International Journal of Impact Engineering 87 (2016) 169–185

Contents lists available at ScienceDirect

International Journal of Impact Engineering

journal homepage: www.elsevier.com/locate/ijimpeng

A direct displacement smoothing meshfree particle formulation for impact failure modeling

Youcai Wu [a], Dongdong Wang [b,*], Cheng-Tang Wu [c], Hanjie Zhang [b]

[a] Karagozian & Case, 700 N Brand Blvd, Suite 700, Glendale, CA 91203, USA
[b] Department of Civil Engineering, Xiamen University, Xiamen, Fujian 361005, China
[c] Livermore Software Technology Corporation, 7374 Las Positas Road, Livermore, CA 94551, USA

ARTICLE INFO

Article history:
Available online 15 April 2015

Keywords:
Meshfree method
Displacement smoothing
Impact failure
Concrete
Steel

ABSTRACT

A direct displacement smoothing meshfree particle formulation is introduced to the material failure modeling of concrete and steel materials due to blast and high velocity impact loadings. A Lagrangian smoothing form of the shape function is developed for the direct displacement smoothing meshfree particle formulation, which is subsequently employed to discretize the variational equation of motion. The weak form is integrated nodally, which maintains the particle characteristics of the meshfree formulation and enables the formulation to track the impact debris evolution naturally. To model the failure process of concrete and steel physically, the physics-based material constitutive laws for these two materials are discussed as well. The computational implementation of the discrete equations is illustrated in detail particularly for the concrete constitutive equations. Numerical results show very favorable agreement with the available experimental data, as demonstrated that the present direct displacement smoothing meshfree particle formulation can effectively model the impact material failure. Moreover, the debris evolution can be efficiently simulated by the proposed meshfree particle formulation as well if the material constitutive law provides a physical means to indicate the damage and failure of the material.

1. Introduction

Failure occurs when a material such as concrete or steel is subjected to blast or high velocity impact loads [1–8]. The mass and velocity distributions of the debris generated during the failure process have been attracting more and more attention in recent years. Due to the cost and difficulties of experimental tests, this information is usually obtained through the numerical simulations. However, the mathematical models of these problems are often ill-posed and the corresponding numerical solutions are generally non-smooth since they involve very high strains and strain rates, large degrees of damage and material separation, and complex contact conditions. For example, severe mesh distortion would occur if Lagrangian finite element method (FEM) is used and thus the solutions are highly dependent on the mesh topology. Furthermore, the mesh based finite element formulation often employ the element erosion algorithms to model the fragmentation process, which is unphysical and also highly dependent on the mesh topology and the criteria used to trigger the erosion [9]. On the other hand, once the erosion is triggered, the element is deleted and hence no information will be available for the debris, which also leads to non-conservation of mass and momentum.

To conserve the mass and momentum and obtain the debris information, various meshfree approaches have been developed during the past two decades [10–17]. For example, a failure criterion is introduced in Ref. [9] but the failed elements are converted into smoothed particle hydrodynamics (SPH) [18] particles rather than been deleted. Belytschko et al. [19,20] analyzed the dynamic fracture in concrete with the element free Galerkin (EFG) method. Wu et al. [21] developed a large deformation Lagrangian meshfree method to model the failure of geomaterials. Rabczuk et al. [22–24] investigated the high velocity concrete fragmentation analysis using the SPH formulation and moving least square SPH methods. The high velocity impact penetration on concrete structures with the EFG method has also been studied by Rabczuk et al. [25]. Rabczuk et al. [26–28] developed meshfree formulation for modeling dynamic evolving cracks for both three dimensional solid and shell elements. Zhuang et al. [29] enriched the meshfree formulation with level sets for modeling three dimensional fracture. Caleyron et al. [30] used a coupling of SPH and FEM for modeling reinforced concrete. Wu et al. [31,32] developed a coupled reproducing kernel (RK) meshfree–FEM formulation to study the fragmentation and debris

* Corresponding author.
E-mail address: ddwang@xmu.edu.cn (D. Wang).

http://dx.doi.org/10.1016/j.ijimpeng.2015.03.013

evolution process. Rabczuk et al. [33] also applied a coupled finite element and meshfree approach for modeling static and dynamic crack propagation problems. Recently, Wu et al. [8] presented a nodally regularized meshfree formulation for modeling concrete failure which adopts a two-level strain smoothing methodology proposed by Wang and Li [34,35].

In the coupled formulation proposed by Wu et al. [31,32], the FE approximation is dynamically coupled with the RK approximation [36,37]. The RK approximation is constructed entirely based on the positions of a set of discrete particles, which reduces the strong dependency between solution accuracy and mesh quality and therefore alleviates the difficulties associated with mesh distortion in large deformation problems for the mesh based formulations such as FEM. The domain integration is performed using the stabilized conforming nodal integration (SCNI) developed by Chen et al. [38,39] for the whole domain, i.e., for both FE and RK domains. By doing so, the particle nature of the meshfree formulation is maintained. One key component of the SCNI algorithm is the strain smoothing methodology [38–41], which was also employed by Vu-Bac et al. [42,43] to develop smoothed finite formulation for fracture analysis. Successful developments and applications of the Lagrangian RK formulation [40] for large deformation problems include the modeling of rubber [45], metal forming [46], geotechnical materials [21,35,47], shear banding [48], plugging failures in high-speed impacts [49], and spall fracture [50], among many others. Furthermore, a semi-Lagrangian reproducing kernel particle formulation was also developed [51,52] to treat extremely large deformation problems such as earth moving bulldozing [53] and high velocity fragment-impact problems [4,31]. Nevertheless, additional stabilization may be needed for SCNI method in some nonlinear applications [54].

On the other hand, a smoothed particle Galerkin method was recently proposed by Wu et al. [55], in which the displacement smoothing is developed with the nodal integration of weak form to achieve efficiency, stability, as well as simplicity. In this work, the direct displacement smoothing approach is formulated for the impact failure analysis. The Lagrangian smoothing shape functions are developed for the direct displacement smoothing formulation. Subsequently, the discrete equation of motion is consistently derived using the introduced Lagrangian smoothing shape functions. The implementation of the proposed formulation in the large deformation regime is described in detail with the constitutive equations for concrete. The physics-based constitutive models for concrete and steel are briefly explained so that the materials are modeled physically. High strain rate responses induced by impulsive and impact loads for concrete and steel structures are presented to illustrate the applications of the proposed Lagrangian direct displacement smoothing meshfree particle formulation.

The remainder of this paper is organized as follows. In section 2, the constitutive equations for steel and concrete are presented. Section 3 describes the Lagrangian displacement smoothing meshfree particle formulations. The discretized equation of motion and its implementation with concrete formulations are described in Section 4. Numerical applications of the proposed formulations are shown in Section 5. Finally, conclusions are drawn in Section 6.

2. Material constitutive modeling

There are two types of inelastic materials used in this study, namely, steel and concrete. Their behaviors are depicted by the von-Mises plasticity model and the K&C concrete (KCC) model [56,57], respectively. The basics of these two models are briefly described in this section.

2.1. von-Mises plasticity model for steel

The multi-linear von Mises plasticity model as shown in Fig. 1 is used in modeling steel behaviors in this work. The yield function for this model is expressed as:

$$\mathcal{F}(\boldsymbol{\sigma},\bar{\varepsilon}^p)=\sqrt{3J_2}-\boldsymbol{\sigma}_y(\bar{\varepsilon}^p) \tag{1}$$

$$\boldsymbol{s}=\mathrm{dev}(\boldsymbol{\sigma}),\quad J_2=\mathrm{tr}(\boldsymbol{s}:\boldsymbol{s})/2,\quad J_3=\det(\boldsymbol{s}) \tag{2}$$

where $\boldsymbol{\sigma}$ is the Cauchy stress tensor and $\boldsymbol{s}$ is its deviatoric part, $\mathrm{dev}(\bullet)$, $\mathrm{tr}(\bullet)$ and $\det(\bullet)$ are the deviatoric, trace and determinant operators. σ_y is the yield stress, $\bar{\varepsilon}^p$ is the accumulated measure of plastic deformation defined as:

$$\bar{\varepsilon}^p=\int_0^t\sqrt{\frac{2}{3}\dot{\varepsilon}^p:\dot{\varepsilon}^p}\,dt \tag{3}$$

in which t denotes time, $\dot{\varepsilon}^p$ is the plastic part of the rate of deformation tensor.

As shown Fig. 1, the yield strength $\sigma_y(\bar{\varepsilon}^p)$ of the material in the nth segment is determined by:

$$\sigma_y^n(\bar{\varepsilon}^p)=\sigma_y^{n-1}(\bar{\varepsilon}_{n-1}^p)+E_T^n\cdot(\bar{\varepsilon}^p-\bar{\varepsilon}_{n-1}^p)\quad \bar{\varepsilon}_{n-1}^p\le\bar{\varepsilon}^p\le\bar{\varepsilon}_n^p \tag{4}$$

where $\sigma_y^{n-1}(\bar{\varepsilon}_{n-1}^p)$ is the yield strength of the $(n-1)$th segment with $\sigma_y^0(\bar{\varepsilon}_0^p)$ being the initial yield strength, and E_T^n is the hardening parameter, typically, it's the tangent of each segment as described in Fig. 1.

2.2. Concrete model

2.2.1. Yield function

In the KCC model [56,57], the following three invariant yield function $\mathcal{F}(\boldsymbol{\sigma},\lambda)$ is used to depict the failure behavior of concrete:

$$\mathcal{F}(\boldsymbol{\sigma},\lambda)=\sqrt{3J_2}-\mathcal{R}(p,J_3,\lambda)\le 0 \tag{5}$$

where p is the pressure (compression in positive) calculated by the equation of state (EOS), λ is a damage variable. $\mathcal{R}(p,J_3,\lambda)$ is the failure envelope:

$$\mathcal{R}(p,J_3,\lambda)=\begin{cases} r_f\chi(J_3)\{\eta(\lambda)[\hat{\sigma}_m(p)-\hat{\sigma}_y(p)]+\hat{\sigma}_y(p)\} & \lambda\le\lambda_m \\ r_f\chi(J_3)\{\eta(\lambda)[\hat{\sigma}_m(p)-\hat{\sigma}_r(p)]+\hat{\sigma}_r(p)\} & \lambda\ge\lambda_m \end{cases} \tag{6}$$

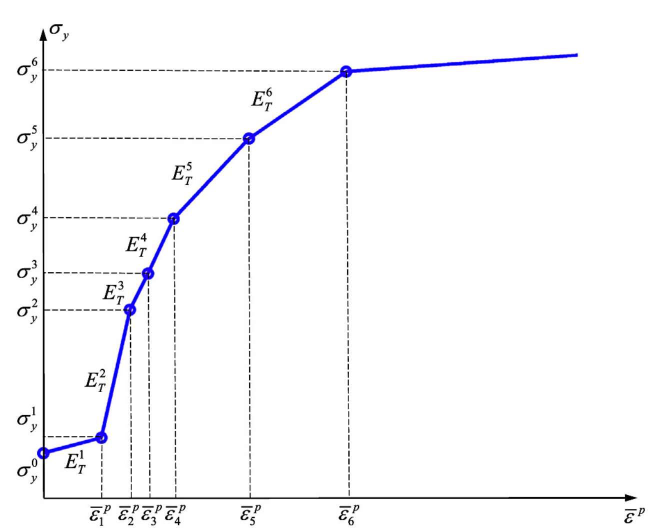

Fig. 1. Schematic illustration of multi-linear von Mises plasticity model for steel.