18th European Mechanics of Materials Conference (EMMC18)

A NEW APPROACH TO ACCOUNT FOR THE STEEL-CONCRETE INTERFACE IN CASE OF INDUSTRIAL STRUCTURE APPLICATIONS USING KINEMATIC PROJECTION

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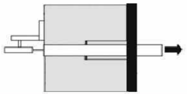
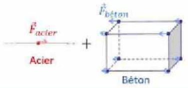
Presentation outline

Interest of the PhD subject: Energy dissipation at the steel-concrete interface level.

Physical description of the interface behaviour.



Experimental characterization of the steel-concrete bond.



Numerical strategies proposed in the literature for the interface modeling.

Suggestion of a new modelling strategy to take into account the behaviour of the steel-concrete interface.

Implementation of the methodology in a beam element.

Energy dissipation at the steel-concrete interface level

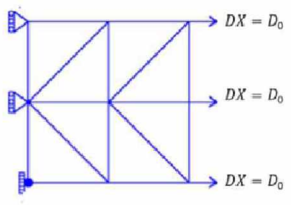
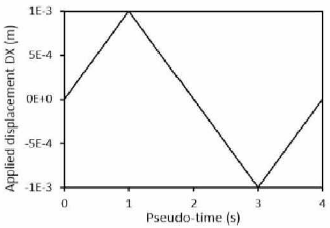
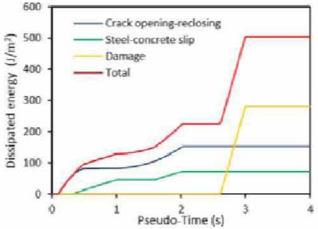
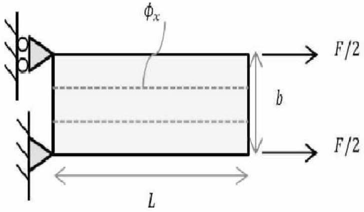
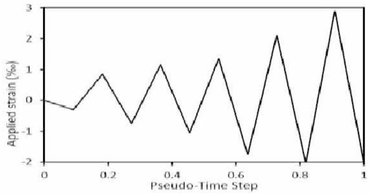
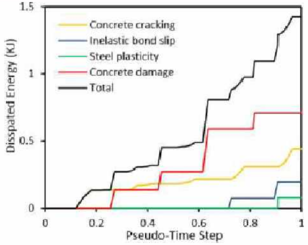
Geometry	Load	Energy dissipation
		
		

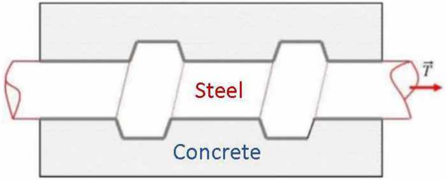
Fig. 5-7. GLRC_HEGIS: Dissipated energy by dissipative mechanism

Energy dissipation due to the interaction between concrete and steel bars may account for up to 15 per cent of the total energy dissipation.

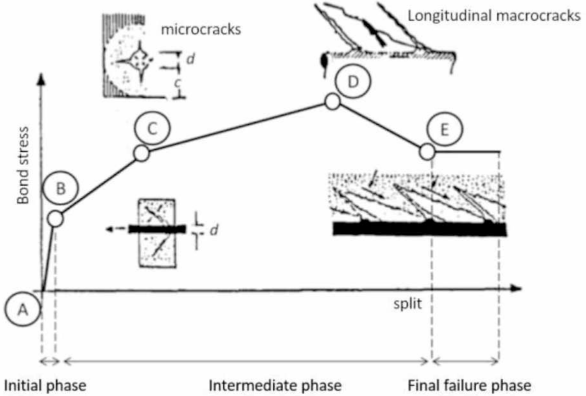
Miquel Huguet (2016)

Physical description of the interface behaviour

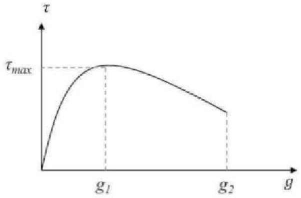
- **Stage AB**: Bond efficiency is ensured by chemical adhesion between the two materials.
- **Stage BC**: This stage is characterized by the occurrence of microcracks surrounding the steel bar.
- **Stage CD**: The slip value between steel and concrete increases and longitudinal macrocracks start to appear at D.
- **Stage DE**: The bond stress starts to decrease where the slip value continues to increase.
- **Stage E-**: This is the final failure phase.



Torre-Casanova (2012)



Frantzeskakis (1987)



$$\tau = k_1 g - k_2 g^2 + k_3 g^3$$

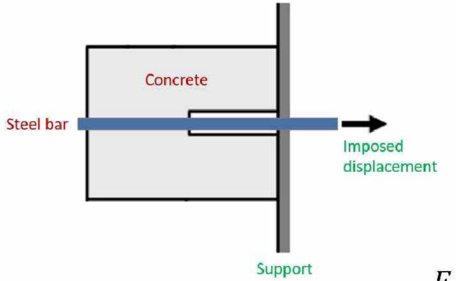
Where : $g_1 = 1.1 * 10^{-2}$ mm ; $\tau_{max} = 5$ MPa.

$g_2 = 2 * 10^{-2}$ mm ; $\tau_{g_2} = 3$ MPa.

Nilson (1968)

Experimental tests

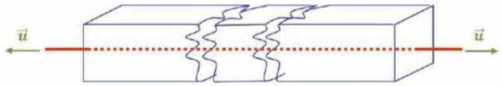
Pull-out



$$\tau_s = \frac{F}{\varphi \pi l}$$

Dahou et al.(2009)

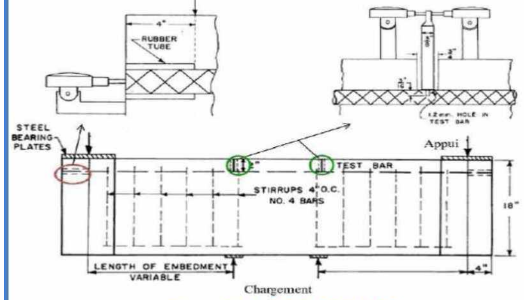
Ties



Clément (1987)

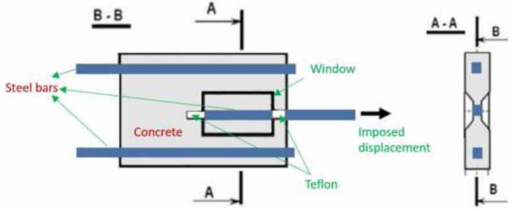
Torre-Casanova (2012)

Beams



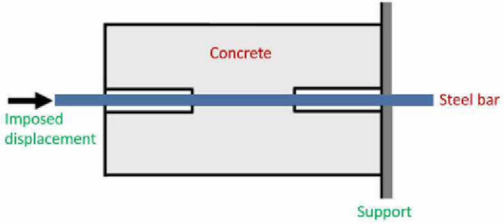
Comité ACI (1964)

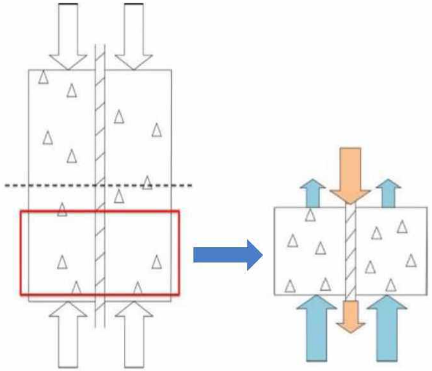
PIAF test



Tran et al. (2009)

Push-in

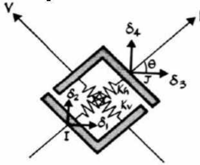




Tixier(2015)

Numerical modeling approaches

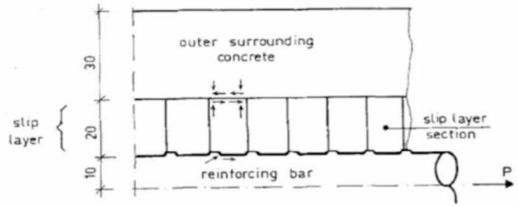
Spring (bar) elements



$$\begin{pmatrix}\sigma_h\\ \sigma_v\end{pmatrix} = \begin{pmatrix}k_h & 0\\ 0 & k_v\end{pmatrix}\begin{pmatrix}\epsilon_h\\ \epsilon_v\end{pmatrix}$$

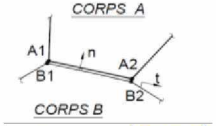
Ngo et Scordelis (1967)

2D and 3D explicit area



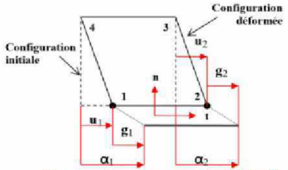
Reinhardt et al. (1984)

Joint element a with zero thickness value



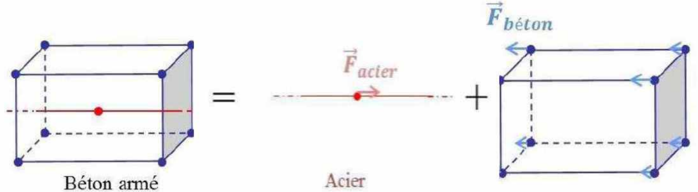
Dominguez (2005)

Extended finite elements method XFEM



Dominguez (2005)

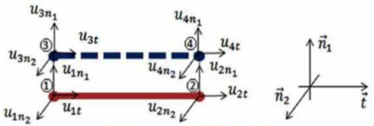
Introduction of internal forces



$\vec{F}_{b/a} = \pm 1\,\pi d_a l \tau \cdot \vec{t}$ $\qquad \vec{F}_{a/bj} = N_j(x_{ba}, y_{ba}, z_{ba})\vec{F}_{a/b}$

Torre-Casanova (2012)

Finite elements with 4 nodes (QUA4)



Mang (2015)

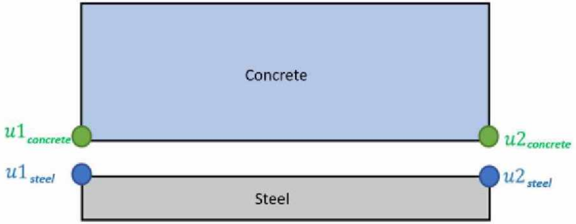
Limitations

These models are in general applied in detailed 2D and 3D analysis in order to represent some structural elements. Applying these methodologies for large scale structures is highly time consuming.

Suggestion of a new modelling strategy for steel-concrete interface : concept

Concept of the proposed strategy

- The main interest is the simplicity of the proposed approach and the possible transition to a large-scale application. This thesis is a direct continuation of the previous works of Torre-Casanova (2012) and Mang (2015).



$$\left.\begin{array}{l} u1_{concrete} = f(u1_{steel}) \\ u2_{concrete} = f(u2_{steel}) \end{array}\right\}$$

f : Nonlinear kinematic relation

- The bond-slip law frequently used in the litterature to represent the interface will be replaced by a kinematic nonlinear relation. This relation links the longitudinal displacements of steel and concrete nodes in a finite elements simulation.
- In order to identify the analytical expression of kinematic relations, numerical pull-out tests with kinematic relations representing the interface are to be modeled. Numerical results can be calibrated with respect to experimental ones.

Advantages

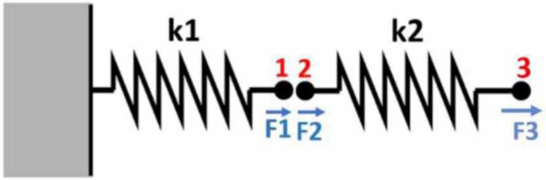
- There is no need to add additional degrees of freedom to the studied problem in order to take into account the numerical modeling of the interface.
- It is easy to integrate the methodology into a conventional finite elements resolution strategy.

Implementation

- Single and double Lagrange multipliers.
- Kinematic projection method.

Suggestion of a new modelling strategy for steel-concrete interface : validation

Validation example



$$\underbrace{\begin{bmatrix} k1 & 0 & 0 \\ 0 & k2 & -k2 \\ 0 & -k2 & k2 \end{bmatrix}}_{K}\underbrace{\begin{bmatrix} u1 \\ u2 \\ u3 \end{bmatrix}}_{U} = \underbrace{\begin{bmatrix} F1 \\ F2 \\ F3 \end{bmatrix}}_{F}$$

$$K \quad U = F$$

+

$$u1 = \alpha u2 \equiv \underbrace{\begin{bmatrix} 1 & -\alpha & 0 \end{bmatrix}}_{L}\begin{bmatrix} u1 \\ u2 \\ u3 \end{bmatrix} = 0$$

L : constraints matrix

Simple Lagrange multipliers

$$KU + L^T\lambda = F$$
$$L\,U = d$$

$$\boxed{\begin{bmatrix} k & L^T \\ L & 0 \end{bmatrix}}\begin{bmatrix} U \\ \lambda \end{bmatrix} = \begin{bmatrix} F \\ d \end{bmatrix}$$

$$\begin{bmatrix} u1 \\ u2 \\ u3 \\ \lambda \end{bmatrix} = \begin{bmatrix} \frac{1}{k1} & \frac{1}{\alpha k1} & \frac{1}{\alpha k1} & 0 \\ \frac{1}{\alpha k1} & \frac{1}{\alpha^2 k1} & \frac{1}{\alpha^2 k1} & \frac{-1}{\alpha} \\ \frac{1}{\alpha k1} & \frac{1}{\alpha^2 k1} & \frac{\alpha^2 k1 + k2}{\alpha^2 k1 k2} & \frac{-1}{\alpha} \\ 0 & \frac{-1}{\alpha} & \frac{-1}{\alpha} & 0 \end{bmatrix}\begin{bmatrix} F1 \\ F2 \\ F3 \\ 0 \end{bmatrix}$$

Double Lagrange multipliers

$$\boxed{\begin{bmatrix} k & L^T & L^T \\ L & -\beta I & \beta I \\ L & \beta I & -\beta I \end{bmatrix}}\begin{bmatrix} U \\ \lambda^1 \\ \lambda^2 \end{bmatrix} = \begin{bmatrix} F \\ d \\ d \end{bmatrix}$$

$$\begin{bmatrix} u1 \\ u2 \\ u3 \\ \lambda^1 \\ \lambda^2 \end{bmatrix} = \begin{bmatrix} \frac{1}{k1} & \frac{1}{\alpha k1} & \frac{1}{\alpha k1} & 0 & 0 \\ \frac{1}{\alpha k1} & \frac{1}{\alpha^2 k1} & \frac{1}{\alpha^2 k1} & \frac{-1}{2\alpha} & \frac{-1}{2\alpha} \\ \frac{1}{\alpha k1} & \frac{1}{\alpha^2 k1} & \frac{\alpha^2 k1 + k2}{\alpha^2 k1 k2} & \frac{-1}{2\alpha} & \frac{-1}{2\alpha} \\ 0 & \frac{-1}{2\alpha} & \frac{-1}{2\alpha} & \frac{-1}{4\beta} & \frac{1}{4\beta} \\ 0 & \frac{-1}{2\alpha} & \frac{-1}{2\alpha} & \frac{1}{4\beta} & \frac{-1}{4\beta} \end{bmatrix}\begin{bmatrix} F1 \\ F2 \\ F3 \\ 0 \\ 0 \end{bmatrix}$$

Suggestion of a new modelling strategy for steel-concrete interface : validation

Kinematic projection method

Concept

Degrees of freedom are divided into two groups : dependent and independent degrees. A projection matrix is introduced. It links the incremental values of dependent and independent degrees. The equilibrium equation is multiplied by the transpose of this projection matrix.

Implementation

$u1 = \alpha u2$; $u1$: dependent, $u2$ and $u3$: independent degrees.

$$\delta U = P\delta U_{libres} ; \begin{bmatrix}\delta u1\\ \delta u2\\ \delta u3\end{bmatrix} = \begin{bmatrix}\alpha & 0\\ 1 & 0\\ 0 & 1\end{bmatrix}\begin{bmatrix}\delta u2\\ \delta u3\end{bmatrix} = \mathrm{P}\begin{bmatrix}\delta u2\\ \delta u3\end{bmatrix}$$; $U^* = U$: virtual degrees fo freedom vector.

PVW : $\delta U^{*T} KU = \delta U^{*T} F$; $\delta U^{*T}_{libres} P^T KU = \delta U^{*T}_{libres} P^T F$; So : $\boxed{P^T KU = P^T F}$ (for linear kinematic relations $\delta U = P\delta U_{libres}$ and $U = PU_{libres}$).

Application

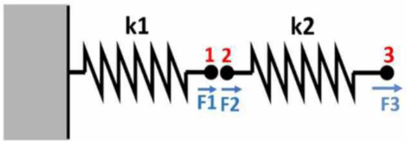
$$P^T kP = \begin{bmatrix}\alpha & 1 & 0\\ 0 & 0 & 1\end{bmatrix}\begin{bmatrix}k1 & 0 & 0\\ 0 & k2 & -k2\\ 0 & -k2 & k2\end{bmatrix}\begin{bmatrix}\alpha & 0\\ 1 & 0\\ 0 & 1\end{bmatrix} = \begin{bmatrix}\alpha^2 k1 + k2 & -k2\\ -k2 & k2\end{bmatrix} ; P^T F = \begin{bmatrix}\alpha^2 k1 + k2 & -k2\\ -k2 & k2\end{bmatrix}\begin{bmatrix}F1\\ F2\\ F3\end{bmatrix} = \begin{bmatrix}\alpha F1 + F2\\ F3\end{bmatrix} ; \begin{bmatrix}u2\\ u3\end{bmatrix} = \begin{bmatrix}\alpha^2 k1 + k2 & -k2\\ -k2 & k2\end{bmatrix}^{-1}\begin{bmatrix}\alpha F1 + F2\\ F3\end{bmatrix}$$

Conclusion

The kinematic projection methodolgy will be adopted because it reduces the size of the problem to be resolved.

Suggestion of a new modelling strategy for steel-concrete interface : validation

Example

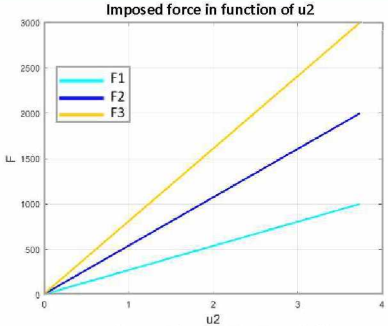


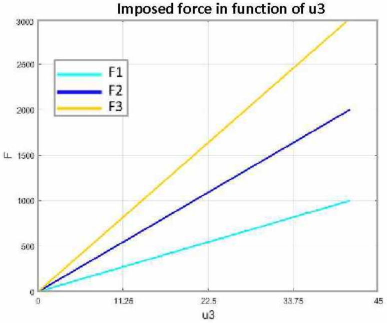
With :

k1 = 40;

k2 = 80.

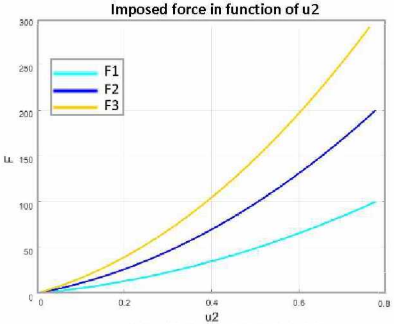
$u1 = 0.1 + 10u2$

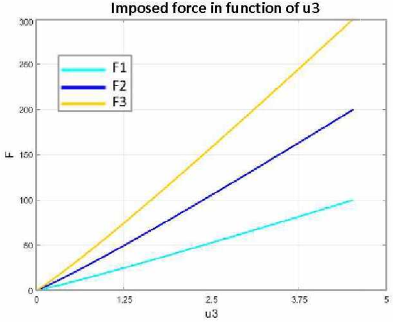




$$\begin{bmatrix} \delta u1 \\ \delta u2 \\ \delta u3 \end{bmatrix} = \underbrace{\begin{bmatrix} 10 & 0 \\ 1 & 0 \\ 0 & 1 \end{bmatrix}}_{P} \begin{bmatrix} \delta u2 \\ \delta u3 \end{bmatrix}$$

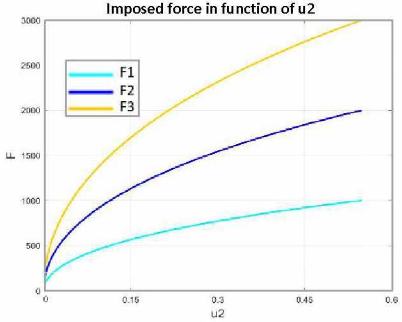
$u1 = 3u2 + 3u2^2$

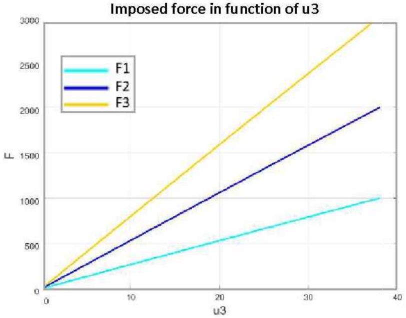




$$\begin{bmatrix} \delta u1 \\ \delta u2 \\ \delta u3 \end{bmatrix} = \underbrace{\begin{bmatrix} 3 + 3u2 & 0 \\ 1 & 0 \\ 0 & 1 \end{bmatrix}}_{P} \begin{bmatrix} \delta u2 \\ \delta u3 \end{bmatrix}$$

$u1 = 40\sqrt{u2}$





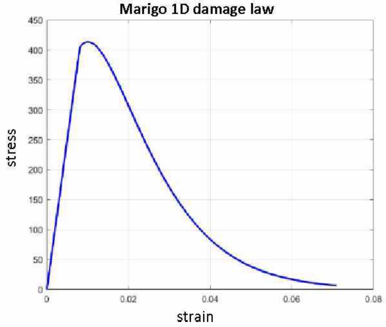
$$\begin{bmatrix} \delta u1 \\ \delta u2 \\ \delta u3 \end{bmatrix} = \underbrace{\begin{bmatrix} \frac{20}{\sqrt{u2}} & 0 \\ 1 & 0 \\ 0 & 1 \end{bmatrix}}_{P} \begin{bmatrix} \delta u2 \\ \delta u3 \end{bmatrix}$$

Suggestion of a new modelling strategy for steel-concrete interface : validation

Marigo 1D damage law

$$f = Y - Y_D - SM\ d$$

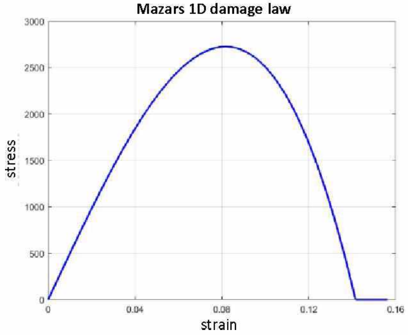
- $Y = \frac{1}{2}E\varepsilon^2$: elastic energy recovery rate.
- SM : the evolution of f in function of the damage.
- Y_D : initial damage threshold,
- d :damage internal variable.



Mazars 1D damage law

$$f = \varepsilon_{eq} - \varepsilon_{d0}$$

- ε_{d0} : strain elastic limit.
- $\varepsilon_{eq} = \sqrt{\langle\varepsilon\rangle_+ : \langle\varepsilon\rangle_+}$.



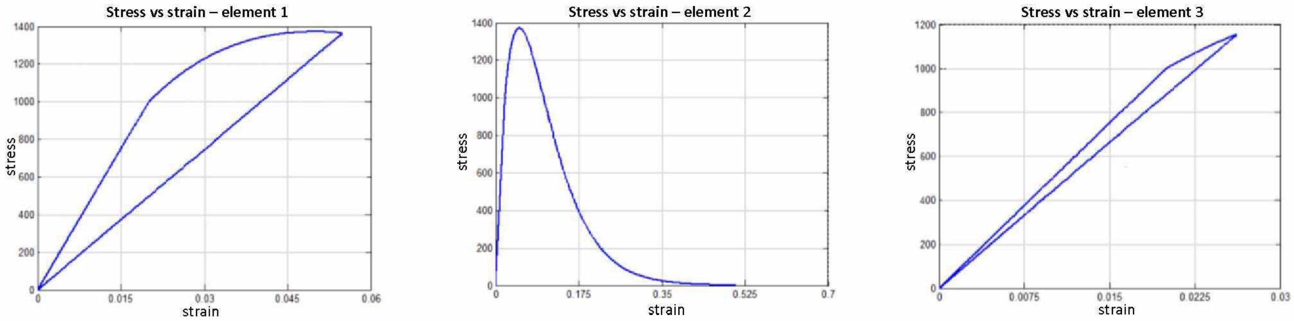
Objective

The aim of the incorporation of damage laws in the 1D validation examples is to test the possibility to couple two types of nonlinearities in one simulation: nonlinear kinematic relations, and nonlinear material behaviour laws.

Suggestion of a new modelling strategy for steel-concrete interface : validation

Validation example with two types of nonlinearities

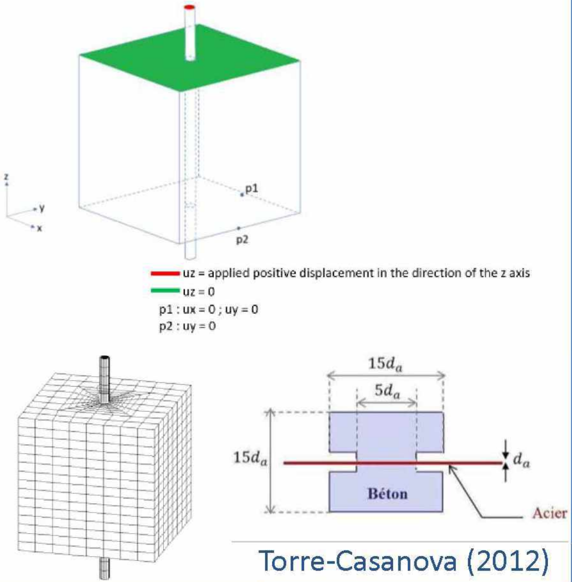
$$u2 = 2u3^2$$



Identical result for element 4.

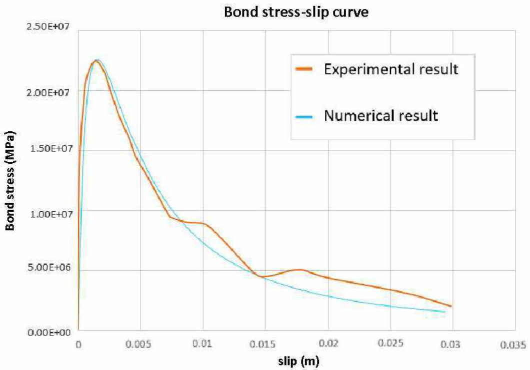
Suggestion of a new modelling strategy for steel-concrete interface : application

Mesh and boundary conditions

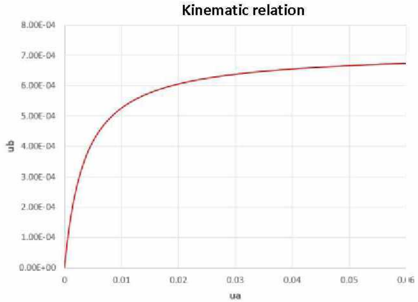


Torre-Casanova (2012)

Calibrated result



Kinematic relation



$$u_b = \frac{u_a}{a + bu_a}$$

Where:

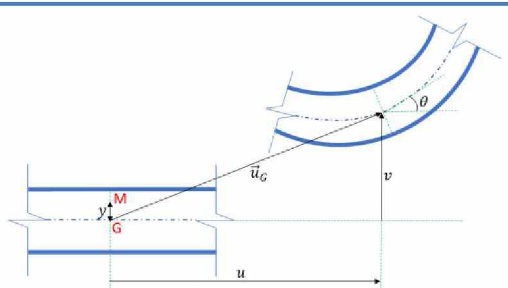
$a = 5\,; b = 1500.$

Conclusions

- These results are an evidence that kinematic relations can be used to represent the steel-concrete interface. In fact, using kinematic relations means in other terms that the slip $(u_a - u_b)$ between the two materials is being imposed.
- The next step for this pull-out example will be the use of nonlinear damage laws for concrete.

Implementation in a beam element

Classic Euler-Bernoulli beam formulation



$$\vec{u}_M = \vec{u}_G + \theta \wedge \overrightarrow{GM} = \begin{bmatrix} u - y\theta \\ v \end{bmatrix}$$

$$\varepsilon_M(x) = \begin{bmatrix} 1 & -y \end{bmatrix} \begin{bmatrix} \dfrac{\partial u}{\partial x} \\ \dfrac{\partial \theta}{\partial x} \end{bmatrix} = \begin{bmatrix} 1 & -y \end{bmatrix} \begin{bmatrix} [B1] \\ [B3] \end{bmatrix} \begin{bmatrix} u_1 \\ v_1 \\ \theta_1 \\ u_2 \\ v_2 \\ \theta_2 \end{bmatrix} = \begin{bmatrix} 1 & -y \end{bmatrix} B_{13}\, u_e$$

Where the matrix B_{13} has the derivate values of the function forms. B_{13} links the strain of an eccentric point M of the beam section to the strain of point G located in the same beam section, on its center line.

Introduction of slip deformation

$$\varepsilon_a = \begin{bmatrix} 1 & -y \end{bmatrix} B_{13}\, u_e + \Gamma\left[\begin{bmatrix} 1 & -y \end{bmatrix} B_{13}\, u_e\right]^{\alpha}$$

The idea is to introduce a slip deformation between steel and concrete. The classic beam theory imposes an identical strain between the two materials.

Because of the modification of the kinematic relations of the classical beam formulation, the beam section will no longer be straight. This means that the steel bar won't be controlled by the rigid body movement of the section. For this reason, the bar is forced to slip with respect to concrete.

This study is in progress.

Conclusions

- The kinematic projection method has the advantage of reducing the size of the system to be solved.

- The pull-out numerical modelling shows that it is possible to represent the steel-concrete interface by a kinematic relationship in order to reproduce the experimental result expressed in terms of bons stress-slip.

Perspectives

- Introduction of a non-linear concrete behavior law for the pull-out example.

- Study on the effect of the material and geometric parameters of the pull-out test on the kinematic relationship expression.

- Implementation of the methodology within beam and plate elements.

- Implementation of the methodology in dynamic analysis.

Thank you for your attention !

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