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A nonlocal triaxiality and shear dependent continuum damage model for finite strain elastoplasticity

Yazhi Zhu[a,b,c,*], Michael D. Engelhardt[b]

[a] Department of Structural Engineering, Tongji University, Shanghai 200092, China

[b] Ferguson Structural Engineering Laboratory, Department of Civil, Architectural and Environmental Engineering, University of Texas at Austin, Austin, TX 78712, United States

[c] Department of Civil and Environmental Engineering, University of California, Davis, CA 95616, United States

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ABSTRACT

Continuum damage mechanics provides a powerful tool to describe the effects of the growth of micro-voids on the response of ductile materials at the macroscopic scale. Within the framework of thermodynamic and finite strain elasto-plasticity, this paper develops a new damage model considering both stress triaxiality and shear stress ratio, both of which influence the micro-void evolution and the ductile fracture process. To overcome the nonconverging mesh dependency problems in finite element modeling in the region of strain and damage localization, the new damage model is coupled with the nonlocal regularization. The model is implemented using a mixed explicit-implicit algorithm. In addition, the arbitrary Lagrangian-Eulerian (ALE) remeshing strategy is introduced to avoid difficulties caused by excessive element distortion. Two numerical examples are provided: tension of a plate under plane strain and tension and torsion tests on M5 zirconium alloy. The results show elimination of mesh dependency using the combined nonlocal and ALE method. Parametric studies on the characteristic length in the nonlocal formulation and the damage related factors illustrate that all the parameters significantly influence the damage distribution and the material response. The validation studies also indicate that the proposed model has significant potential to represent material response and predict ductile fracture at both low and high triaxialities.

1. Introduction

Strain localization is a common phenomenon in a material undergoing large plastic deformation. With this phenomenon, the mode of deformation transitions from a homogenous to a discontinuous pattern, with intense straining occurring in a narrow region. Some well-known manifestations of strain localization are necking in ordinary tensile testing of ductile metals and shear banding of soils and rocks subject to compression or shear. This plastic instability condition is caused by either mechanical, geometrical, microstructural, or thermal effects or combinations of these, and is often a precursor to a complete failure, since the localized deformations significantly increase the cumulative damage. Other than the strain softening models used to represent strain localization of geotechnical materials, strain hardening material models are often adopted to simulate plastic behavior of metals. In contrast to strain softening materials, the loss of material stability in metals is dependent on the strain hardening process and accumulation of internal damage within the material as well as on the geometric evolution of the structure.

It is widely accepted that ductile fracture in metals results from the microscopic process of void nucleation, growth and coalescence (Rice and Tracey, 1969; Anderson, 2017). Many physics-based models have been developed to describe the micromechanical process of ductile fracture. Among those, the Gurson model (Gurson et al., 1977) and its extensions (Tvergaard and Needleman, 1984; Xue, 2008; Nahshon and Hutchinson, 2008) have been widely used to predict void volume fraction evolution and its effect on plastic yield and flow rules during the ductile fracture process. The Gologanu-Leblond-Devaux model (Gologanu et al., 1993) improved the Gurson-type models by coupling the void shape effect with material behavior. A more phenomenological group of approaches is attributed to continuum damage mechanics (CDM) models. In these approaches, a damage variable, defined at the macro-scale, is introduced to represent the influence of micro-cracks and micro-void growth on degradation of material properties. This category of models is established essentially based on macroscopic considerations. The internal damage is further incorporated into constitutive equations representing the continuous deterioration of elastic properties and the yield stress using the notion of effective stress. Some

* Corresponding author. Department of Structural Engineering, Tongji University, Shanghai 200092, China.
E-mail address: yzzhu@utexas.edu (Y. Zhu).

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key contributions of CDM model development and application includes work by Kachanov (1978), Saanouni et al. (1994), Germain et al. (1983), Lemaitre (1985), Lemaitre and Desmorat (2005), Rousselier (1987) and Rousselier (2001). Among these, the Lemaitre damage model (Lemaitre, 1985) is popular and provides a basis for many other damage-coupled yield criteria. Its underlying function relates the damage increment to the equivalent plastic strain increment and the strain energy density release rate, which facilitates description of stress triaxiality dependency of the damage process. This allows the Lemaitre model to well describe the characteristics of ductile fracture. In general, the evolution of the damage variable leads to strain softening in structural metals, and is one important source that induces bifurcation and the strain and damage localization phenomena. This paper will focus on such damage-dominated strain softening and localization modeling.

As is well recognized that once the classical continuum approach is adopted to describe the bifurcation problem, the analytical solution of the governing equations of equilibrium loses its ellipticity and becomes physically meaningless (Bažant and Jirásek, 2002). In this case, finite element results show an inextricable mesh dependency where reducing the mesh size does not lead to convergence. With increasing mesh refinement, the damage and strain tend to localize into a band with zero thickness and with zero energy dissipation. To overcome these shortcomings, many enhanced continuum models and numerical solution strategies have been proposed. A common idea behind these approaches is to consider the stress at a material point depending on the strain field of the point itself as well as on its neighborhood by introducing a characteristic or intrinsic length scale. Some typical formulations following this idea are Cosserat, strain gradient and nonlocal theories. An early approach is provided by Cosserat et al. (1909), who treated the material particle with rotational degrees of freedom in addition to the displacement degrees of freedom in the continuum description. Further, the development of Cosserat continua to the couple-stress and the micropolar theories facilitates this family of approaches to regularize the momentum balance equations for strain localization cases. Another group of methods incorporate the higher gradients of displacements (the gradients of strains) into the material constitutive model and into the finite element formulation as additional degrees of freedom (Fleck and Hutchinson, 1993, 1997). The third family of approaches is known as nonlocal models of the integral type. These enriched continuum models are based on a spatial smoothing of certain variables at a point over its surrounding volume. Some early studies of nonlocal approaches applied to elastic problems include Eringen (1966) and Eringen and Edelen (1972). These attempts, which considered the stress as a function of spatial averaged strain, aimed at describing interaction of crystal defects at small scales. Further development of nonlocal models extended to inelastic materials. Among these, Eringen (1981) and Eringen (1983) developed a nonlocal formulation for isotropic hardening and perfect plasticity, where the nonlocal variable is the elastic stress. Bažant et al. (1984) introduced the nonlocal total strain tensor to a strain softening damage model to recover a well-posed boundary value problem. Bažant et al. (1988) proposed nonlocal plasticity models, in which the variables subjected to nonlocal spatial integration are either the plastic strain or the rate of the plastic multiplier while the elastic part of the strain remains unchanged. Nonlocal formations were coupled with continuum damage mechanics to describe quasi-brittle materials, which show strong strain softening behaviors (Bazant and Pijaudier-Cabot, 1988; Jirásek and Rolshoven, 2003; Bažant and Jirásek, 2002; Borino et al., 2003; DE and De Vree, 1996; Grassl and Jirásek, 2006). The application of nonlocal approaches to describe softening and fracture phenomena of ductile materials is relatively recent (Tvergaard and Needleman, 1995; Brunet et al., 2004; Andrade et al., 2009; Belnoue et al., 2009; Chow et al., 2011). Nonlocal averaging treatments were introduced into either continuum damage models for macroscopic fracture problem (Belnoue and Korsunsky, 2012; Belnoue et al., 2010; Korsunsky et al., 2005) or micromechanics based material constitutive equations to study the response of metal matrix composites (Drabek and Böhm, 2005, 2006; Brunet et al., 2005). Other studies showed the numerical validity and efficiency of nonlocal approaches applied to ductile metals (Andrade et al., 2011; Belnoue et al., 2007; Poh and Swaddiwudhipong, 2009; Peerlings et al., 2012). With its ability to overcome numerical instability resulting from strain softening, to avoid nonconvergent mesh sensitivity, and to capture size effects, the nonlocal approach becomes a valuable tool to describe ductile fracture.

Even though regularization approaches are adopted in numerical modeling, highly distorted elements in the localization region are sometimes inevitable. This issue is more prominent for strain localization of metal materials characterized as highly ductile, e.g. structural steels. The localized effect leads the elements to have unexpected shapes and aspect ratios in narrow zones under large deformations. This will in turn affect the effectiveness of the nonlocal treatment and mesh dependency issues. Therefore, a sufficient numerical grid consisting of appropriately shaped elements is needed during the deformation history. In contrast to the Lagrangian framework that cannot deal with the element distortion issue, the adaptive remeshing strategy based on arbitrary Lagrangian-Eulerian (ALE) formulations provide a useful strategy to maintain high-quality in the spatial mesh and trace the boundary. The idea of the ALE approach is to allow the mesh movement independent of material flow, which circumvents the limitation of the Lagrangian approach by taking advantage of the Eulerian approach. Early applications of the ALE technique to one and two-dimensional localization problems includes work by Huerta et al. (1992), Pijaudier-Cabot et al. (1995) and Askes et al. (1998). Though the spatial discretization of the localization zone is improved through ALE remeshing optimization, the governing equation of equilibrium is still ill-posed. On the other hand, the connectivity as well as the number of the elements remain unchanged with the ALE framework. Consequently, it is possible to apply this method to a nonlocal-coupled finite element formulation for the localization problem. The motivation to pursue this approach is to avoid an unreasonable numerical solution caused by spurious localization and element distortion, and to achieve numerical convergence to a physically realistic solution.

In a Lagrangian formulation, the average operator of the nonlocal model is evaluated at either the deformed configuration, i.e. Eulerian-type, or the undeformed configuration, i.e. Lagrangian-type. For small strains, these two averaging strategies lead to negligible differences. This may not be true in a finite strain case. This is not only related to the averaging weight factor of each material point, but also because the number of material points that account for the nonlocal influence would be dramatically changed. As the ALE approach is adopted to the finite strain formulation, it gives rise to a more complex comparison between the two strategies. Besides, these two averaging strategies have significant effect on the computational efficiency. The Lagrangian-type allows the averaging computation to be carried out only at the beginning of each analysis, while for the Eulerian-type, the averaging operator needs to be updated at every time increment. Considering their performances in both computational cost and numerical accuracy, it is necessary to evaluate and compare these two strategies within the combined nonlocal model and ALE framework.

The objective of this paper is to propose a shear stress and triaxiality dependent nonlocal continuum damage model to deal with strain softening. For numerical modeling, the ALE approach is coupled with nonlocal treatment. The combination of these two strategies is aimed to eliminate spurious mesh sensitivity for the strain localization problem completely. The mixed explicit and implicit scheme is adopted for numerical implementation. Evaluation of the proposed method will be performed based on a comparison of ALE and nonlocal model in terms of damage and strain localization zone length and load-displacement response. Two numerical examples will be carried out to illustrate the performance of the proposed nonlocal model, the validation of the ALE remeshing strategy, and the efficiency of the numerical algorithm.