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A thermodynamically consistent nonlocal damage model for concrete materials with unilateral effects

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Abstract

This paper proposes a thermodynamically consistent constitutive model for concrete materials to solve several problems encountered in the existing damage modeling. Two separated equivalent strains and the corresponding new damage evolution laws are used to enhance the representation of asymmetrical behaviors of concrete, of which the different strengths and post-peak behaviors between tension and compression cannot simultaneously be reproduced by the classical strain-driven models. The crack opening–closure criterion related to the unilateral effect is described, using the trace of the strain tensor rather than the spectral decomposition of a specific second-order tensor, which leads to either a discontinuous stress–strain response or spurious energy dissipation upon closed load cycles. An integral-type nonlocal regularization is incorporated to solve the problem of strain-softening induced mesh non-objectivity involving mesh-size and mesh-bias dependencies. The strain-driven formalism and the explicit integration of constitutive equations improve the robustness of the numerical algorithm. Correlative studies using available benchmark test results are presented to demonstrate the performance of the model.

Keywords: Thermodynamic consistency; Damage modeling; Asymmetrical behavior; Unilateral effect; Strain-softening; Nonlocal regularization

1. Introduction

The performance-based design requires an adequate constitutive model to predict the concrete behavior in nonlinear structural analysis. Generally, the framework of the coupled damage and plasticity is appropriate for constitutive modeling of concrete [1–5]. However, a model incorporating damage alone is able to reasonably describe the concrete behavior in certain applications, especially when tension is the main cause of structural failure [6–8]. The damage of concrete is an anisotropic phenomenon in nature [9]. Nevertheless the isotropic damage models are used extensively due to their simplicity, efficiency and rationality [10–15]. Therefore, this paper focuses on damage modeling in which the damage evolution is assumed to be isotropic.

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Despite the noteworthy progresses in recent years, a number of issues in damage modeling of concrete materials still represent serious challenges. The first issue in material modeling is the asymmetrical behavior of concrete, of which the different strengths and post-peak behaviors between tension and compression cannot be reproduced simultaneously by the classical strain-driven models [16–18]. Further, the predicted asymmetrical strength in biaxial stresses is far from satisfactory when the strain-based damage criteria are used [10,16–19]. A better solution to this problem is the use of stress-based damage criteria [6,11,20,21]. However, stress-based criteria have lower algorithmic efficiency than strain-based criteria in which the stress corresponding to a given strain can be evaluated directly [22]. Consequently, this paper offers an improved solution to reproduce the asymmetrical behavior of concrete in the context of strain-based damage criteria.

The second issue is the unilateral effect characterized by a total or partial recovery of the degraded stiffness during the tension–compression load reversal, which is already verified by experimental evidence [23]. The unilateral effect is usually described by the spectral decomposition of a specific second-order tensor (e.g., stress, strain or effective stress tensor, etc.) into positive and negative components in earlier models [1,8,24]. However, as pointed out by several researchers [25–27], this approach exhibits the following serious theoretical shortcomings: (i) the loss of energy conservation at a fixed thermodynamic state; and (ii) unrealistic discontinuities in stress–strain relations across the tension–compression interface. However, it is noteworthy that the deficiency of loss of energy conservation is less obvious in practical numerical simulations [28]. Nevertheless, this study intends to model the unilateral effect more rationally, it thus adopts a new approach that satisfies the conditions of physical realism and thermodynamic consistency in proper modeling of this phenomenon.

The third issue is related to the strain-softening, the stage in which concrete is still able to transfer residual stresses. However, a strain-softening continuum model usually suffers from a strong mesh-dependency, which involves mesh-size [29] and mesh-bias [30] dependencies. The mesh-size dependency means that the numerical results not only depend pathologically on the size of the finite element (FE) mesh, but also are physically unrealistic as the mesh is infinitely refined due to that the failure occurs without energy dissipation [22]. A common remedy for the mesh-size dependency is the introduction of a localization limiter (material characteristic length) in the constitutive model to prevent strain localization in zero volume zones, such as crack band [29] and nonlocal [31] models. It is noteworthy that the crack band models are only objective for the energy dissipation in the sense that the global responses do not exhibit spurious mesh-size dependency upon mesh refinement, but the numerically resolved localization band tends to zero if the infinitesimal mesh size is used [32].

The mesh-bias dependency means that the numerical solution cannot properly capture the direction of the strain localization band, which prefers to propagate along continuous mesh lines rather than follows the realistic direction [30]. The current debate about its cause can be divided into two perspectives: (i) the mesh-bias dependency is a result of the ill-posedness of the rate boundary value problem (BVP) due to the loss of ellipticity of the governing partial differential equations for static problems [33], irrespective of the spatial discretization procedure; and (ii) it is caused by the deficiency in the spatial discretization [30] of the partial differential equations but not in the differential equations themselves. Following the first perspective leads to enhanced regularization models, examples of which are nonlocal (including the integral-type [31,34,35] and the gradient-type [36–38]), micropolar [39], and viscous or rate-dependent models [11]. Following the second perspective leads to remedies aiming at reducing the discretization error, such as adaptive remeshing methods [40], X-FEM (eXtended Finite Element Method) [41] and E-FEM (Elemental enrichment Finite Element Method or Embedded discontinuity Finite Element Method) [42], mixed stabilized FE methods [43,44] and smeared–embedded continuum crack models [45]. Moreover, the crack tracking algorithms (e.g., [46]), which have been successfully applied to continuum smeared models [47], can circumvent the mesh-bias dependency. Further, it is the authors' opinion that the discretization procedure contributes to the mesh-bias dependency, since the crack band model incorporated with SLA (sequentially linear analysis) [48], the method of which ensures the well-posedness of the rate BVP, still suffers a mesh-bias dependency [49] without the use of the crack tracking algorithm [47]. Due to that the nonlocal method not only act as a localization limiter but also can completely overcome or substantially alleviate the mesh-bias dependency if small enough elements are used to subdivide the strain localization band [50], a nonlocal method is adopted in this paper.

The objective of the present paper is to propose a constitutive model using the internal variable theory of thermodynamics, in an attempt to overcome the above discussed problems. Assuming the unique dissipation mechanism is damage in concrete, the present model aims at describing several significant features of concrete that include stiffness degradation, asymmetrical behavior between tension and compression in terms of strength and post-peak behavior, the