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A review of lattice type model in fracture mechanics: theory, applications, and perspectives

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ABSTRACT

The lattice model is a discrete model that is typically used to simulate the fracture process of brittle materials. This review summarizes the main achievements during the development history of the state-of-the-art lattice model during the past 80 years from the theory and application viewpoints. It is found that the classical lattice spring model (LSM) can only simulate a fixed Poisson's ratio. This problem has been partially or fully solved in developed versions of novel lattice models by using (1) extra nodal DOFs, (2) extra shear springs, (3) extra nonlocal energy parameters, and (4) higher dimensional normal springs. The lattice model has already been successively applied in simulations of fracture processes of different materials and under different loads. However, the applications in fracture analyses of metals, dynamic load-induced fracture, and real large-scale structures, are not sufficient. Innovative areas of future research in reference to the use of the lattice model in engineering practice include constitutive relations, failure criteria, anisotropic material modeling and efficient computing techniques to expand its use and range of applications.

1. Introduction

Brittle materials, such as mortar and concrete, are vulnerable to cracking owing to their low tensile strength. To simulate the fracture process of brittle materials, several discrete numerical models have been proposed and developed [1–5]. One of them is the so-called "lattice model" which can be traced back to the 1940s. To solve the elasticity problem, Hrennikoff [6] proposed a framework methodology that may be considered the prototype of the lattice model. In the 1970s and 1980s, the lattice model was introduced into the field of theoretical physics to study the fracture process of disordered media [7–12]. In the 1990s, the lattice model was further and considerably developed by various researchers [13–16]. With the rapid development of computers and computational techniques at the beginning of this century, the previous 2D lattice models were extended to 3D [17–19]. In addition, several new features were introduced. For example, Hou [20] proposed an improved

Abbreviations: FEM, finite element method; LSM, lattice spring model; LBM, lattice beam model; RPM, random particle model; CSL, confinement-shear lattice model; LCM, lattice-cell model; DLSM, distinct lattice spring model; VCPM, volume-compensated particle model; DPM, discrete particle model; MD, molecular dynamics; PD, PeriDynamics; DOF, degree of freedom; GB, generalized beam; ITZ, interfacial transition zone; LDPM, lattice discrete particle model; DEM, discrete element method; AMR, adaptive mesh refinement; FA, fly ash; BFS, blast furnace slag; SF, silica fumes; HPC, high performance concrete; UHPC, ultra high performance concrete; RC, reinforced concrete; FRC, fiber-reinforced concrete; SFRC, steel fiber-reinforced concrete; CUDA, compute unified device architecture; GPU, graphics processing unit.

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Nomenclature

σ	nominal stress of element in failure criterion
$[\sigma]$	maximum allowed nominal stress of element in failure criterion
σ_t	tensile stress of element
α_N, α_M	normal force and bending influence factors to modify tensile stress in element
F	normal force of element
A_e	cross-sectional area of element
W_e	cross-sectional flexural modulus of element
M_i, M_j	nodal bending moment of element
f_t	tensile strength
f_c	compressive strength
σ_n	normal stress
τ	shear stress
c	cohesion of material in Mohr-Coulomb criterion
ϕ	friction angle of material in Mohr-Coulomb criterion
ε	nominal strain of element in failure criterion
$[\varepsilon]$	maximum allowed nominal strain of element in failure criterion
ε_t	tensile strain of element
u	difference of nodal displacements along normal direction
φ	difference of nodal bending angles
α_S	bending angle factor to modify tensile strain in element
h_e	height of rectangular cross-section of element
d_e	diameter of circular cross-section of element
E	elastic modulus of material
υ	global poisson's ratio
ρ	density
ξ	damage degree of element
k_n, k_s	stiffnesses of normal and shear springs
$k_\alpha, k_\beta, k_\gamma$	stiffness of 4D spring in 4D LSM
λ^{4D}	4D stiffness ratio

lattice model to consider the effects of large strains. Guo et al. [21] used the lattice model to simulate the fatigue problem of concrete. Liu et al. [22] incorporated fiber and rebar in the lattice model. Transport problems of moisture and chloride ions have also been studied by the lattice model [23–26]. To overcome the fixed Poisson's ratio issue in classical lattice models, and correctly simulate the behavior of materials with an arbitrary Poisson's ratio, numerous novel models have been developed [27–32], especially after 2000. A timeline listing the important milestones during the historical evolution of the lattice model is shown in Fig. 1. The full names of the abbreviations in the figure can be found in the abbreviation list of this paper.

The general concept of the classical lattice model requires the discretization of a continuum into several connected spring (truss) or beam elements, and conduction of a series of linear analyses on the discrete model. The fracture process is simulated by removing the critical elements from the model, which are determined based on a failure criterion in a step-by-step manner. Generally, the lattice model has two major advantages: (1) lattice models are based on a discontinuous formulation, which avoids singularity-related issues in continuum-based numerical simulation methods, such as the finite element method (FEM), and (2) the material heterogeneity can be easily implemented. Owing to the first advantage, the lattice model is usually adopted to simulate the fracture process, especially for brittle materials, e.g., in uniaxial tensile experiments of concrete [17,33], and rebar corrosion in concrete [34,35]. Owing to the second advantage, the lattice model is especially preferred in research applications at the meso- or microscales where the effect of material heterogeneity should be considered.

This study mainly reviews the evolution of the lattice model from 1990 onwards from the theory and application viewpoints. The presented work is divided into three parts. In the first part, the general theoretical background of classical lattice models and recent developments are briefly introduced. More detailed reviews on the general aspects of classical lattice models can be found in other Refs. [36–39]. In the second part, the applications of the lattice model are reviewed in accordance to three specific aspects: benchmarks of classic tests, types of materials, and types of loads. Finally, some future challenges and perspectives of the lattice model are presented. Some possible solutions to the challenges are also proposed. Through this review, it is expected that researchers can gain an understanding about the history and the state-of-the-art status of the lattice model, and the possible development concerns and applications, or the hurdles for its future applications.

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