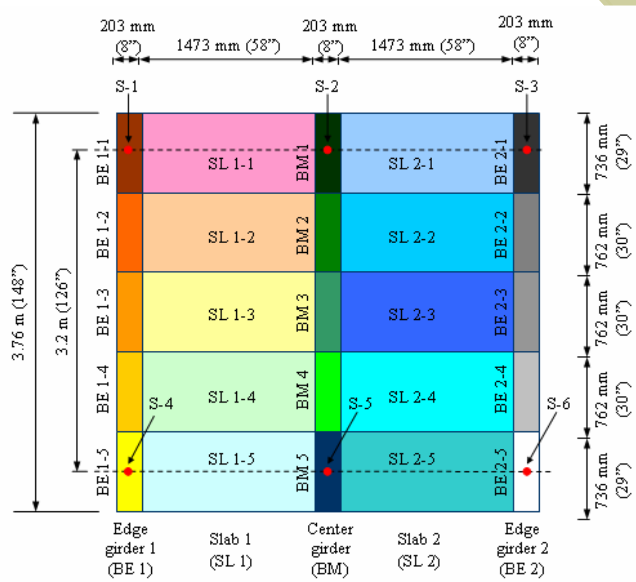
k_j* = unknown stiffness of the jth member of structure for which M eigenvalues are known

k_j = known stiffness of the jth member of FE model for which M eigenvalues are known

α = NEx1 matrix with fractional changes in stiffness between FE model and structure

Z = nx1 matrix containing fractional changes in eigenvalues between two systems

F = nxNE stiffness sensitivity matrix relating fractional changes in stiffness to eigenvalues



Parameters used:

5 Slab 1 stiffness

5 Slab 2 stiffness

5 Edge Beam 1 stiffness

5 Edge Beam 2 stiffness

5 Mid Beam 1 stiffness

6 spring stiffness

TOTAL of **31parameters**

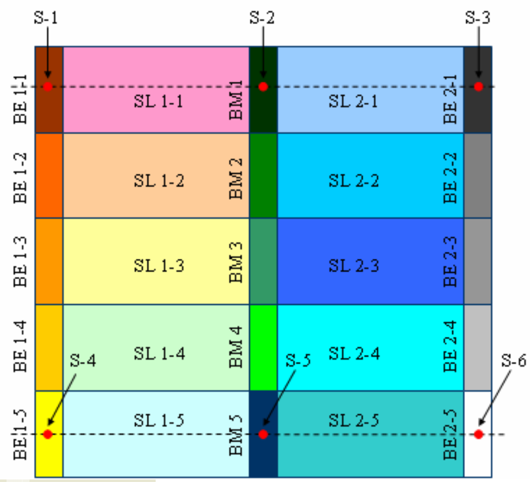
Targets for system ID → Measured **Frequencies** and **Modal Amplitudes (*n* numbers)**

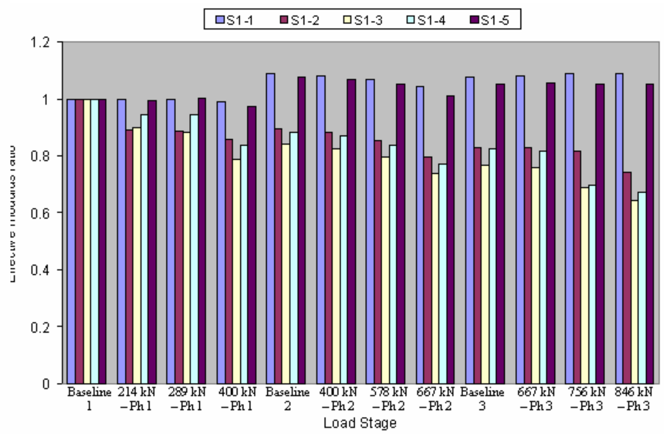
Z = [n x 1]

F = [n x 31] → α = [31 x 1]

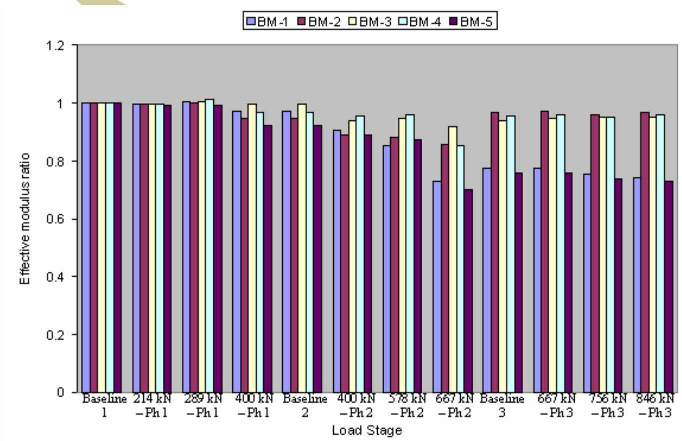
Part 2-Damage severity estimation

$$(Parameter\ \ Ratio)_i = \frac{Updated\ \ Parameter\ \ Value\ \ at\ \ Stage\ \ i\ \ of\ \ Test}{Updated\ \ Parameter\ \ Value\ \ at\ \ Baseline\ \ 1}$$



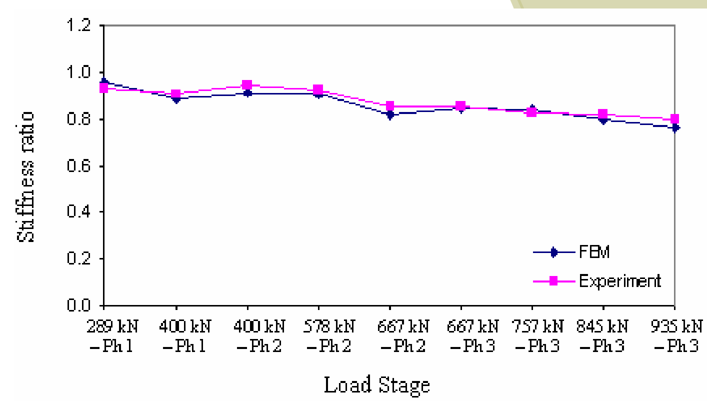


Changes in slab stiffness



Changes in girder stiffness

$$(Stiffness\ \ Ratio)_i = \frac{\left(\dfrac{\text{Load, } P_i \text{ at Stage i}}{\text{Deflection corresponding to Load, } P_i \text{ at Stage i}}\right)}{\left(\dfrac{\text{Load, } P_B \text{ at Baseline Load Stage}}{\text{Deflection corresponding to Load, } P_B \text{ at Baseline Load Stage}}\right)}$$



Comparison of stiffness ratios in Slab

Conclusions

- An energy-based analytical model is proposed to predict the debonding failure in FRP-strengthened RC beams;
- Design considerations incorporating different failure modes are made in using FRP composites to retrofit/strengthen existing RC beams;
- NDE is needed to quantitatively monitor over time the appearance/progression of damage in composite strengthened structure
- A combination of Global and Local NDE techniques are required; Modal Testing and IR Thermography have shown promise to be implemented for field applications

Questions / Comments ?