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Localized nonlinearity and size-dependent mechanics of in-plane RC element in shear

Masoud Soltani[a,*], Xuehui An[b], Koichi Maekawa[c]

[a] *Department of Civil Engineering, Tarbiat Modares University, Jalaale-al Ahmad Ave., Tehran, Iran*
[b] *Department of Hydraulic Engineering, Tsinghua University, Beijing 100084, China*
[c] *Department of Civil Engineering, The University of Tokyo, Hongo 7-3-1, Bunkyo-ku, Tokyo 113, Japan*

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Abstract

Structural nonlinearity and stress-carrying mechanics of reinforced concrete are greatly associated with local kinematics at crack planes and non-uniform stress fields in un-cracked concrete regions mobilized in the vicinity of cracks, especially when much less and/or highly anisotropic amounts of reinforcement are placed in space. An exact local stress field approach is implemented to in-plane reinforced concrete elements for deriving size-independent/dependent spatial averaged stress–strain relation, stress carrying mechanics and their interaction of high complexity. Much attention is directed to size sensitivity of overall responses involving transient tension softening–stiffening, interlock shear hardening–softening and average yield strength of reinforcing bars, which were previously formulated based on mere superimposition of these constituent mechanics under uniaxial stresses. Single crack localization and transitory phase of lightly reinforced concrete in-plane elements are chiefly investigated since those are out of scope of non-localized stress field approach with smeared crack concept.
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1. Introduction

Spatial averaged constitutive modeling of in-plane reinforced concrete (RC) elements has brought about engineering success to nonlinear mechanics of reinforced concrete [1] and its size-independency of smeared crack modeling has been theoretically and experimentally verified within some applicability conditions in terms of reinforcement ratios that guarantee distributed stable cracking in space. Here, the modeling derives from simple superimposition of constituent mechanics of cracked concrete in tension, compression and shear. Successful compression field theory [2], its subsequent modified version (MCFT) [3,4] and softened truss method [5,6] can be classified in this category of non-localized stress field approach. The compression, tension and shear along cracking are formulated basically without mutual interaction.

As a further development, non-orthogonal multi-directional fixed crack theory [1,7] was presented to install mutual nonlinear shear interaction among cracking with different orientations so that it can strictly deal with the interacting kinematics of shear cracks that governs the entire nonlinearity of elements. With this generalization, non-orthogonal crack-to-crack interaction problems can be solved with reasonably larger sized finite elements [1].

However, stable crack dispersion is nevertheless assumed for its multi-crack formulation and simple superposition is similarly applied around the axis of active cracking. Then, when light reinforcement or highly anisotropic amount of steel is placed in space, this non-localized stress field approach tends to deviate from the reality. For solving this problem with engineering manner, discrete zoning approach [8–10] was adopted for lightly reinforced concrete structures so that size-dependent capacity of RC can be simulated with comparatively smaller numbers of degree of freedom. Here, size independent constitutive modeling stated above is adopted in RC zones and size-dependent

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[*] Corresponding author. Fax: +98 21 4423660.
E-mail address: msoltani@modares.ac.ir (M. Soltani).

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Nomenclature

A_s, I_s	area and moment of inertia of bar section
d	diameter of reinforcing bar
$e_c, e_{\max}$	normalized compressive strain and its maximum value
e_p, k	equivalent plastic strain and fracture parameter
E_s	elastic modulus of bar section
$f_t,\ f_c'$	tensile strength and cylindrical compressive strength of concrete
f_y	yield strength of steel bar
$g(\varepsilon_s)$	strain reduction function in bond–slip model
G_f	fracture energy of plain concrete
G_{fc}	compressive fracture energy
K	foundation stiffness of concrete
L_b, L_c	bond deterioration and curvature influencing length
L_{c0}	curvature influencing length in the elastic range
L_{cs}	length of element in compressive principal direction
L_e	length of reinforcing bars between two adjacent cracks
L_θ	average crack spacing
$M(x), V(x)$	bending moment and shear force along the bar axis
s	non-dimensional slip
S	local slip along reinforcing bar
S^{cr}	axial pullout of reinforcing bar at crack plane
x	distance from the middle of re-bars between adjacent cracks
y	local coordinate of steel fiber from center of bar section
α	inclination of reinforcement
β	angle between reinforcement and crack
δ	deflection of reinforcing bars
$\tilde{\boldsymbol{\varepsilon}}_{\boldsymbol{xy}}$	second order tensor of strain
ε_c	compressive strain correspond to peak stress
ε_f, σ_f	fiber strain and stress of bar cross section
ε_s, σ_s	local strain and stress of steel bar
$\bar{\varepsilon}_s, \bar{\sigma}_s$	average strain and stress of steel bar
$\varepsilon_x, \varepsilon_y, \gamma_{xy}$	normal strains (ε) and shear strain (γ) of element in global directions (x–y)
$\varepsilon_1, \varepsilon_2, \gamma_{12}$	normal and shear strains of concrete in local coordinate system (1–2)
$\phi(x)$	curvature of reinforcing bar
λ	parameter reflecting concrete flaking
μ	non-dimensional damage parameter
θ	directional angle normal to the crack plane
ρ	reinforcement ratio
$\tilde{\boldsymbol{\sigma}}_{\boldsymbol{xy}}$	second order tensor of stress
$\tilde{\boldsymbol{\sigma}}_{\boldsymbol{Cxy}}$	second order tensor of stress of concrete
$\tilde{\boldsymbol{\sigma}}_{\boldsymbol{Sxy}}$	second order tensor of stress of reinforcing bars
σ_{br}, σ_d	bridging and dilatancy stresses transfer across crack
σ_s^{cr}	local stress of steel bar at crack location
σ_{sd}	projection of dowel stress on 1 direction
$\sigma_x, \sigma_y, \tau_{xy}$	normal stresses (σ) and shear stress (τ) of element in global directions (x–y)
$\sigma_1, \sigma_2, \tau_{12}$	normal and shear stresses of concrete in local coordinate system (1–2)
$\tau(\varepsilon_s, s), \tau$	local bond stress
$\tau_{\text{agg}}, \tau_{sd}$	shear stress transfer by aggregate interlock and reinforcing bars
τ_{st}	contribution of steel to shear transfer across crack
$\tau_0(s)$	intrinsic bond stress for strain equal to zero
ω_{av}, δ_{av}	average opening and shear slipping of crack
ζ	reduction factor for fracture parameter

plain concrete modeling assuming an intrinsic single crack is applied to the plain concrete (PL) one.

Although so-called zoning method [9] implicitly results in combination of size-dependent tension in concrete and steel/bond size-independency and brings success for size-effect analysis, geometrical zoning has to be performed with engineering judgment based on detailed arrangement of steel. Furthermore, highly nonlinear mutual interaction among local shear stress transfer with contact damaging [11], bond deterioration close to crack planes and local curvature induced in reinforcing bars [12] cannot be explicitly taken into account. These can be ignored for the case of dispersed cracking field, but are crucial for the cases where a very few localized cracks may rule the whole nonlinearity of RC domains.

Thus, the authors aim at explicitly deriving highly localized kinematics of RC elements from the exact local stress field approach without any empirical smoothing of stress fields [13], and offering a strict meso-level modeling for re-evaluation of non-localized stress field approach with the most straightforward manner. It is also expected that applicability of the non-localized stress field approach having high cordiality with nonlinear structural analyses will be strictly and rationally defined, and that the semi-theoretical and partially empirical size-dependent modeling, such as crack shear transfer softening along cracking [1] and averaged yield strength reduction of steel under non-orthogonal intersection with cracking [7], will be verified.

2. Exact local stress fields

RC panel is modeled as a multi-component structural system composed of reinforcing bars and concrete as well as their interaction. Structural nonlinearity and local stress field comprise deferent size dependent stress transfer mechanisms and phenomena (Fig. 1) such as:

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