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FINITE ELEMENT ANALYSIS OF THE INTERFACE BETWEEN FRP AND CONCRETE

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THE WORLD'S GATHERING PLACE FOR ADVANCING CONCRETE

aci CONCRETE CONVENTION

Outline

- Introduction
- The approach
- Material models
- Finite element model
- Numerical results
- Concluding remarks

Introduction

Externally bonded fiber-reinforced polymer (FRP) :

- a widely recognized technique;
- easy to implement;
- effective.

FRP-strengthened damaged structural elements often regain their initial load-carrying capacity and stiffness. Structural elements with externally bonded FRP possess significantly higher mechanical characteristics and ductility than identical elements without external reinforcement in composite material.

Proper FRP application requires a sound knowledge of the adhesive layer behavior. Premature debonding failure can significantly reduce the theoretical tensile strength of the FRP (Täljsten, 1996).

Introduction – Debonding failure

Mixed mode conditions, or a combination between mode-I (opening) and mode-II (shear):

- at the interface between the flexural FRP reinforcement and curved concrete beams or arches (De Lorenzis et al., 2006);
- at lap joints (Kafkalidis and Thouless, 2002);
- at the interface between FRP and concrete, in the vicinity of inclined cracks, or at the edge of the FRP plate (Bruno et al., 2007; Pan and Leung, 2007; Yao et al., 2005);
- increasing curvature can generate both shear and opening stresses at the interface between FRP and concrete for initially straight structural elements loaded in flexure (beams or slabs) (Kim and Horwitz, 2021).

Introduction – Strength based debonding models

The ‘strength-based models, pioneered by Täljsten (1996), assume linear, elastic, and isotropic material response; the probability of debonding is predicted by defining a limit load level.

- ‘Concrete Tooth model’ (Zhang et al., 2021);
- ‘Interfacial Stress model’ (Verhoosel et al., 2009);
- ‘Shear Capacity model’ (Oehlers and Moran,1990).

Debonding onset is associated with the exceedance of some critical material strength.

These models neglect the nonlinear response of the concrete and the concrete failure behavior and may, therefore, potentially provide inaccurate predictions.

Introduction – Debonding models based on cohesive FE

Ueda and Dai (2005) used cohesive finite elements to simulate the ‘interface tensile stress – opening displacement’ relationship, based on the assumption that concrete failure behavior in tension can be lumped into the link elements between concrete and FRP, expecting a degradation in concrete only in a thin layer adjacent to the interface.

Fracture mechanics-based models (Pascuzzo et al., 2020; Yu et al., 2017; Houachine et al., 2013; Rabinovitch, 2008) can capture high-stress intensities and account for the fracture properties of concrete, FRP, and adhesive. These models use a traction-separation relationship in the cohesive zone to model the nonlinear mechanical behavior of the interface between FRP and concrete.

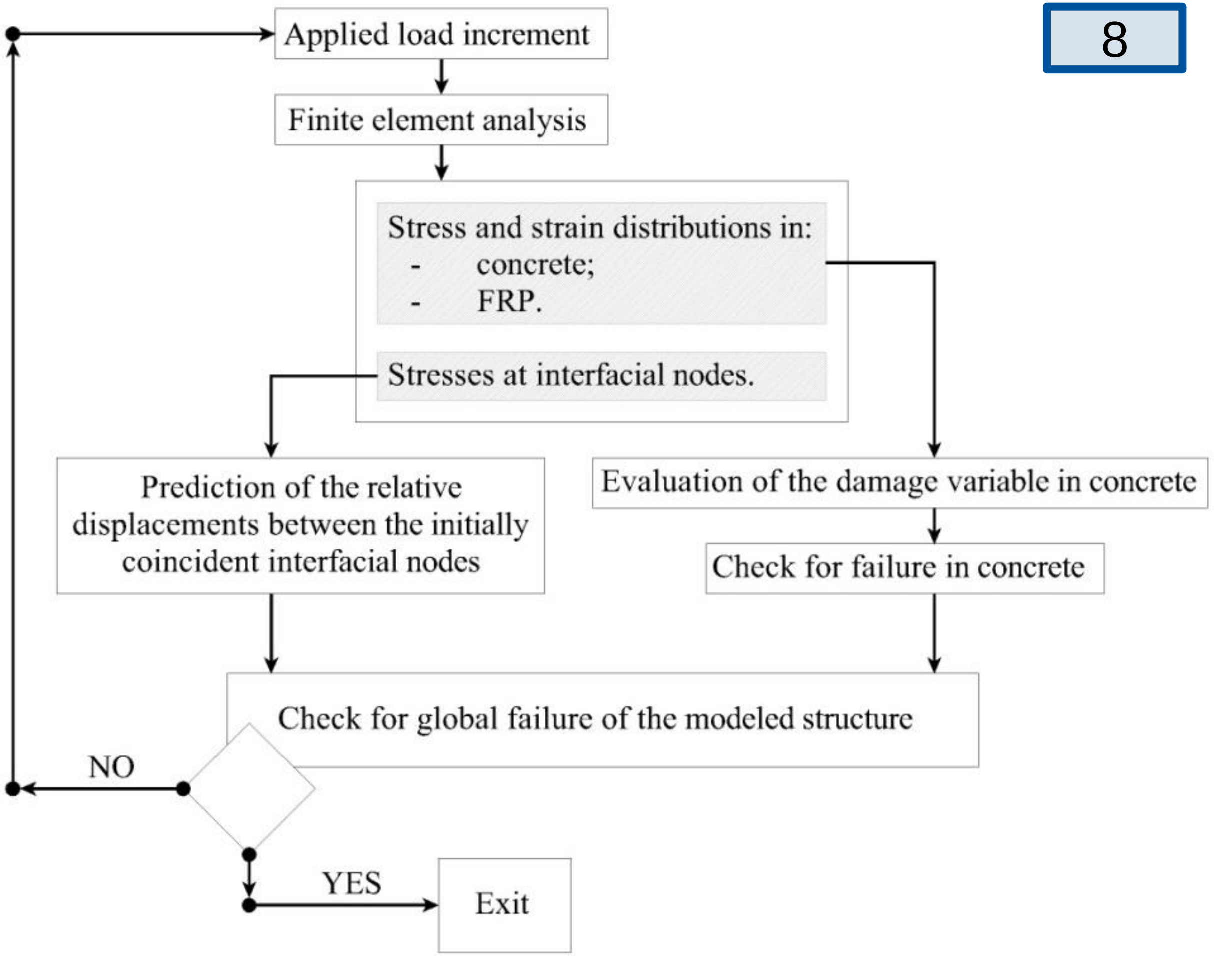
Models with cohesive finite elements work well, provided the crack trajectory is known in advance (as is the case in the case of FRP delamination). If the crack trajectory is unknown, the potential need for re-meshing might result in a computationally demanding solution.

Introduction – The approach to be presented

- Material models are defined for the FRP material, the adhesive layer, and the concrete.
- The material models are applied in finite element simulations, replicating experimental setups (Kim and Horwitz, 2021), to examine numerically the FRP-concrete interface.
- The scope of the study is limited to normal-strength concrete.
- Failure due to tensile stress components is expected to occur first in the concrete substrate, based on empirical evidence.
- Therefore, an empirical 'shear stress-slip' relationship is used to simulate the adhesive layer response, since the tensile stresses at the interface should not damage the adhesive layer.

The approach

- Explicit modeling (in terms of geometry) of the concrete substrate and the FRP plate.
- A numerical algorithm governing the state of the interface nodes (coupled or separated) is developed and implemented instead of explicitly model the adhesive layer.
- The material models defined for the concrete, the adhesive (interface), and the FRP are employed in an algorithm realized in ANSYS Mechanical APDL.


Applied load increment

Finite element analysis

Stress and strain distributions in:
- concrete;
- FRP.

Stresses at interfacial nodes.

Prediction of the relative displacements between the initially coincident interfacial nodes

Evaluation of the damage variable in concrete

Check for failure in concrete

Check for global failure of the modeled structure

NO

YES

Exit

Material models

- Concrete

$$\boxed{\sigma_{ij} = \frac{\nu_c}{(1+\nu_c)(1-2\nu_c)} E_{c,0}(1-D)\varepsilon_{kk}\delta_{ij} + \frac{1}{(1+\nu_c)} E_{c,0}(1-D)\varepsilon_{ij}}$$

$E_{c,0}$ - initial Elasticity modulus

$$D = f\left(\varepsilon_{eqv}, \varepsilon_0, C_{i,t}, C_{i,c}, D_c\right) \quad i = 1,2$$

- damage variable

ν_c - Poisson's ratio

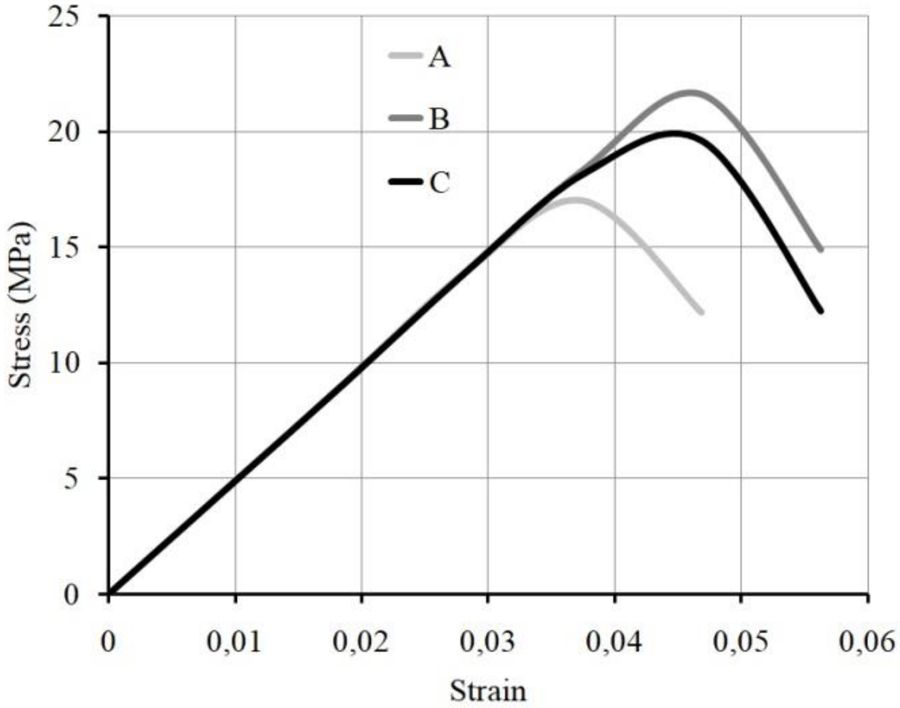
$$\varepsilon_{eqv} = \sqrt{\sum_{j=1}^{3} \langle \varepsilon_j \rangle^2} \quad \langle \varepsilon_j \rangle = \begin{cases} 0 & if \quad \varepsilon_j \le 0 \\ \varepsilon_j & if \quad \varepsilon_j > 0 \end{cases} \quad \frac{dD}{dt} \begin{cases} = 0 & if \quad \varepsilon_{eqv} < \varepsilon_0 \\ > 0 & if \quad \varepsilon_{eqv} \ge \varepsilon_0 \end{cases}$$

Local failure

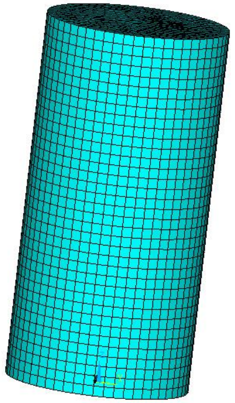
$$D = D_c$$

Material models

- Concrete



- Identification of the model constants



$$E_{c,0} \xrightarrow[\text{Tuning (sets A, B, and C)}]{\varepsilon_0, C_{i,t}, C_{i,c}, D_c} f_c^{'}$$

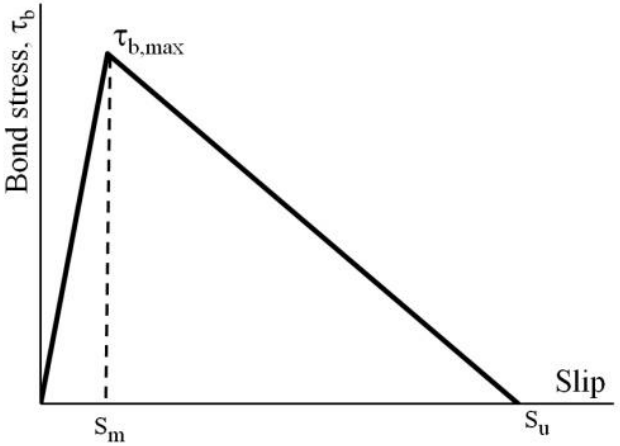
$E_{c,0}$ - Elasticity modulus of the undamaged concrete

$f_c^{'}$ - Compressive strength of concrete

[1 MPa = 145.033 psi]

Material models

- Concrete;
- Adhesive layer



The ‘bond stress - slip’ relationship for the interface

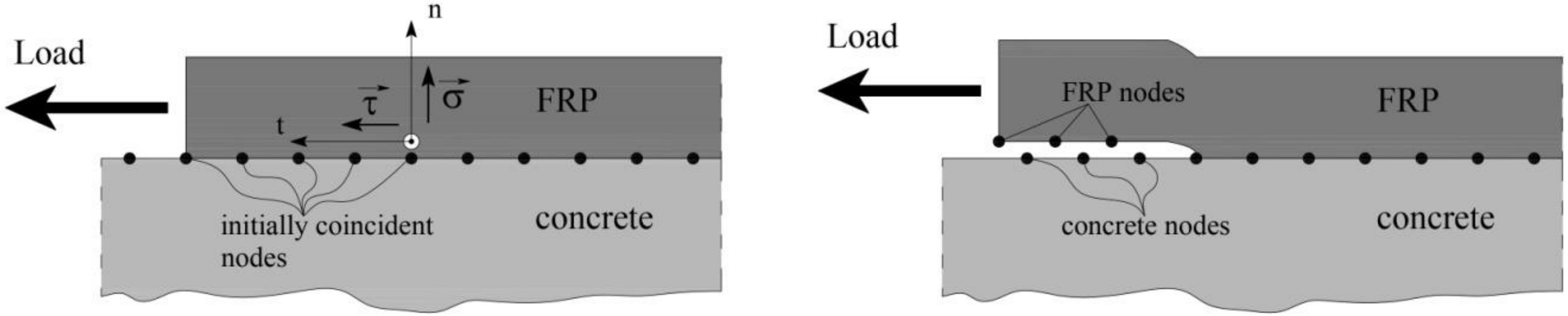
- An empirical bond stress-bond slip relationship is employed;
- Given that $f_{e,u} > f_{c,t}$, no constitutive relationship for tension is postulated.

$f_{e,u}$ - tensile strength of the adhesive

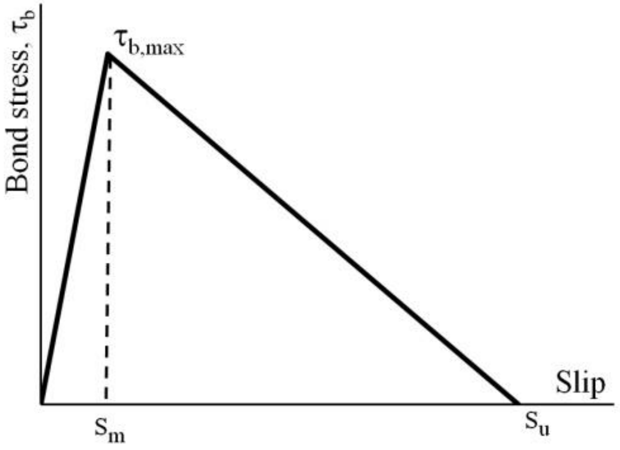
$f_{c,t}$ - tensile strength of concrete

Material models

- Concrete;
- Adhesive layer



The state of the initially coincident nodes, ‘coupled’ or ‘uncoupled, with maximum prescribed relative displacement,” is governed by the adopted constitutive relationship.

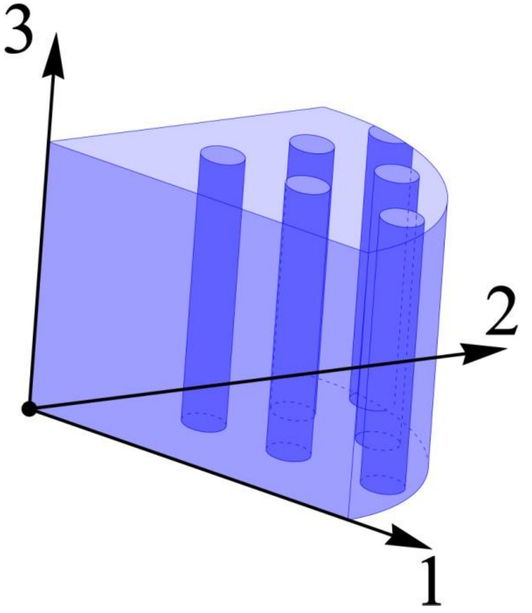


The ‘bond stress - slip’ relationship for the interface

Material models

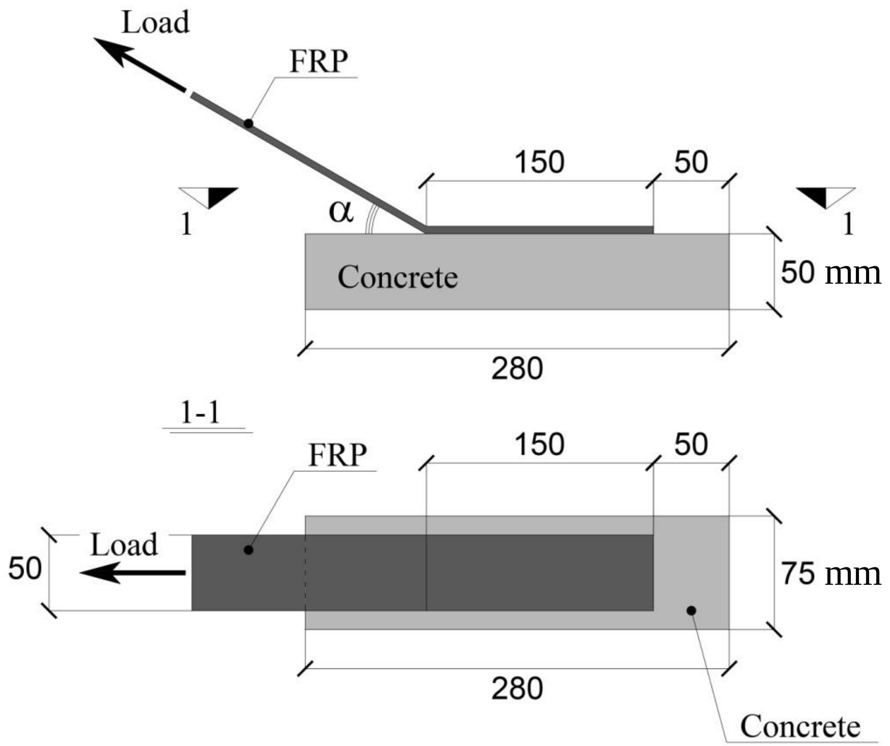
- Concrete;
- Adhesive layer;
- FRP.

Transversely isotropic material with a linear elastic response

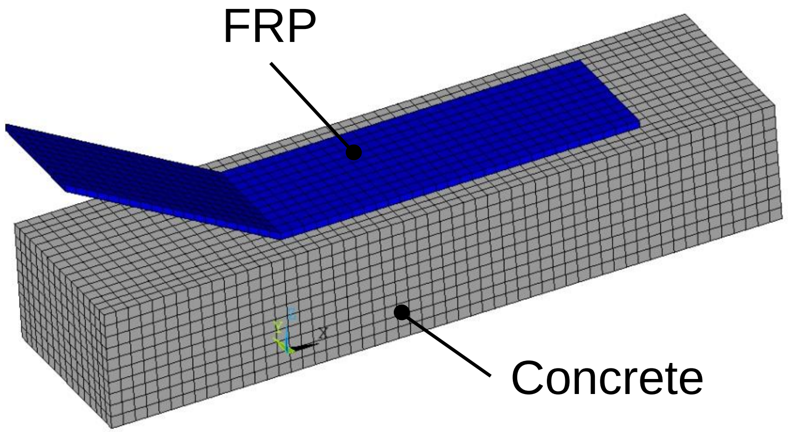


$$\begin{pmatrix}\sigma_{11}\\ \sigma_{22}\\ \sigma_{33}\end{pmatrix}=\begin{bmatrix}C_{11} & C_{12} & C_{12}\\ C_{12} & C_{22} & C_{23}\\ C_{12} & C_{23} & C_{22}\end{bmatrix}\begin{pmatrix}\varepsilon_{11}\\ \varepsilon_{22}\\ \varepsilon_{33}\end{pmatrix}\qquad\begin{pmatrix}\sigma_{23}\\ \sigma_{13}\\ \sigma_{12}\end{pmatrix}=\begin{bmatrix}C_{44} & 0 & 0\\ 0 & C_{55} & 0\\ 0 & 0 & C_{55}\end{bmatrix}\begin{pmatrix}2\varepsilon_{23}\\ 2\varepsilon_{13}\\ 2\varepsilon_{12}\end{pmatrix}$$

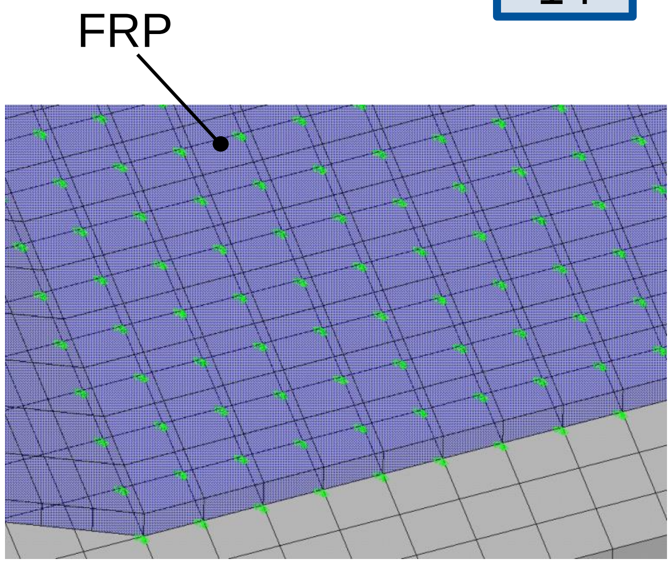
Finite element model



The modeled experimental setup (Kim and Horwitz, 2021) [1 mm = 0.039 in]



The finite element mesh

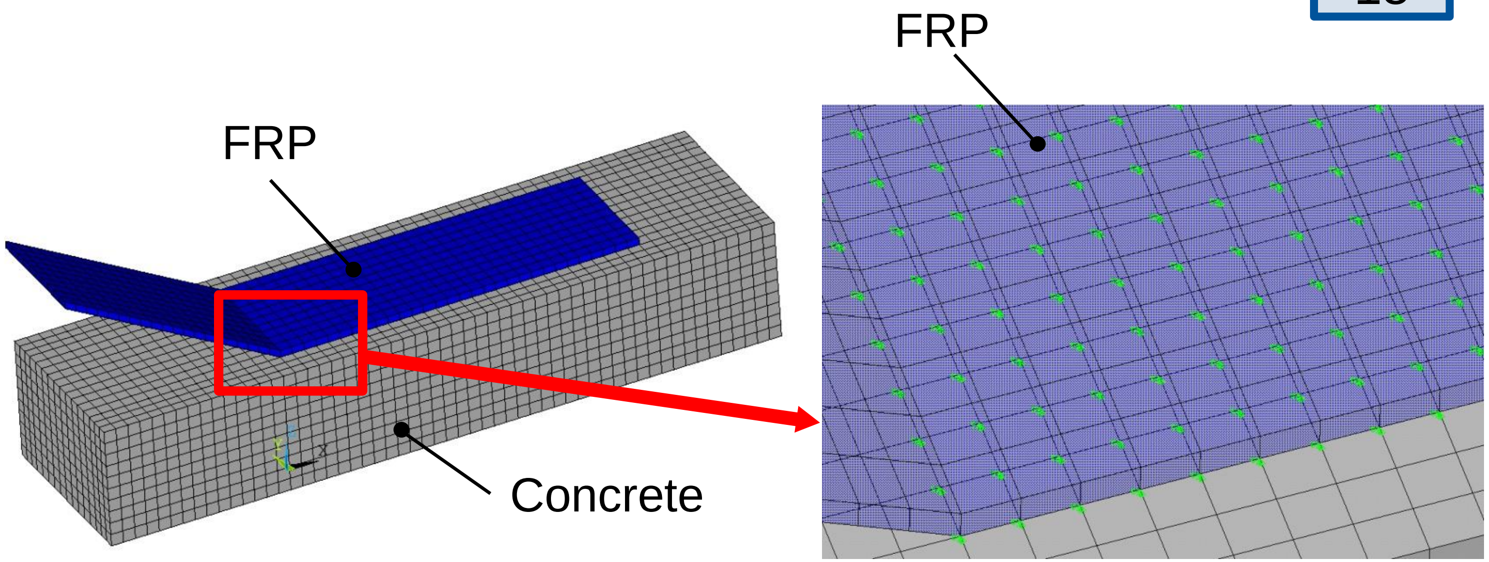


Initially coincident nodes

Finite element model

SOLID185
A 3D solid element with 8 nodes, each node having three translational DOF

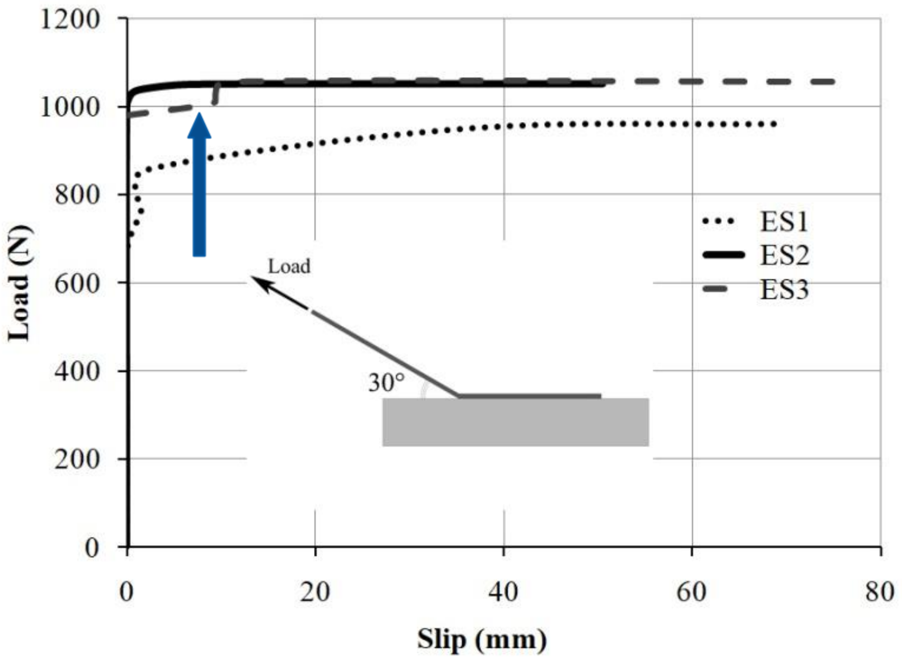
Mesh200 (not solved)
Provides a 'source' for the subsequent mesh generation in the FRP and the concrete



The finite element mesh

Initially coincident nodes

Numerical results



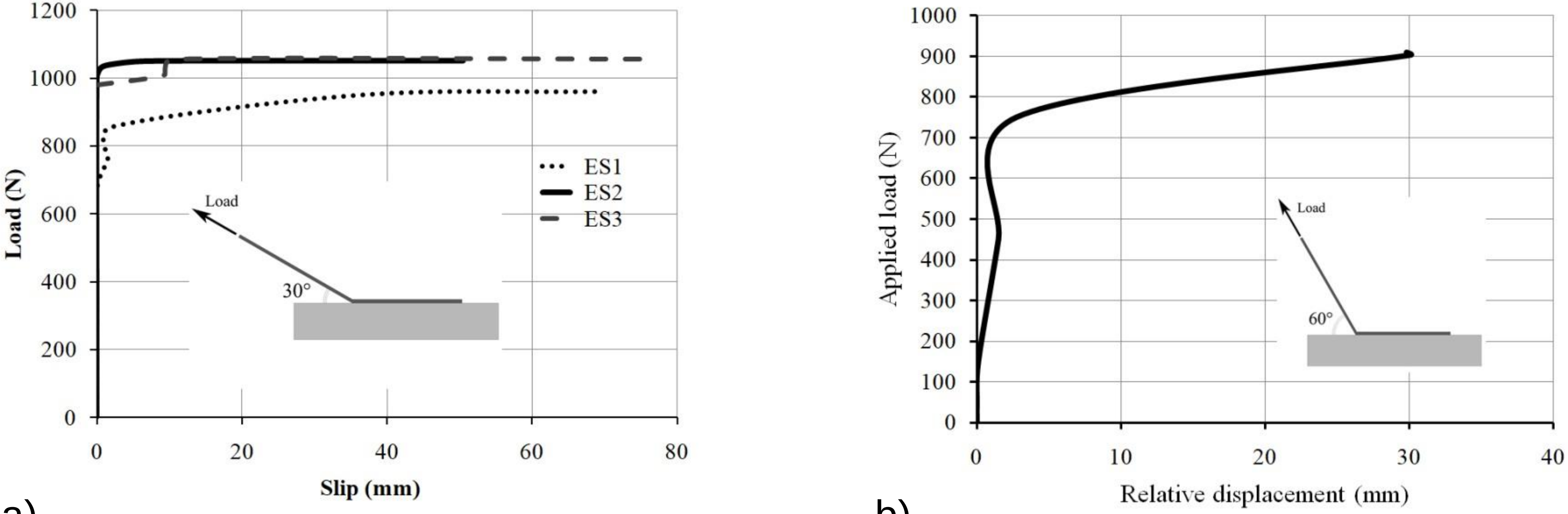
Numerically obtained load-slip relationship for α=30°
[1 N = 0.22 lb; 1 mm = 0.039 in]

The mesh sensitivity study shows that the model output is mesh-sensitive.
However, results converge with the decrease of the finite element size.

	Maximum FE size (edge) (mm)
ES1	20
ES2	16
ES3	12

[1 mm = 0.039 in]

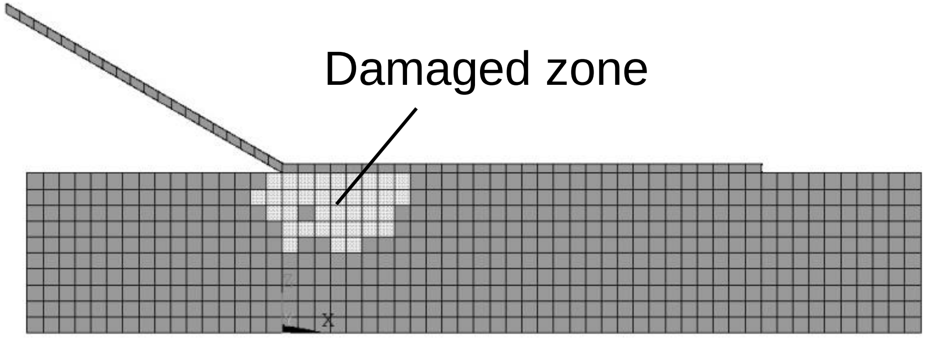
Numerical results

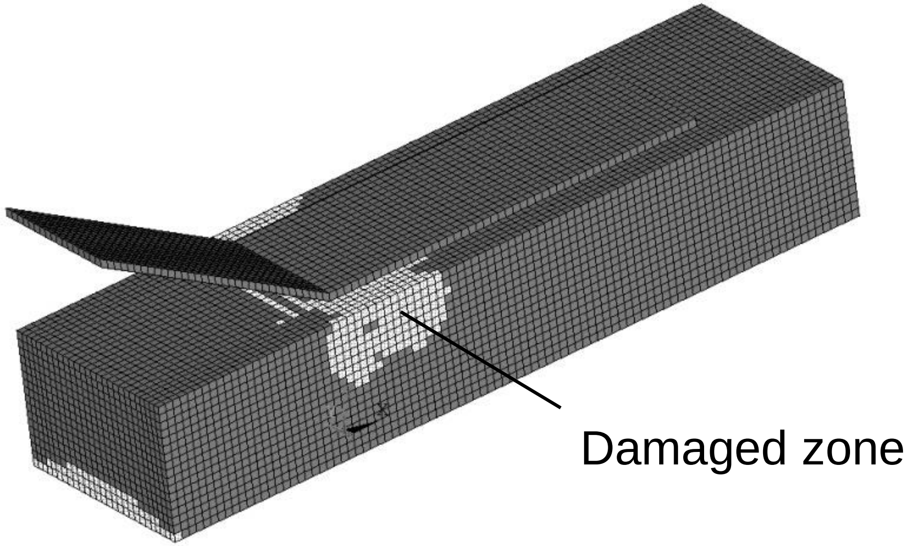


a) b)

Numerically obtained load-slip relationship for α=30° (a) and for α=60° (b)
[1 N = 0.22 lb; 1 mm = 0.039 in]

Numerical results





A well-pronounced activation in the concrete block

Concluding remarks

- A numerical procedure designed to model the debonding failure in an FRP-strengthened concrete element has been presented.
- The contribution employs an approach based on continuum damage mechanics to predict the failure behavior of the concrete combined with an empirical relationship for the response of the adhesive joint in shear.
- It is observed in the simulations that the stress transfer from the FRP plate to the concrete block, induces damage in concrete, throughout the concrete block.
- The adhesive joint may affect the overall behavior of FRP-strengthened concrete elements, even though anchorage devices may be used to minimize the likelihood of debonding failure.

Concluding remarks

- A mesh-sensitivity study has been presented.
- Additional work is underway to explore various loading scenarios.
- The model validity can be expanded by implementing a constitutive relation to account for tensile stresses in the adhesive layer.
- That will allow investigation into the behavior of FRP structures made of high-strength concrete, where failure may occur in the adhesive layer, by using an appropriate failure criterion.
- The final step is to implement the algorithm in a finite element simulation of large-scale FRP-strengthened structural elements with a subsequent validation against experimental data.
- We believe that finite element simulation results can be employed to assess and refine formulae in design guidelines for FRP-strengthened structures.

Thank you for your attention!

Questions?

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