The Immersed Smoothed Particle Galerkin Method in LS-DYNA® for Material Failure Analysis of Fiber-Reinforced Solid Structures

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Abstract

This paper presents a novel immersed meshfree approach [1-3] for modeling and failure analysis of fiber-reinforced composite solids. The fiber and solid parts are discretized by finite element truss/beam and solid element formulations respectively and independently. This modeling process does not require a conforming mesh. In other words, the fiber elements, e.g. truss or beam elements, are embedded into FEM mesh for immerse computation. The Smoothed Particle Galerkin (SPG) method [4] is employed for the immerse computation. Both fiber inclusion and base material are allowed to fail correspondingly in the nonlinear analysis. Since the base material is modeled by SPG method, a bond-based failure criterion is utilized to model the failure in base material. In contrast, the failure in trust/beam element is modelled by finite element erosion.

Several numerical benchmark tests are conducted and presented. Both non-failure and failure analyses are considered to study the convergence and mesh sensitivity using the proposed method. The results are compared to the existing approaches based on finite element method. The numerical results suggest that the immersed SPG method can effectively model the fiber-reinforced solid in large material deformation and failure analysis.

Introduction

The fiber-reinforced materials have been widely applied to major industrial fields in recent years. In the automotive industry, the use of Carbon fiber-reinforced plastics (CFRP), for example, is expected to increase rapidly in the next two decades to help meet the regulation target of reducing the CO2 emission per unit distance through the novel light-weight design [5]. In order to model the composite structures, the conventional finite element analysis (FEM) requires a matching (conforming) mesh so that the kinematic constraints between fibers and base materials can be imposed through sharing nodes of conforming mesh. However, generating matching meshes suitable for FEM is difficult and time-consuming in most of industrial applications where the geometries are usually irregular and complex. Therefore from users' point of view, it is advantageous to use non-conforming discretization at the interfaces of fibers and base materials.

Number of numerical methods have been developed to couple mismatching meshes across the interfaces. The interface constraints can be either explicitly imposed by introducing Lagrange multiplier or penalizing the jump conditions, or implicitly satisfied by modifying and enriching the conventional approximation space through partition of unity method (PUM) or immerse finite element methods. However, there are limitations and computational complexity for these methods to be effectively applied to three-dimensional analysis in real industrial applications, especially when dealing with large deformation and material failure.

The smoothed particle Galerkin (SPG) method [4, 6] was recently developed for modeling large deformation and material failure in ductile and semi-brittle materials. SPG is a purely particle method which relies on discrete nodes to construct approximation and spatial domain integration. A special smoothing scheme in displacement field is introduced to stabilize the numerical solution. For large material deformation in explicit analysis, SPG is able to minimize tensile instability and maintain the time step size by combining the smoothing scheme with kernel update, which helps to improve the overall computational performance. SPG uses a phenomenological bond based failure mechanism to fail and separate material, and the failure criterion can be easily defined in phenomenological material constitutive laws. The SPG formulation has been uniquely implemented into LS-DYNA. To impose coupling between FEM beam elements of fiber material and SPG solid through non-conforming discretization, the FEM nodes of beam elements are immersed into SPG discretization through immerse meshfree method [1-3], which is equivalent to add extra nodes in SPG discretization and make them the sharing nodes with beam elements. It is very straightforward to involve these immersed nodes in constructing displacement approximation and performing domain integration since SPG is truly particle based meshfree method. This paper presents the current implementation of immersed SPG method in LS-DYNA and demonstrates its capability in modeling large deformation and material failure for fiber-reinforced solids.

LS-DYNA Keywords of Immersed Smoothed Particle Galerkin (SPG)

SPG is currently implemented for 3D solid explicit analysis with element formation ELFORM=47 in the keyword *SECTION_SOLID_SPG. The SPG nodes are automatically generated from the nodes of the users' input FEM solid elements (4/6/8-noded solid element), which makes it very convenient for users to switch to SPG formulation using the same FEM model and couple SPG with FEM parts through either sharing nodes or existing contact algorithms. The following is a snapshot of *SECTION_SOLID_SPG cards 2 and 3:

Card 2	**DX**	**DY**	**DZ**	ISPLINE	**KERNEL**	LSCALE	SMSTE	SUKTIME
Default	1.5	1.5	1.5	0	0	0	15	0
Card 3	**IDAM**	**FS**	STRETCH	ITB				
Default	0	0.0	1.2	1				

(1) Nodal support size: DX, DY, DZ
Like many other meshless method, the approximation function in SPG is constructed based on discrete nodes, which, by default, are from FEM model. The support size of a given node is determined by the size of surrounding element edges with the scaling parameters DX, DY and DZ. For non-uniform mesh, the absolute nodal support sizes vary across the computational domain due to the variation of element size. The recommended range of scaling parameters in SPG is 1.4~1.8, and the default value, 1.5, is good for most of applications.

(2) Kernel types: KERNEL
SPG currently has three different kernels: KERNEL=0 updated Lagrangian (UL) kernel, KERNEL=1 Eulerian (E) kernel, and KERNEL=2 pseudo-Lagrangian (PL) kernel. The UL-kernel is suitable for tension dominant problems. The E-kernel can be widely used in the application involving large and extreme deformation and material failure where the material response is more global, while the PL-kernel works for the cases where material deformation and failure is more local. The typical applications of E-kernel include jointing (riveting, drilling, etc.), metal shearing and cutting. PL-kernel can be applied in machining (metal grinding, etc.) and high-velocity impact problems.

(3) Bond-based material failure model: IDAM & FS
IDAM=1 defined bond-based failure model, where the average effective plastic strain (EPS) of paired nodes in support zone is examined and compared to the user input value FS. It is known that using the conventional element erosion to fail material often leads to underestimate of reaction forces and nonphysical failure pattern.

The SPG bond failure mechanism preserves the mass and momentum, which provides the potential to predict more accurate force and more physical failure modes.

To immerse the FEM beam elements into SPG solid, the keyword *CONSTRAINED_IMMERSED_IN_SPG is developed to define the coupling between slave beam parts and master SPG part as follows

Card 1	**SPGPID**	**IPID1**	**IPID2**	**IPID3**	**IPID4**	**IPID5**	**IPID6**	**IPID7**
Default	0	0	0	0	0	0	0	0

Each keyword card supports up to seven slave beam parts (IPID1-IPID7) to be immersed into master SPG part (SPGPID). For each immersed node from beam parts, the support size is automatically calculated by averaging the support size of neighboring SPG nodes. Since the immersed nodes are shared by beams and solid, their total mass consists of the mass from beams and that from solid. The immersed nodal solid mass is calculated by redistributing the mass locally among the neighboring SPG nodes. The schematic plot of immerse coupling is shown in Fig. 1.

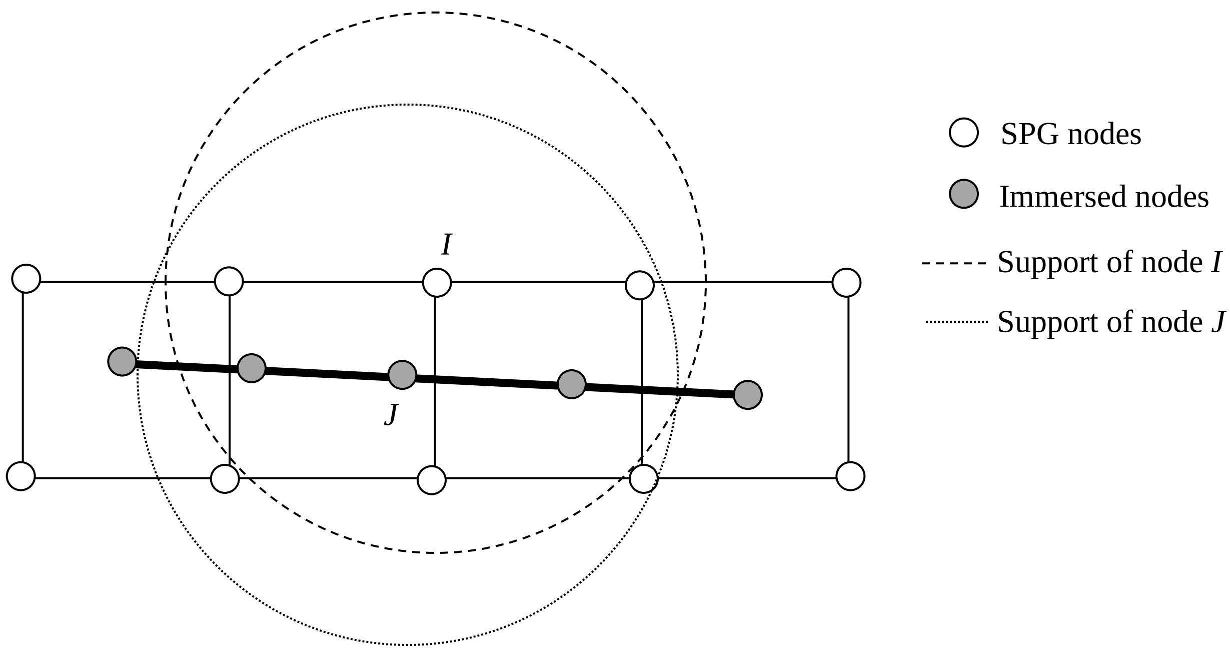

Figure 1. Schematic plot of immerse coupling between FEM beam and SPG solid.

Numerical Examples

Three point bending with fiber-reinforced plastic plate is considered as shown in Fig 2. The dimension of plate is $84 \times 12 \times 2$ modeled by solid (FEM ELFORM= 2, SPG ELFORM= 47). There are 12×2 long fibers with length 83 modeled by FEM beam (ELFORM= 1). The impactor and support are modeled by rigid shell elements, and the impactor has prescribed z-velocity as shown in Fig 2. In order to compared with FEM solid formulation and perform convergence study, the plate is discretized by two sets of uniform 8-noded solid elements with mesh size 0.5 and 0.25, respectively. The beam elements have the same uniform mesh size. In this case, the beam nodes are shared with solid mesh. The non-forming mesh between beams and solid is also created by shifting the solid mesh in x direction so that there is no sharing node. In this case, only immersed SPG method is used to perform the analysis. Both fiber and solid are using the same material type *MAT_PLASTIC_KINEMATIC: Young's modulus $E_{fiber} = 2380.0$, $E_{solid} = 300.0$; Yielding stress $\sigma_{y_{fiber}} = 4.0$, $\sigma_{y_{solid}} = 0.4$; Tangent modulus $E_{t_{fiber}} = 4.0$, $E_{t_{solid}} = 0.4$; Effective plastic strain for eroding elements $FS_{fiber} = 0.1$, $FS_{solid} = 0.2$. Note that the bond based failure model (IDAM= 1) is used in SPG formulation so that, when using SPG ELFORM=47 for the solid part, the "FS" in material card should be 0.0 and the "FS" in the card 3 of *SECTION_SOLID_SPG is set as 0.2.

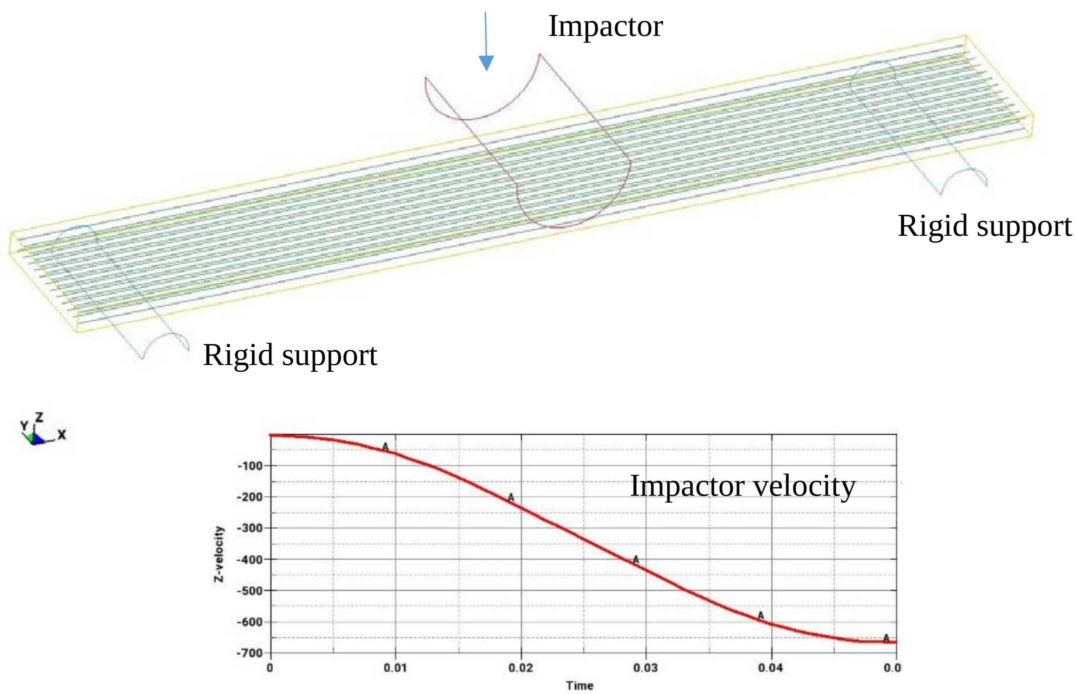

Figure 2. Three point bending with fiber-reinforced plastic plate.

Fig.3 shows the effective plastic strain contour and deformation profiles obtained by FEM with conforming mesh. A large number of solid elements are eroded when EPS reaches 0.2, which leads to loss of mass and momentum conservation and part of contact surface between the plate and the impactor. Meanwhile, some beam elements lose the coupling with solid elements due to erosion and directly contacting with impactor, which leads to severe local deformation.

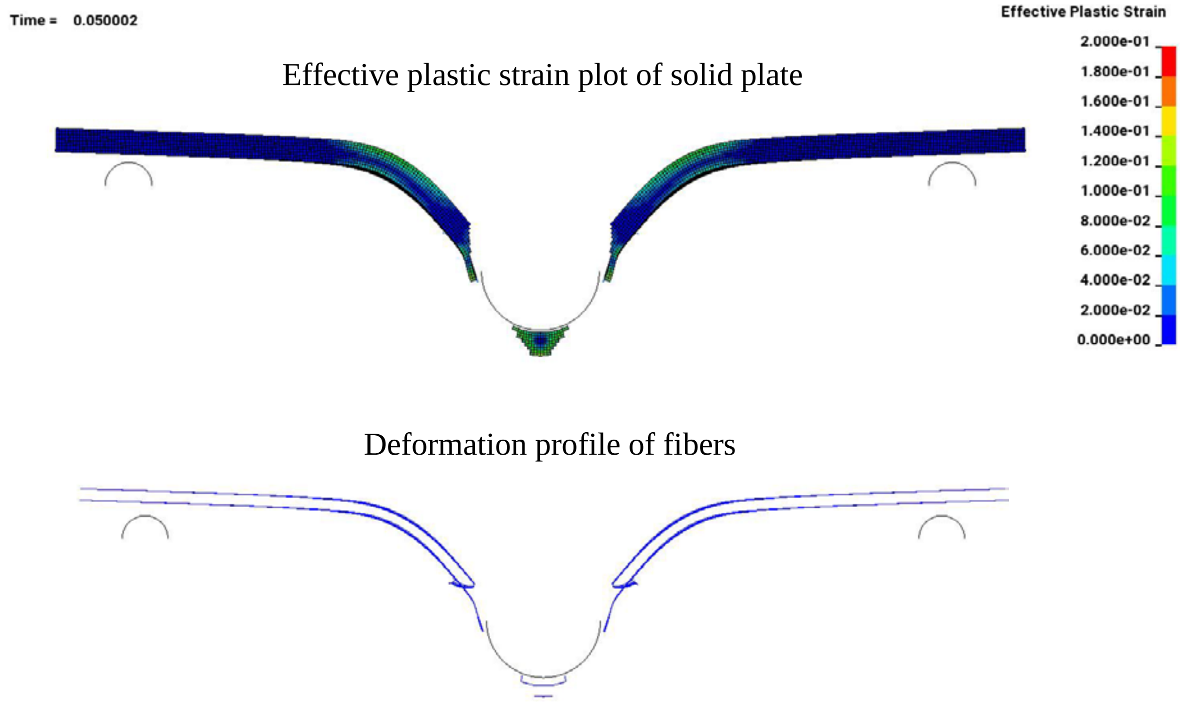

Figure 3. FEM (conforming mesh) results.

Fig.4 shows the results obtained by SPG with conforming mesh. Since the material failure is modeled by breaking individual bonds between pairs of SPG nodes, there is not loss of mass and momentum conservation. The coupling between beams and SPG solid are preserved throughout the analysis, which gives better results in terms of deformation profile and failure pattern of beam elements.

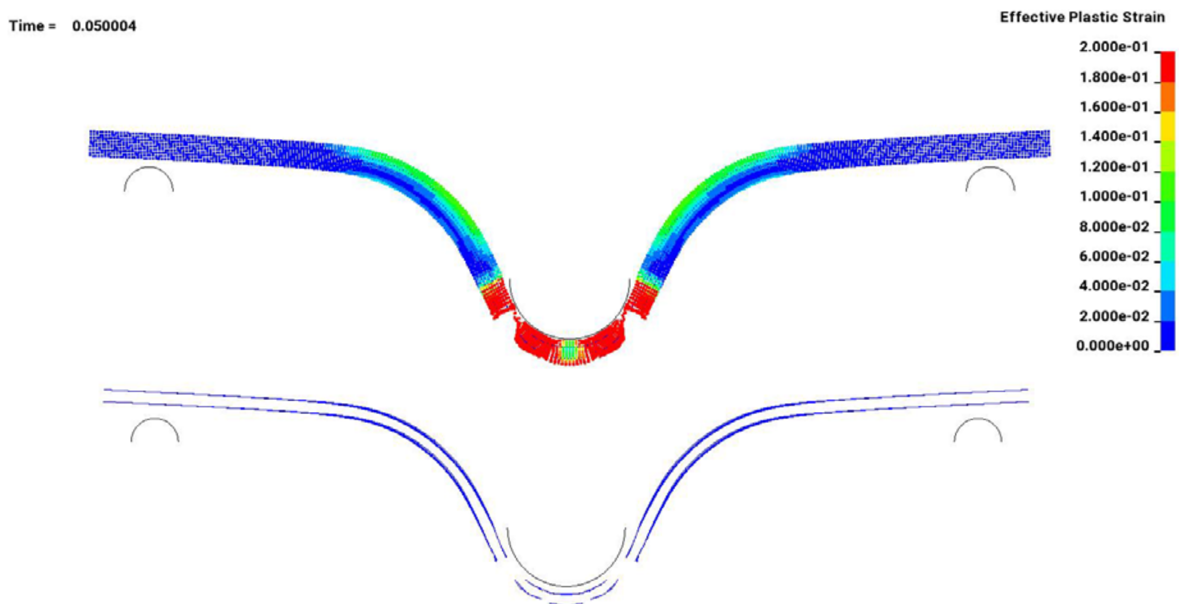

Figure 4. SPG (conforming mesh) results.

Fig.5 shows the results obtained by SPG with non-conforming mesh, which is very similar to that of SPG with conforming mesh. The slightly un-symmetry in results is due to non-uniform discretization of beam and solid.

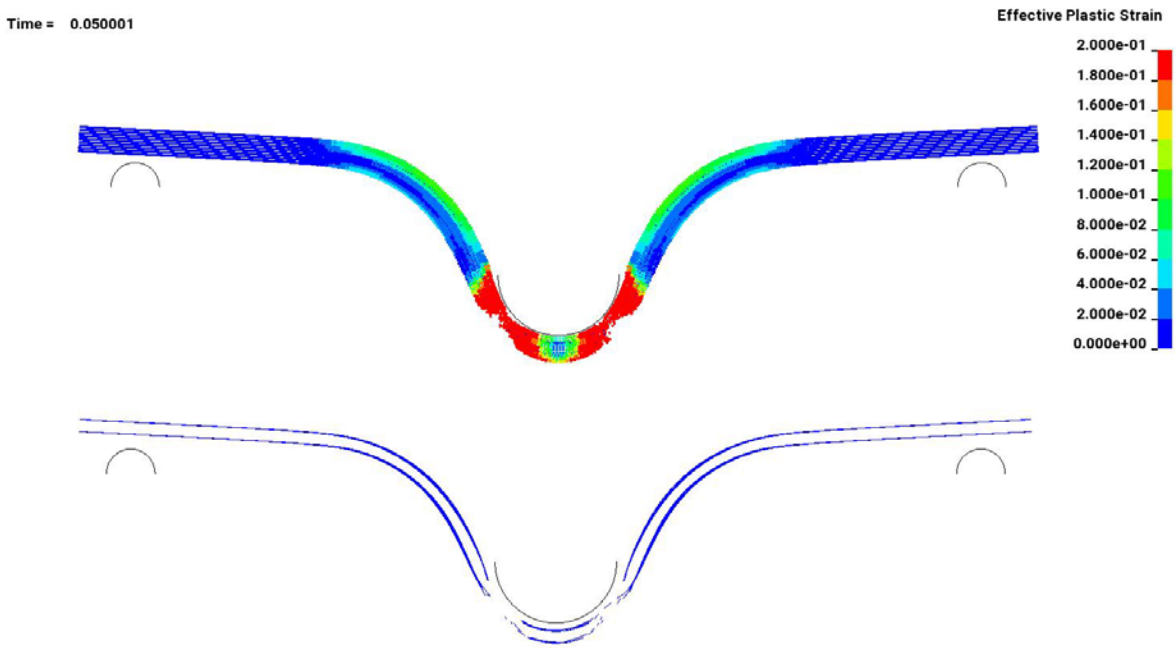

Figure 5. SPG (non-conforming mesh) results.

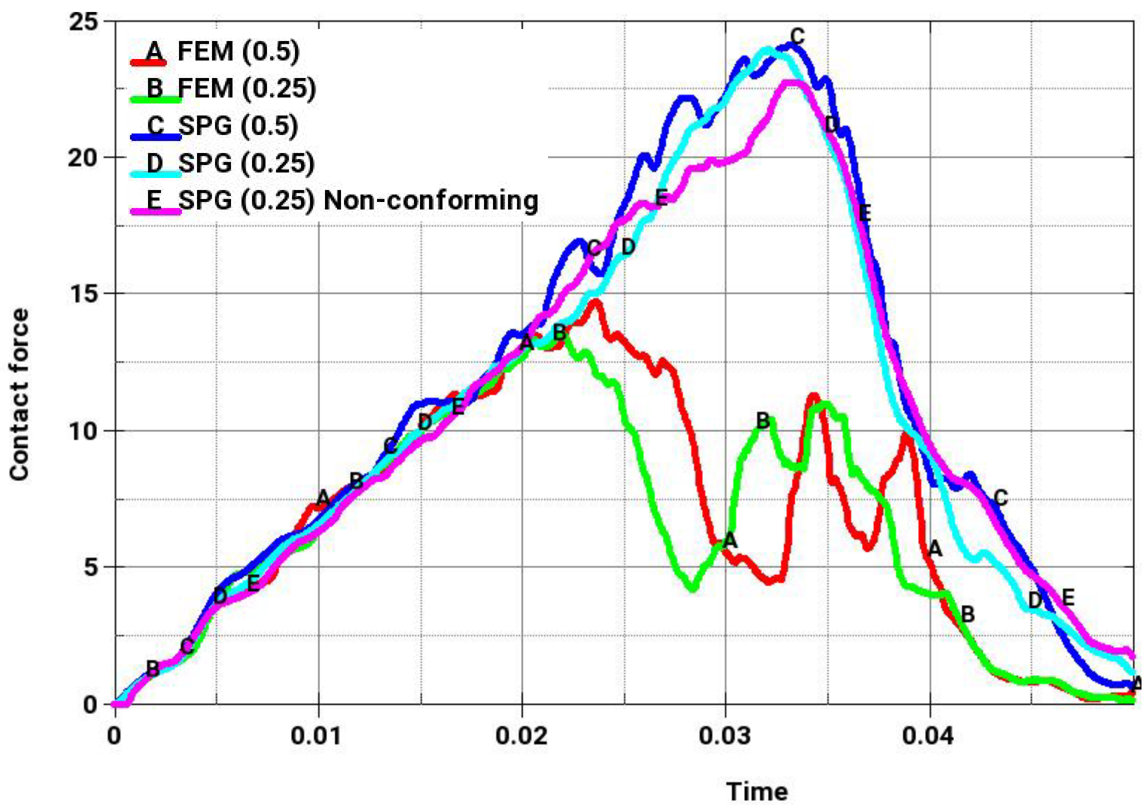

Figure 6. Convergence study on contact force.

Fig.6 shows the convergence study on contact resultant force. The FEM results fail to capture the peak force, and the undesired force response results from the direct contact between fibers and impactor after element erosion. The contact force obtained by FEM is not well converged from mesh size $h = 0.5$ to h= 0.25. SPG results are pretty consistent when using different mesh size and non-conforming mesh.

Conclusion

This paper presents the immersed smoothed particle Galerkin method for large deformation and material failure analysis in fiber-reinforced solid. The SPG with bon-based failure model conserve mass and momentum during material failure, which leads to stable and convergent results with minimized sensitivity to the discretization. Immersed SPG is implemented to impose the kinematic constraints between FEM beams and SPG solid for non-conforming mesh, which provides users a cost-effective tool to model fiber-reinforced material. The numerical demonstration shows a promising result obtained by immersed SPG compared to the conventional FEM with element erosion.

References

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