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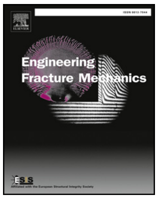

Numerical analysis of reinforced concrete structures with oriented steel fibers and re-bars

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ABSTRACT

In this study, a new strength and stiffness numerical analysis approach of fiber reinforced concrete with oriented fibers and re-bars is proposed. The model is based on discrete lattice simulation that is obtained from standard tetrahedron mesh. Area of cross section of lattice members is obtained by homogenization of each tetrahedron finite element. A non-linear material constitutive model that takes into account fiber orientation, concrete damage and plasticity of re-bars is proposed. Re-bars are embedded in fiber concrete lattice by using a special joint elements that are consistent with re-bar's surface pattern. The numerical model is validated by using four-point bending test results of high performance fiber concrete with oriented fibers. Moreover, the model showed a good agreement with re-bar pull-out test results for ultra-high performance concrete with oriented fibers. The proposed model is used to analyze a ribbed concrete panel with oriented fibers and best optimal fiber orientation for three-point bending is proposed.

1. Introduction

High performance fiber reinforced concrete (HPFRC) and ultra-high performance fiber reinforced concrete (UHPFRC) is becoming more popular among society of civil engineers. However, fracture mechanics of HPFRC and UHPFRC is not well understood, especially when fibers are oriented and material is additionally strengthened with traditional reinforcement bars (re-bars). Additional factors that affect properties of fiber concrete are fiber shape, aspect ratio, volume fraction and properties of concrete itself [1–3].

One of possibility to obtain oriented fibers is to use the effect that fibers tend to be aligned perpendicular to flow in self-compacting concrete. Meanwhile, fiber orientation depends on the type of mould, the location of pouring point, pouring speed and other parameters [4,5]. This effect with special pouring technique is used to manufacture HPFRC with oriented fibers [6–8]. Another way to achieve necessary fiber orientation is to use flow speed and local effects near surfaces of formwork [9–12]. Accurate numerical models can help to understand better mechanical behavior of load bearing structures from HPFRC and UHPFRC.

Currently, there are available numerical models for pure concrete [13], fiber concrete [14,15] and reinforced concrete [16,17] that are based on continuum theory. Meanwhile, there are stress resultant based models that are used for beam, plate and shell structures [18–20]. Micro and meso structure of concrete is difficult to represent as a continuum, since there are large number of different size aggregates, voids and other heterogeneities [13,14,21]. Duo to heterogeneity of concrete, load is transferred by discrete load paths. Discrete nature of concrete has promoted to develop discrete element models (DEM) that are based on triangular, hexahedral or another type of lattices [22].

A thermodynamically consistent cohesive model for DEM of cement based materials is presented in [23]. The crack propagation in pure concrete can be studied by using a cubic distinct lattice spring model [24]. Fracture analysis of reinforced concrete structures can be done by using micropolar peridynamic analysis framework [25]. Mechanical behavior of ultra-high performance concrete

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Nomenclature

$\overline{A}_L$	cross section area of lattice member that is average value from 12 load cases
A_L	cross section area of lattice member that is obtained from one load case
E_c	Young's modulus for fiber concrete
E_{init}	Initial (without damage) Young's modulus of material
L_{fiber}	length of fiber
L_i	length of i-th lattice member
$L_{lattice}$	average length of lattice member
U_L	strain energy in discrete lattice element
f_c	compressive strength of FRC
$f_{t,0}$	tensile strength of FRC when fiber are oriented at 0 degrees to load direction
$f_{t,90}$	tensile strength of FRC when fiber are oriented at 90 degrees to load direction
f_t	tensile strength of FRC
k_ε	a strain multiplier that is used to obtain strain at peak stress
$\boldsymbol{u}_i$	a displacement vector of i-th load case
D	a damage variable ($D = 0$ undamaged, $D = 1$ damaged material)
E	Young's modulus
U	strain energy in continuum element (tetrahedron)
V	volume
n	a parameter that characterize accuracy of fiber alignment
ν	Poisson's ratio
$\boldsymbol{B}$	a standard strain-displacement matrix used in FE formulation
$\boldsymbol{C}$	material's stiffness matrix
$\boldsymbol{u}$	displacement vector
Ω_Δ	a domain that is occupied by the tetrahedron
ε_i	axial strain in i-th lattice member
ε_t	strain at peak stress
θ	orientation angle between lattice member and average fiber orientation
μ	a shape parameter that defines stress-strain curve of FRC
$\boldsymbol{\varepsilon}$	strain tensor
σ	stress tensor
CTOD	crack tip opening displacement
DEM	discrete element models
FEM	finite element method
FRC	fiber reinforced concrete
HPFRC	high performance fiber reinforced concrete
UHPC	ultra-high performance concrete
UHPFRC	ultra-high performance fiber reinforced concrete

(UHPC) was successfully approximated for projectile penetration impact loads by using lattice discrete particle model [26].

So far, there are not available information on the numerical models of HPFRC and UHPFRC with oriented fibers and re-bars. Meanwhile, there are not available numerical models that can accurately take into account fiber orientation effect on the macroscopic re-bar pull-out behavior.

A new method for discrete modelling of HPFRC and UHPFRC is presented. This method is based on lattice model that is obtained using standard tetrahedral finite element mesh where each edge of tetrahedron represents a lattice member. This approach provides a possibility to use standard mesh generation routines in contrary to other DEM methods [25,26]. Moreover, the constitutive model takes into account the damage of concrete that is represented by the damage variable, plasticity of steel re-bars and damage in cohesive zone between re-bars and concrete. Material parameters are calculated using non-linear interpolation depending on orientation angle between the lattice member and the average fiber orientation. Size of cross sections of each lattice member is obtained by the homogenization of each tetrahedron and the principle of strain energy equivalence.

2. Discrete tetrahedron lattice modelling approach

Non-linear and discrete nature of the fiber concrete can be approximated by using discrete lattice model. Each lattice member is obtained from edge geometry of the standard tetrahedron mesh. Lattice model consists of concrete lattice, re-bars and re-bar-concrete joint elements.

Lattice members are discretized by 3D non-linear truss finite elements. Small strain theory is used.

2.1. Calculation of bar stiffness using homogenization of tetrahedron

A stiffness of lattice member plays an important role in the analysis. For each tetrahedron, all six edges are assumed to have the same stiffness that is defined by cross-section area and Young's modulus. Young's modulus $E = E_c$ are assumed to be the same as for fiber concrete. Cross-section areas are calculated by using a homogenization technique where the energy equivalence criterion [27] is used. The homogenization is done by assuming linear elastic material properties.

The strain energy of a four-node tetrahedron are computed using a standard FEM approach [28]:

$$U = \frac{1}{2}\int_{\Omega_\Delta} \boldsymbol{\varepsilon} : \sigma dV = \frac{1}{2}\int_{\Omega_\Delta} \boldsymbol{u}^T \cdot \boldsymbol{B}^T \cdot \boldsymbol{C}(E,\nu) \cdot \boldsymbol{B} \cdot \boldsymbol{u} \cdot dV \tag{1}$$

where $\boldsymbol{\varepsilon}$ – strain tensor, σ – stress tensor, $\boldsymbol{C}$ – materials stiffness matrix, ν – Poisson's ratio, $\boldsymbol{B}$– a standard strain-displacement matrix used in FE formulation, $\boldsymbol{u}$ – displacement vector, Ω_Δ – domain that is occupied by the tetrahedron, V – volume of the terahedron.

Meanwhile, the strain energy is calculated also for the discrete lattice model by summing strain energies in all six bars: