A guideline and review on the modelling techniques used in finite element simulations of concrete structures strengthened using FRP

Dr Robin Kalfat

SWINBURNE UNIVERSITY OF TECHNOLOGY

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Presentation outline

- ❑ The use of Fiber reinforced polymers (FRP) and their use in strengthening of concrete structures
- ❑ Why Finite element modelling?
- ❑ Modelling concrete compression.
- ❑ Modelling of concrete cracking.
- ❑ Defining concrete fracture energy.
- ❑ Influence of shear retention factor.
- ❑ Effect of bond between steel reinforcement and concrete.
- ❑ Modelling of the FRP-to-concrete interface.
- ❑ Influence of mesh size and element type .
- ❑ Modelling FRP sheets and fabrics.
- ❑ Calibration of material parameters.
- ❑ Examples.
- ❑ Summary of recommended modelling approaches.

Why Finite Element Modelling?

- Provide a predictive model for structural failure, expand the range of experimental data and provide information on key phenomena in the absence of experimental data (Zhang and Teng 2014).

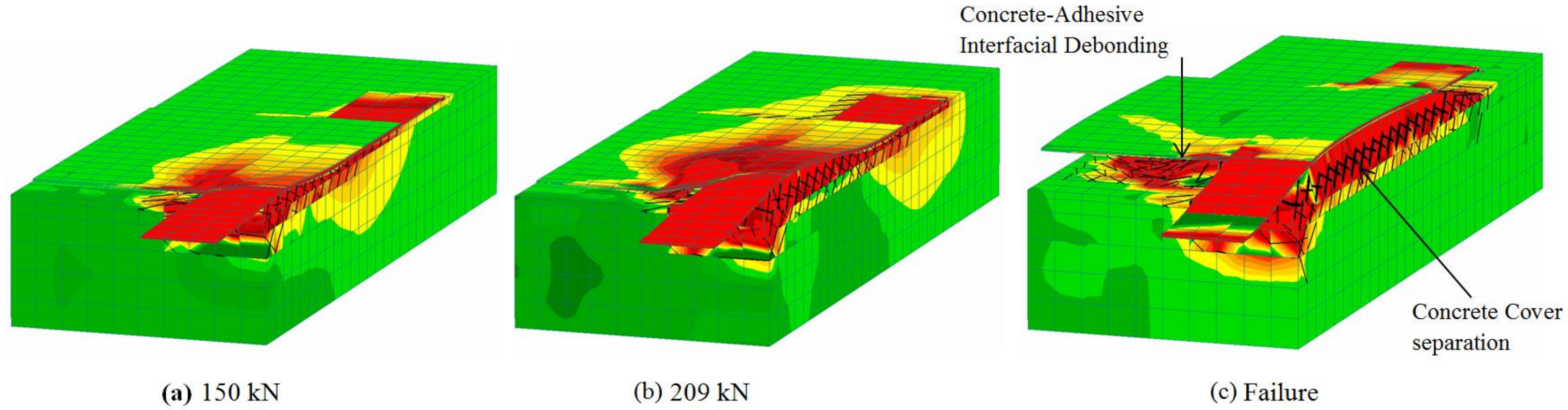


Figure – FRP debonding failure progression(FEM Model) depicting exaggerated deformations;

Modelling Concrete Compression

The compressive response of concrete is highly non-linear and can be described numerically using several approaches defined by Chen (2007):

(1) Representation of the stress strain relationship by curve fitting methods;

(2) Linear and non-linear elasticity theories (Ortiz 1985);

(3) Perfect and work hardening plasticity theories (Han and Chen 1985, Grassl et al. 2002)

(4) The endochronic theory of plasticity (Bażant 1978).

Modelling Concrete Cracking

(1) *<u>Discrete crack models –</u>* Discrete crack models rely on simulating individual cracks as geometrical identities within a model by introducing discontinuities within a finite element mesh at element boundaries.

(2) *<u>Smeared crack models –</u>* The cracked material is treated as a continuum and the deterioration caused by the crack is spread across the element by changing the element stiffness, a phenomenon also known as strain softening.

Fixed vs rotating crack models

- Fixed crack models utilise a constant crack orientation during the entire computational process
- Rotating crack models the crack direction changes during loading in accordance with the principal stress directions.
- Acceptable fixed crack results can only be achieved when a near zero shear retention factor is employed.
- The rotating smeared crack concept provides acceptable stress/strain rotations and a better prediction of model stiffness because of the shear retention function that provides coaxiallity between the principal stresses and strains.
- One disadvantage of the general rotating crack concept is that it does not retain a memory of damage orientation.

Modelling Concrete Cracking

(1) *Discrete crack vs smeared crack approach -* When the crack band model is adopted, the discrete crack and the smeared crack models yield approximately the same results provided that the crack opening displacement in the discrete crack model is taken as the cracking strain accumulated over the width of the crack band in a smeared crack model.

Defining concrete fracture energy

Fracture mechanics have demonstrated three modes in which a crack may propagate:

- ❑ Mode I fracture (G_F^I) is classified as an opening mode where the tensile stresses are normal to the plane of the crack.
- ❑ Mode II (G_F^{II}) is a sliding mode where crack propagation is propelled by shear stresses acting parallel to the plane of the crack and normal to the crack front.
- ❑ Mode III fracture (G_F^{III}) is classified as a tearing mode with shear stresses acting parallel to the crack plane and parallel to the crack front.
- ❑ <u>FRP debonding is a </u>Mode I fracture (G_F^I) phenomena.

Defining concrete fracture energy

- Fracture energy models are based on aggregate size, concrete strength and water cement ratio.
- A preferred approach is to use standard test procedures such as a notched beam test (JCI-S-001 2003) to obtain a more accurate estimation of concrete fracture energy.

Influence of Shear Retention Factor

- Due to the mechanism of concrete cracking the shear stiffness of the material is usually reduced. This reduction is generally known as shear retention.
- Shear retention should theoretically decrease for large crack strains as less shear stress is capable of being transmitted across the crack.
- Use of a constant shear retention factor results in a stiffer post peak response and too little structural softening (Rots and de Borst 1987).
- Researchers have found that models which used a shear retention factor of zero or a constant factor were not able to predict the measured failure load accurately.
- Only the use of a variable shear retention factor in which the crack shear resistance decreases with the crack opening has provided good correlations between numerical and experimental results (Scotta et al. 2001).

Effect of bond between steel reinforcement and concrete

Perfect bond or Bond slip?

The assumption of perfect bond between the steel reinforcement and the concrete results in:

(1) A more distributed diagonal crack pattern (Chen 2012).

(2) Lesser crack widths and a delay in the deboning failure load in the case of FRP strengthened beams.

(3) Higher shear retention and an artificial increase in the shear capacity of the beam.

Effect of bond between steel reinforcement and concrete

Common reinforcement bond-slip models implemented in many FE software such as ABAQUS (2001), Cervenka (2002) and DIANA (de Witte 2003) are proposed by:

CEB-FIB Model code 90 (1993) and Bigaj (1999).

The laws are generated based on:

(1) Concrete compressive strength

(2) Reinforcement diameter and

(3) Reinforcement type (bond quality).

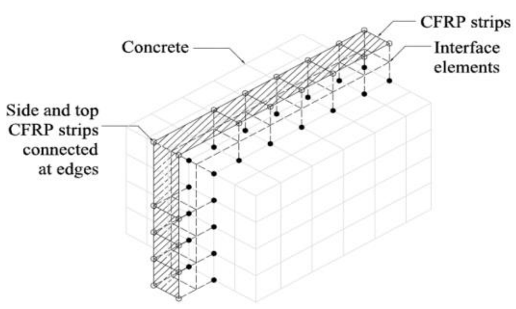
Modelling of the FRP-to-concrete interface

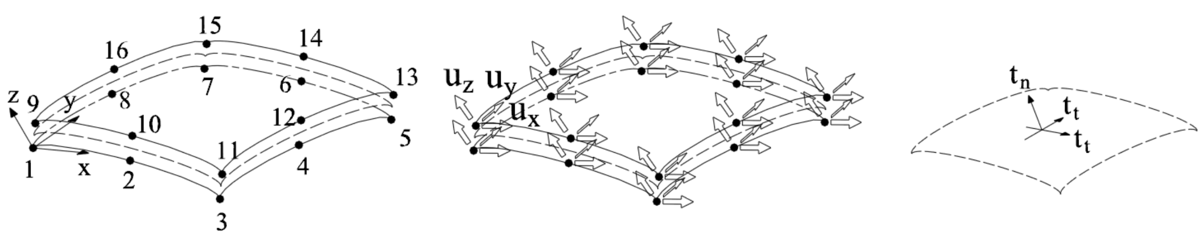
Approaches for modelling of FRP-to-concrete Interface:

(1) Perfect bond at the interface,

(2) The use of one-dimensional nonlinear spring elements between the adjacent concrete and adhesive layers (Luo 2011) and

(3) A layer of interface elements between the FRP and the concrete (Wu et al. 2009).





(a) (b) (c)

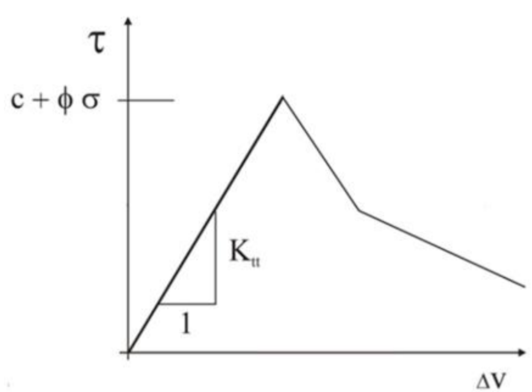
Modelling of the FRP-to-concrete interface

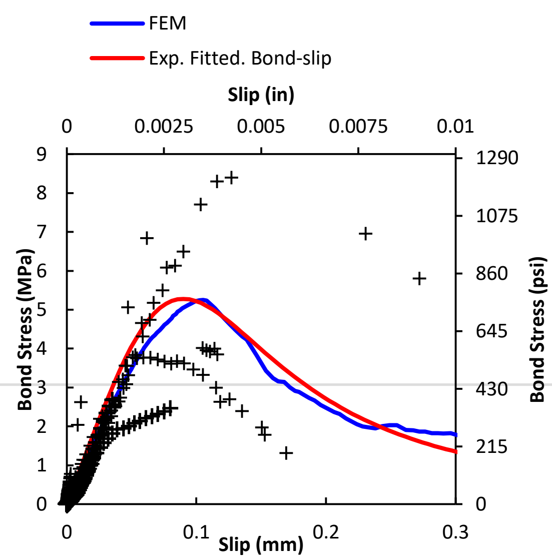
The use of Bond-Slip laws in FRP-to-concrete Interface (Popovics, 1973)

$$\tau = \frac{E_f(\varepsilon_{f,i+1} - \varepsilon_{f,i})t_f}{\Delta L} \qquad s_i = \frac{\varepsilon_{f,i+1} + \varepsilon_{f,i}}{2}\Delta L + s_{i-1}$$

Where E_f and t_f are FRP elastic modulus and thickness; $\varepsilon_{f,i+1}$ and $\varepsilon_{f,i}$ are axial FRP strains measured in the direction of the fibers at two discrete locations (i, i+1); and ΔL is the distance between strain gauges.

Typical interface model behaviour in shear with cohesion softening law; (a) Numerical definition (Cervenka 2007); (b) bond-slip curve for interface derived from experimental data.





Influence of mesh size and element type

- ❑ Objectivity of any numerical solution should be confirmed by parametric studies on mesh size to ensure that the solution is not mesh dependant.
- ❑ Finer mesh predicts the crack patterns more realistically
- ❑ Parametric studies on mesh dependency of FRP-to-concrete bonded joints conducted by Kalfat (2014) highlighted that a concrete element size of 0.2 in (5 mm) directly below the FRP laminate was necessary to accurately capture the bond-slip behaviour realistically

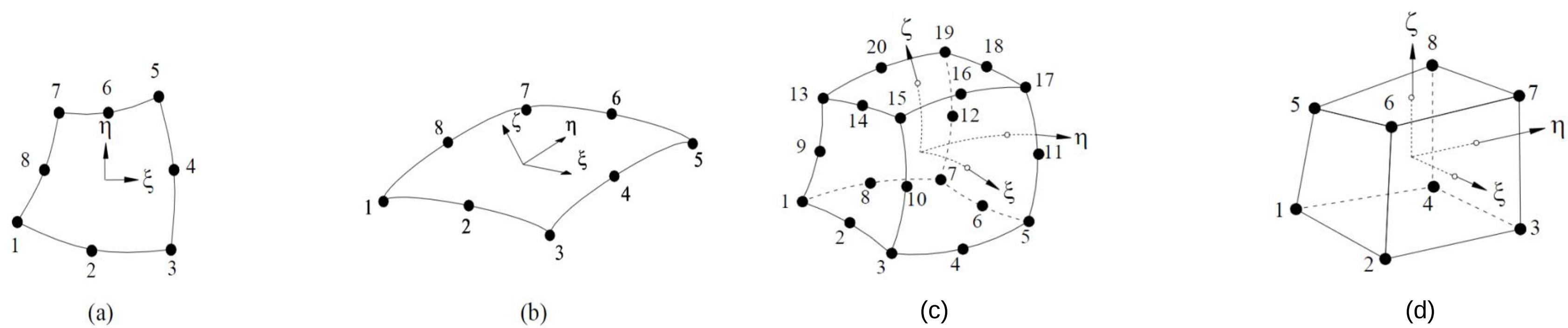


Figure - (a) Typical eight-node quadrilateral isoparametric plane stress element; (b) Typical eight-node quadrilateral isoparametric curved shell element; (c) Typical twenty-node isoparametric solid brick element and (d) Typical eight-node isoparametric solid brick element

Modelling FRP sheets and fabrics

Researchers have defined the FRP material using several approaches:

(1) An orthotropic material in a shell element

(2) Isoparametric brick elements defined with an isotropic 3D material representing the adhesive and unidirectional smeared reinforcement for the fibers

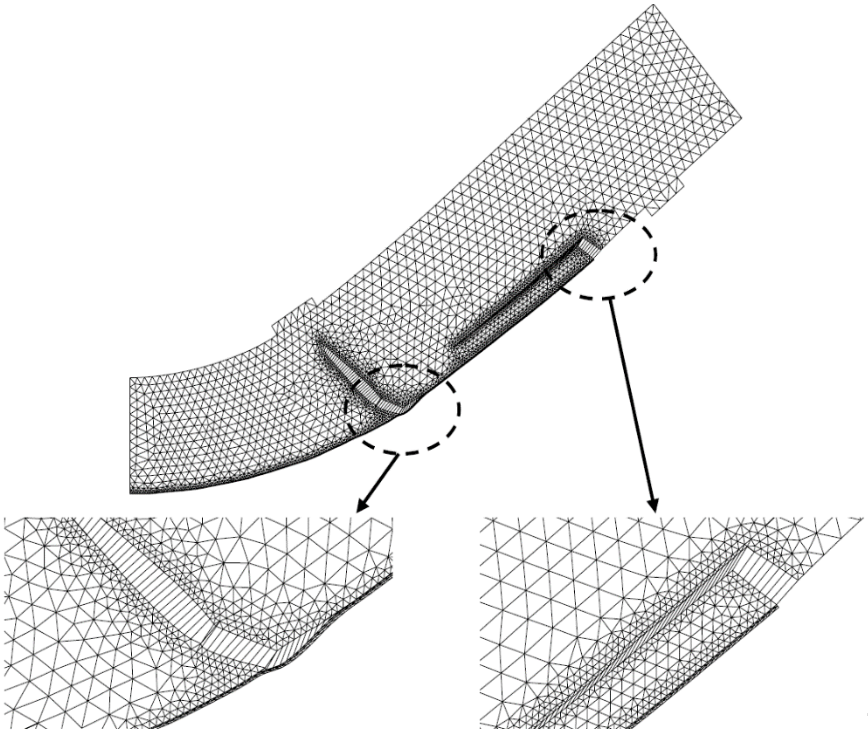
(3)1D beam element in the case of 2D FE models

Calibration of material parameters

- Use average and not characteristic values from experimental tests for the highest accuracy
- Cylinders or cubes should be tested at the time of testing to determine the average concrete compressive strength
- The concrete tensile strength may be obtained using the concrete compressive strength and established formulations derived from existing codes
- The tensile strength and modulus of elasticity of other materials such as: steel reinforcement, FRP and epoxy should also be established using standard testing procedures

FE simulations of debonding failure models for beams strengthened in flexure

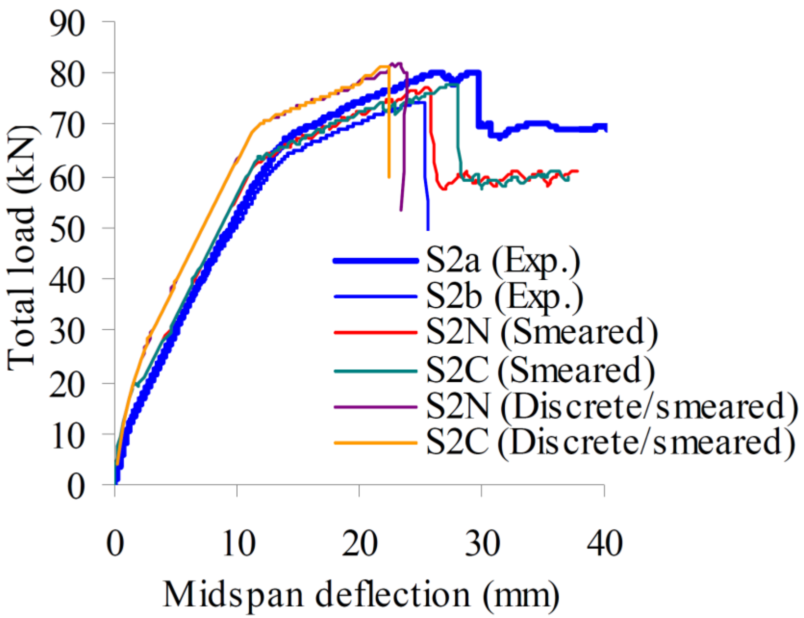
Case 1 - Intermediate crack induced debonding and concrete cover separation failure modelled using the discrete crack approach (Pham 2005).



- A fracture energy based rotating smeared crack model was used for the concrete elements below the tension reinforcement with zero shear retention.
- Concrete above the level of the tensile steel reinforcement was modelled using a fix crack model and adopted a shear retention factor of 0.05.
- The discrete crack model made use of an interface crack model in which concrete degradation in both tension and shear was modelled

FE simulations of debonding failure models for beams strengthened in flexure

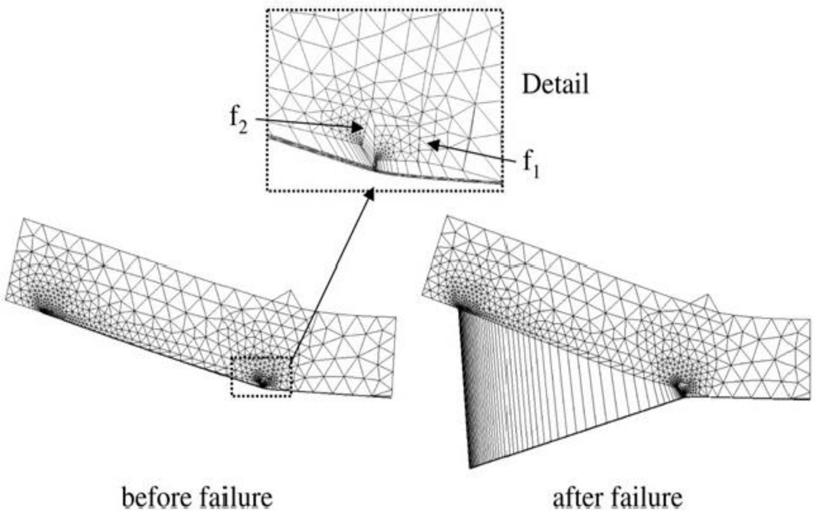
- Both discrete and smeared crack models were investigated and yielded similar results.
- Interface elements and a cubic function proposed by Dorr (1980) was used to describe the bond-slip relation between the reinforcement and concrete
- A bond-slip relation was used to describe the bond between the FRP and concrete and was derived experimentally from shear-lap tests.

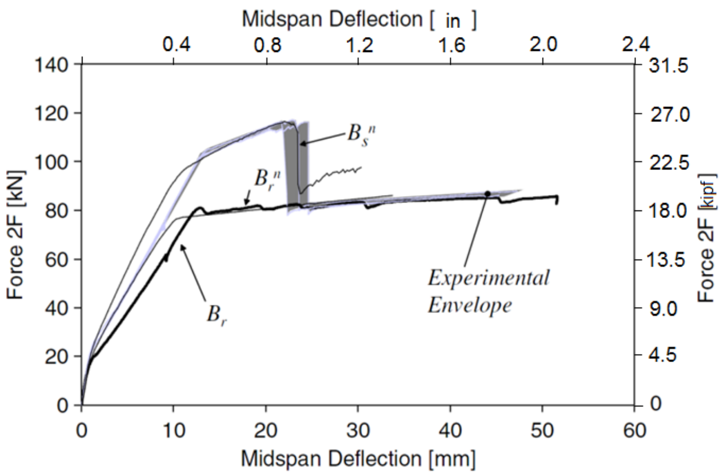


(Pham 2005)

FE simulations of debonding failure models for beams strengthened in flexure

Case 2 - Camata et al. (2007) combined the discrete crack method with a smeared crack model in areas outside of discrete crack and achieved similarly good predictions which correlated well with experimental results





Summary of recommended modelling approaches

- The concrete material model should consist of a suitable damage plasticity, model. However, non-linear elasticity models for concrete in compression may also be used to good effect.
- Concrete cracking may be simulated using either the discrete crack or smeared crack approaches. However, if the smeared crack approach is to be used, the crack band model should be used to avoid strain localisation and mesh dependency.
- A variable shear retention factor should be used to most accurately represent the shear behaviour of cracked concrete in conjunction with a rotating crack model. If a fixed crack model is adopted, then a near zero shear retention factor is recommended.
- Mode I fracture energy should be used to represent the phenomenon of FRP debonding. Standard testing procedures are recommended for determining the concrete fracture energy most accurately, alternatively fracture energy models such as CEB-FIB Model code 90 (1993) have been used with success.

Summary of recommended modelling approaches

- A bond-slip model between the internal steel reinforcement and the concrete should be implemented in the FE model.
- The FRP-to-concrete interface should be defined using an appropriate bond-slip law derived from the experimental data.
- If debonding is to be simulated in the FE analysis by fracturing of the concrete, the element sizes directly in contact with the FRP and within the debonding failure plane should be sufficiently refined in order to adequately capture the local stress concentrations. Parametric studies should be conducted to verify mesh independency of the proposed solution.
- All parameters used to inform the various material models used in the FE analysis should have physical basis.

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