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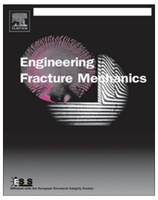

Stress resultant nonlinear constitutive model for cracked reinforced concrete panels

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ABSTRACT

The paper proposes a novel stress resultant nonlinear constitutive model for Reinforced Concrete (RC) panels adapted to cyclic loadings. An analytical multi-scale analysis is applied by taking a concrete strut with embedded steel reinforcement between two consecutive cracks as representative volume element. Some suitable assumptions are adopted in order to incorporate the most important nonlinear phenomena characterizing reinforced concrete behavior: concrete damage, concrete cracking, bond-slip stress (at the origin of the tension stiffening effect) and steel yielding. The model is validated by comparison with experimental data concerning tension and tension-compression uniaxial tests on RC beams and a cyclic (non-reversing) shear test on an RC wall.

1. Introduction

1.1. Nonlinear finite element modeling of reinforced concrete panels

Industrial buildings, in particular Nuclear Power Plants (NPP), have to fulfill severe structural requirements according to the modern design codes. The computational time required for nonlinear structural analyses of this type of large-dimension Reinforced Concrete (RC) facilities, sometimes necessary for their seismic assessment, is significant. However, the so-called global or effective modeling approaches can ensure numerical efficiency and robustness. These approaches are characterized by the use of relatively large size Finite Elements (FE) where the material model represents the reinforced concrete behavior as an equivalent homogeneous material, as opposed to approaches based on distinct concrete and steel modeling and the introduction of some kinematic and/or stress transfer conditions. In civil engineering, this type of global modeling strategy is usually coupled with linear elastic behavior assumptions.

Nevertheless, recent safety requirements for NPP have introduced the necessity of using more realistic models able to reproduce the actual nonlinear behavior of RC structures, both for static and dynamic load cases. In particular, these models should be able to take into account the cracking onset and its development, in order to correctly estimate the crack widths (and also spacing and direction) since engineering design standards provide some bounds to these values to fulfill prescribed

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Nomenclature

A_{sx}, A_{sy}	steel section per unit length in the x and y reinforcement directions
$\mathbb{A}$	global elastic stiffness tensor
$\underline{b}^c$	volume forces acting on concrete
$\mathbb{B}$	global crack stiffness tensor
$\mathbb{C}$	global steel plasticity stiffness tensor
$\mathbb{A}_c$	concrete stiffness tensor
d	damage scalar variable
$\dot{D}$	power dissipation surface density
D	global crack energy tensor
e_x, e_y	bar spacing in x and y reinforcement directions
E_c, E_s	concrete and steel Young's modulus
E	global inelastic bond-slip energy tensor
f_c, f_{ct}	concrete compression and tensile strength
f_i	threshold functions for nonlinear phenomenon i
f_{sy}	steel yield stress
$\boldsymbol{F}$	global steel plastic energy tensor
$\underline{g} = (g_n, g_t)$	concrete stresses at cracks: normal and tangential to crack components
G_f	concrete fracture energy
$\boldsymbol{G}$	global crack – inelastic bond-slip coupling energy tensor
h	thickness of the panel
k_o	threshold for the energy release rate
k_t	average tension stiffening concrete stress coefficient
K_l	local bond-slip stiffness
$\boldsymbol{K}^p$	steel tension stiffening stress tensor
$\boldsymbol{K}^s$	concrete tension stiffening energy tensor
$\boldsymbol{K}^\tau$	global bond-slip stiffness tensor
L_x, L_y	characteristic lengths in the plane of the RC panel in x and y reinforcement directions
$\boldsymbol{M}^{vw}$	geometrical transformation tensor: crack displacement - slip
$\mathbb{M}^{\varepsilon w}$	geometrical transformation tensor: crack displacement - strain
$\boldsymbol{N}$	in-plane stress resultant tensor
$\underline{q}_r = (q_{r,n}, q_{r,t})$	thermodynamic force associated with the crack displacement
$\underline{q}_s = (q_{s,x}, q_{s,y})$	thermodynamic force associated with the steel plastic strain
$\underline{q}_v = (q_{v,x}, q_{v,y})$	thermodynamic force associated with the inelastic steel-concrete slip
s_r	crack spacing
s_{rx}, s_{ry}	crack spacing in the equivalent tie beam in x and y reinforcement directions
$s_{r,x}, s_{r,y}$	crack spacing seen by the x, y reinforcement
$\underline{s} = (s_x, s_y)$	steel-concrete relative slip
$\underline{v} = (v_x, v_y)$	steel-concrete slip at crack
$\underline{v}^p = (v_x^p, v_y^p)$	crack inelastic steel-concrete slip
$\underline{w} = (w_n, w_t)$	crack displacement: normal and tangential to crack components
Y	energy release rate
γ_d	parameter of the damage function
Γ_r	crack surface
$\boldsymbol{\varepsilon}^c, \boldsymbol{\varepsilon}^{sx}, \boldsymbol{\varepsilon}^{sy}$	concrete and steel local strain tensors
$\boldsymbol{\varepsilon}^r$	crack equivalent strain tensor
$\underline{\varepsilon}^{ps} = (\varepsilon_x^{ps}, \varepsilon_y^{ps})$	steel plastic strain
$\boldsymbol{\epsilon}$	generalized membrane strain
$\zeta(d)$	damage function
θ_r	crack orientation
$\dot{\lambda}_i$	plastic multiplier for nonlinear phenomenon i
ν_c	concrete Poisson's ratio
$\rho_c, \rho_{sx}, \rho_{sy}$	concrete and steel reinforcement ratio
$\boldsymbol{\sigma}^c, \boldsymbol{\sigma}^{sx}, \boldsymbol{\sigma}^{sy}$	concrete and steel local stress tensors
$\underline{\tau} = (\tau_x, \tau_y)$	bond stress
$\underline{\tau}^o = (\tau_x^o, \tau_y^o)$	average tension stiffening effect
ϕ_x, ϕ_y	steel reinforcement bar diameter
ψ^o	Helmholtz free energy surface density
Ω	volume of the RVE

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