A Meso-Macro Scale Method for Jointed Structures and Their Failure Analysis

Wei Hu, CT Wu, Xiaofei Pan, Youcai Wu
Livermore Software Technology, LLC, Livermore, USA

Abstract

As automotive industry moves rapidly towards electrified and digitalized world, the use of lightweight materials and new joining technologies becomes crucial to counteract the weight of electronic and autonomous equipment for energy efficiency as well as to maintain safety and performance. Numerical modeling the joined structures including their failure behavior has been a big challenge in the modern lightweight vehicle safety design.

In this study, a two-scale method developed in LS-DYNA® is introduced for modeling jointed structures and their connection failure. In the meso-scale, a new particle stabilization method via a velocity smoothing algorithm is developed for simulating the large deformation and material failure of joint models. The meso-scale joint model characterizing the baseline of joint structure is bridging with macro-scale shell structures using an immerse approach. As a result, a topological coupling between solid and shell formulations is achieved without the need of matching discretization. This two-scale method facilitates the modeling of most connection failures in different joint models and minimizes human interactions with software. A crushing tube example is utilized to demonstrate the effectiveness and applicability of the present method in modeling the joined structures and failure behavior for the modern lightweight vehicle safety design.

Keywords: Particle method; Multi-scale; Joint failure; Immersed

1. Introduction

Over the past decades, computer modeling has been shown to speed up the car design process by simulating experiments. Nowadays, extensive crashworthiness simulation using LS-DYNA has become a routine during the vehicle's virtual development process before the body-in-white structure is ready for production. While thousands of fasteners and joints are used to connect the components, those joints are often considered the weakest points as regards to structural strength. When connection failure occurs, the load is shifted from one part to another depending on the types of joints, materials and geometries, which may result in very different deformation results affecting the passenger safety during the vehicle crash. Therefore, simulating various connecting failure especially in lightweight vehicles is an urgent subject [1,2,4,5] for automotive industry.

Modeling the connection failure in the car structure is a two-scale problem. Most notably, this two-scale system should be described by a concurrent meso-macro scale model. Figure 1 provides a comprehensive view of Process-Structure-Property-Assembly-Performance loop in the multi-physics and multi-scale vehicle manufacturing and safety simulation in which a two-scale technique for modelling the jointed structures and their failure behavior will be introduced in this study.

The objective of this study is to present a two-scale computational method that addresses the critical need in higher-level modeling of different joints and their connection failure behavior for the crash analysis of lightweight vehicles. In the meso-scale, a Lagrangian particle method is employed to simulate the interfacial and pullout ruptures in the 3D continuum joint model. This meso-scale joint model is embedded concurrently into the macro-scale shell structures using a type of kinematical coupling schemes based on the particle immersion technique [6,7] to achieve the coupling effect, thus bypassing the numerical limitations in the tie-contact approach. The remainder of the paper is organized as follows: In Section 2, the Momentum-consistent

Smoothed Particle Galerkin method [3,10] for simulating the large deformation and material failure in meso-scale joint models is briefly reviewed. Section 3 describes the framework for the two-scale problem using the immerse technique. The implementation procedures are provided in the same section. Numerical examples are given in Section 4, and conclusions are made in Section 5.

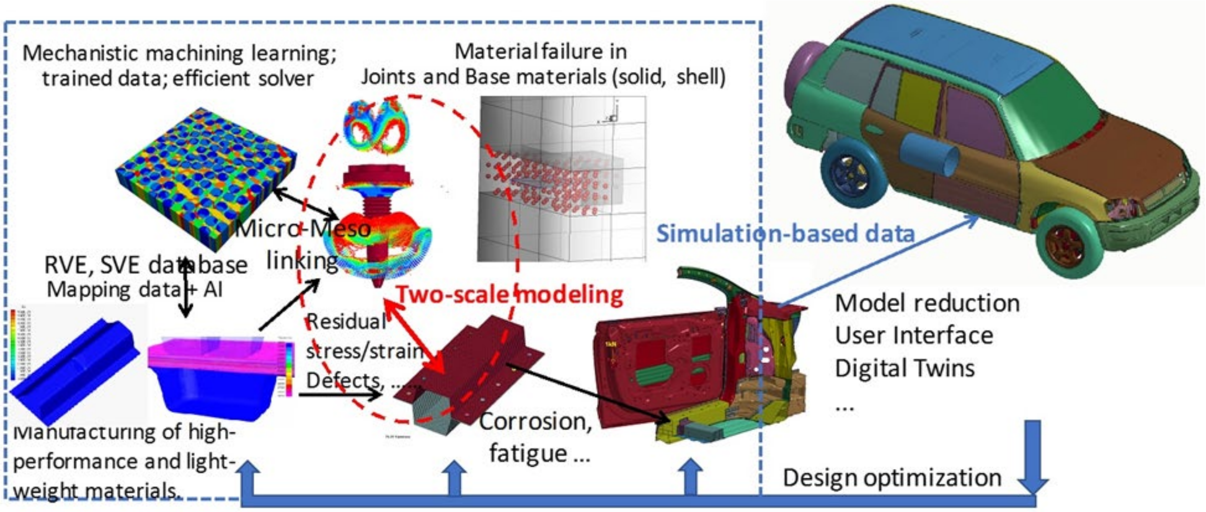


Figure 1. A comprehensive view of Process-Structure-Property-Assembly-Performance loop in the multi-physics and multi-scale vehicle manufacturing and safety simulation

2. MC-SPG method for material failure analysis in meso-scale

The Smoothed Particle Galerkin (SPG) method [8,9] is one of the stabilized Lagrangian particle methods introduced to simulate the extensive plastic deformation and ductile failure for metal fabrication applications [9]. A new version of SPG formulation was recently developed [3] to improve the computational efficiency. Since this new SPG formulation is consistently fulfilling the conservation of linear and angular momentum, it was called the Momentum-Consistent Smoothed Particle Galerkin (MC-SPG) method [10]. In what follows, the MC-SPG method is used to simulate the pullout rupture of meso-scale joint model in the connection failure analysis.

MC-SPG has been implemented into 3D solid element formulation 47 in the keyword *SECTION_SOLID_SPG for the explicit dynamic analysis. FEM solid element model can be directly used as input model of LS-DYNA and the MC-SPG particles are automatically generated from the FEM nodes. The input deck format of *SECTION_SOLID_SPG for card 2 and card 3 is described as follows:

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	1.2	1				

The flag ITB=3 enables the new MC-SPG. For the large material deformation analysis, the updated Lagrangian kernel by setting KERNEL=0 is recommended, where the kernel is anisotropic and updated constantly over a period of time. The shape domain of this anisotropic kernel, defined for particle neighbor-search, deforms and rotates according to the Lagrangian motion between each two adaptive Lagrangian kernel steps [7]. Using the adaptive anisotropic Lagrangian kernel, the deformation gradient differentiates the incremental form from the total form in numeric. Our numerical experiences suggest that the update procedure combining the incremental form of deformation gradient and adaptive anisotropic Lagrangian kernel is very suitable for the large deformation analysis of metal plasticity problems [7,9].

The bond-based failure algorithm by setting IDAM=1 is employed to simulate the ductile failure in joints. In engineering practice, a failure criterion of FS measured by the effective plastic strain is often considered. Since the bond is a representation of a connection between two particles, two neighboring particles can simply be regarded as disconnected during the neighbor searching when their averaged effective plastic strain reaches a respective critical value defined by FS. Additionally, we recommend setting the stretch ratio criterion STRETCH to be greater than 1.0 so that the bond failure does not occur under compression. This implication is valid for most joint failure process. It is important to note that the effective plastic strain at each particle increases monotonically during the course of deformation. Because of that, the kinematic disconnection in a particle pair is a permanent and irreversible process. This is a substantial characteristic for the bond-based failure mechanism in metal failure analyses since the non-physical material self-healing issues resulting from generic neighbor searching algorithm can be completely exempted from the material failure simulation. This simplicity and unique computational properties of bond-based failure algorithm make SPG method an attractive numerical tool in ductile metal failure analysis.

3. Concurrent two-scale problem

Under the framework of variational formulation, the meso-scale joint model using SPG method can be easily embedded into LS-DYNA to perform large scale structural analysis with connection failure.

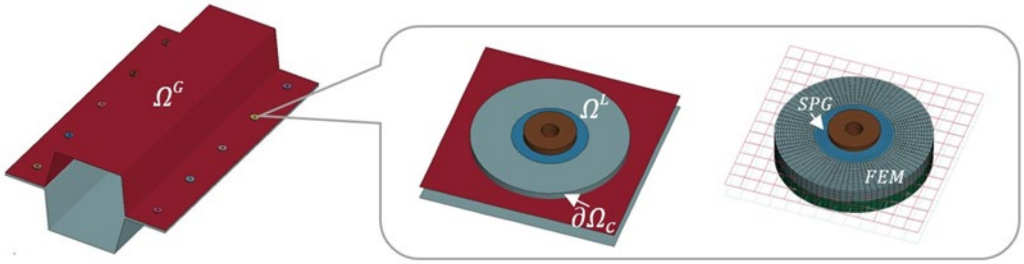


Figure 2. Two-scale models of joints (bolts) in large scale structure

In a typical two-scale modeling as shown in Fig. 2, the macro-scale structure Ω^G usually consists of shell elements, and the meso-scale joint Ω^L is modeled by solid elements with much smaller mesh size. To accelerate the meso-scale computation, SPG is only applied to the area involving large deformation and material failure as shown in Fig. 2. Although there are thousands of joints in a car model, they are often standardized as a few different types, e.g. spot weld and rivet etc., with geometry and material parameters. Therefore, the preprocessing of meso-scale model can be much simplified: users only need to define a set of positions along with joint types and parameters, and the meso-scale models are automatically generated and positioned from the existing library of joint models.

The two-scale models are exchanging information at the non-conforming coupling interface $\partial\Omega_c$ shown in Fig. 2, where the meso-scale model has the kinematic constraints from the macro-scale model using immerse method and returns the constraint forces as response to the macro scale. As the results, the meso-scale solid joint deforms and fails driven by the macro-scale through the coupling interface and provides the jointing force to constrain the macro structure. When one meso-scale joint completely fails, it will be removed from the computation and provide no more constraint at the joint position in the macro structure. Note that the material failure is simulated only in the refined meso scale solid, which is not able to be captured by the macro scale shell with coarse mesh. Figure 3 shows how the meso scale model is immersed into the macro scale, and the immersed nodes at the coupling interface $\partial\Omega_c$ are following the deformation of the macro-scale shell in both translational and rotational DOFs.

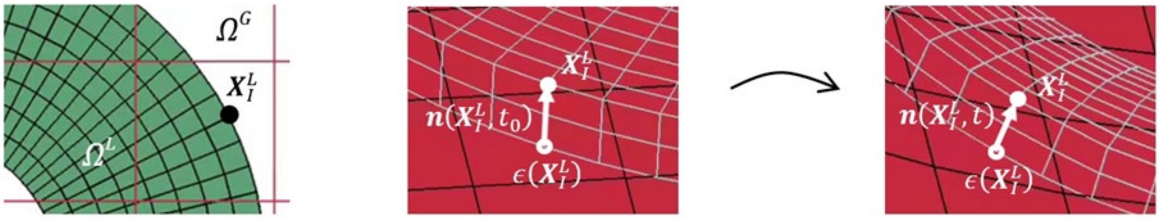


Figure 3. The non-conforming coupling interface between shell (macro-scale) and solid (meso-scale)

Modeling joints in the meso scale requires a refined discretization of solid and consequently smaller time step size ($\Delta t^G \gg \Delta t^L$) in explicit dynamic computation. Instead of imposing the same small time step size on the whole two-scale model, we designed a co-simulation framework that the macro and meso models are computed independently using the sub-cycling technique. The co-simulation is performed using master/slave setup, where the collective communication between master (macro) and slave (meso) jobs is carried out at synchronization points currently through MPI. An adaptor API is called by two scale jobs to exchange data and synchronize the time integration so that the main structure of existing finite element code needs no change to be adopted in both jobs. Figure 4 shows the proposed co-simulation flowchart using central difference time integration scheme.

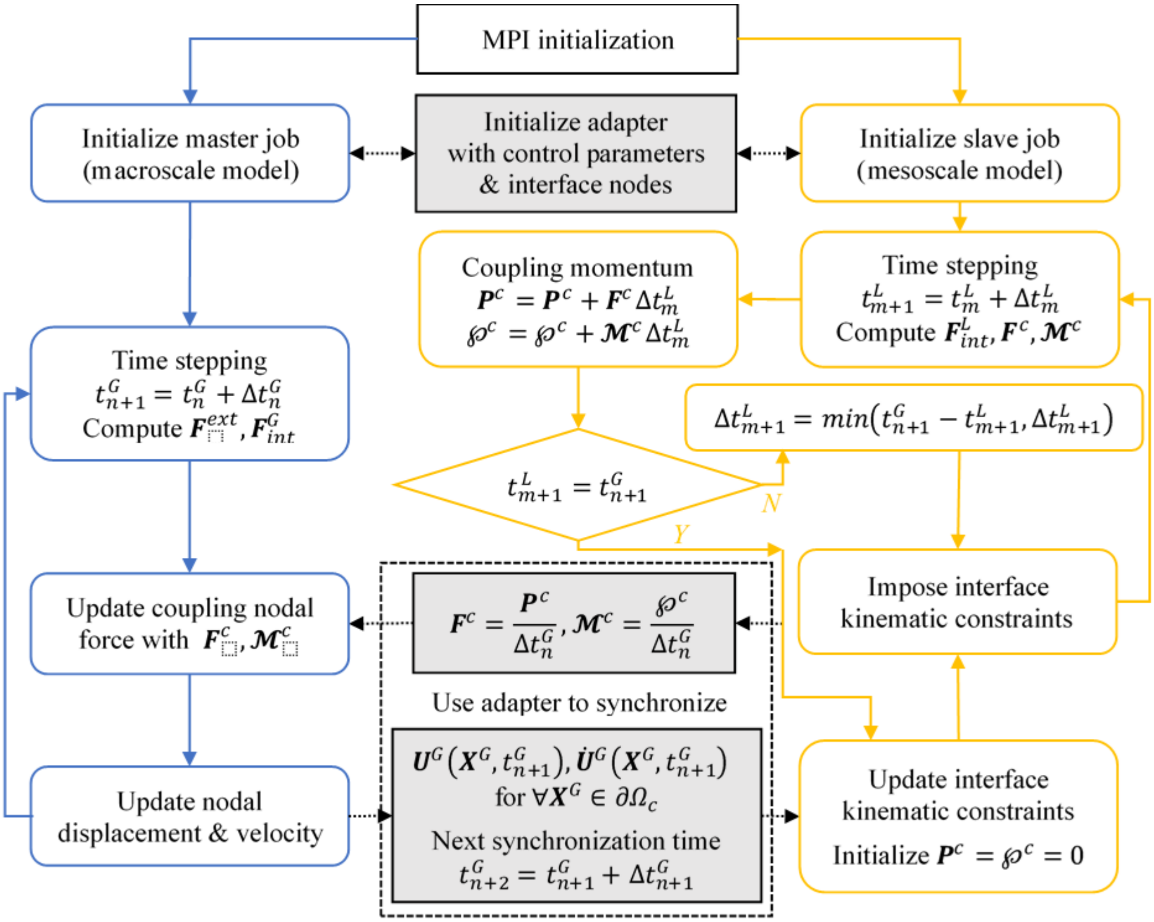


Figure 4. The co-simulation flowchart

4. Numerical examples

4.1 Simple tension problem

Consider a tension test on a coupon using both single-scale solid and two-scale shell/solid models as shown in Fig 5. The dimension is $24 \times 8 \times 4mm\ (L \times W \times H)$. The material density is $7.85 \times 10^{-3} g/mm^3$, the Young's modulus is $210GPa$ with the yield stress $1GPa$ and the kinematic hardening $E_t = 1GPa$. The constant velocity $20mm/s$ is applied on both ends. SPG with bond breakage $\bar{\varepsilon}^P_{crit} = 0.5$ is used in the center portion of solid models to better simulate material large deformation and separation. The time step size of the single-scale solid model and macro-scale shell model is $3.5 \times 10^{-5}s$ and that of the meso-scale model is $8.5 \times 10^{-6}s$. We expect to observe material necking due to plastic deformation in both width and thickness directions using solid formulation.

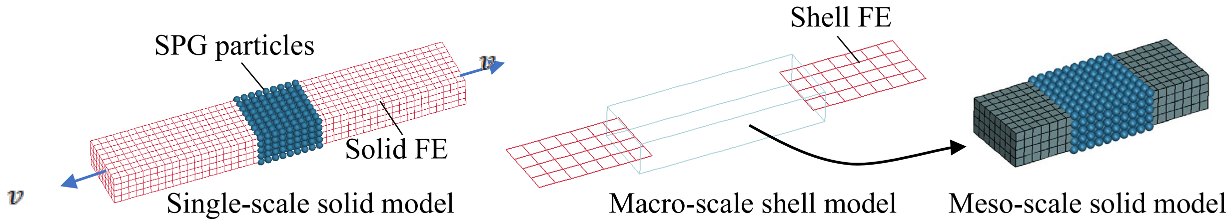


Figure 5. Simple tension test

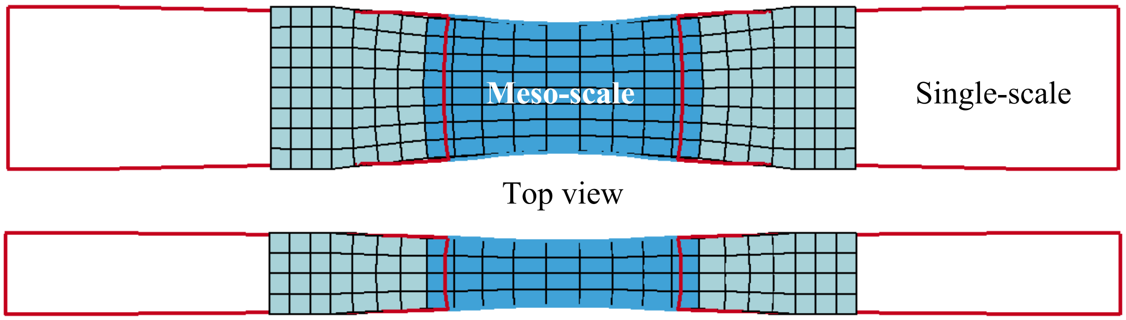


Figure 6. Deformation profile

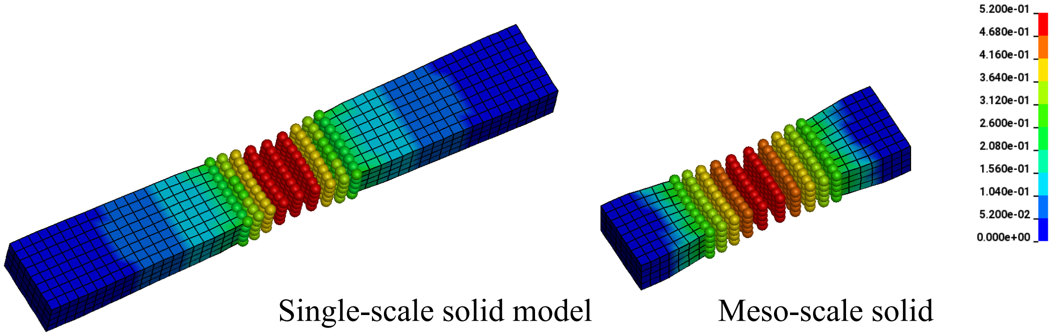


Figure 7. Effective plastic strain (EPS) contour

Figure 6 shows that the shape of necking obtained by the two-scale model matches the single-scale result very well. The overall distribution of effective plastic strain (EPS) is very similar between two models as shown in Fig. 7 although the meso-scale result is relatively more localized. The meso-scale resultant force curve in Fig. 8

agrees with the single-scale result during the loading process, where the minor oscillation comes from the macro-meso coupling.

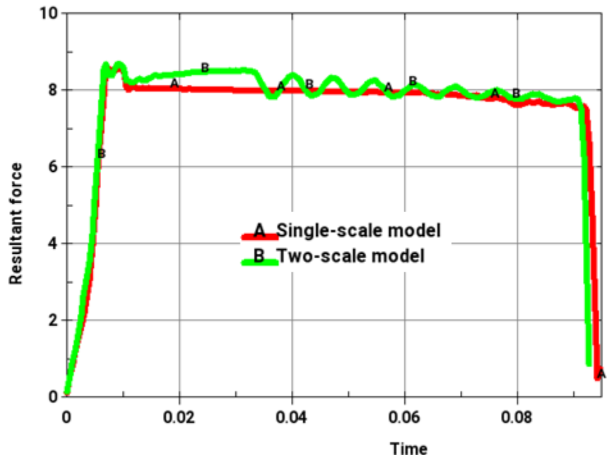


Figure 8. Resultant force curve

4.2 Single connection failure analysis

Consider a single joint (bolt) as shown in Fig. 9, where two shells with $1mm$ thickness are connected by a rigid bolt. The surrounding base material of the joint is modeled by solids in the meso scale, and SPG with bond breakage $\bar{\varepsilon}^P_{crit} = 0.1$ is used where the large material deformation and failure is expected to occur. The material density is $7.85 \times 10^{-3} g/mm^3$, the Young's modulus is $210GPa$ with the yield stress $0.2GPa$ and the kinematic hardening $E_t = 20GPa$. The constant velocity $10mm/s$ is applied on the edges as shown in Fig. 9. The time step size of the macro-scale shell model is $1.66 \times 10^{-4}s$ and that of the meso-scale model is around $2.0 \times 10^{-5}s$.

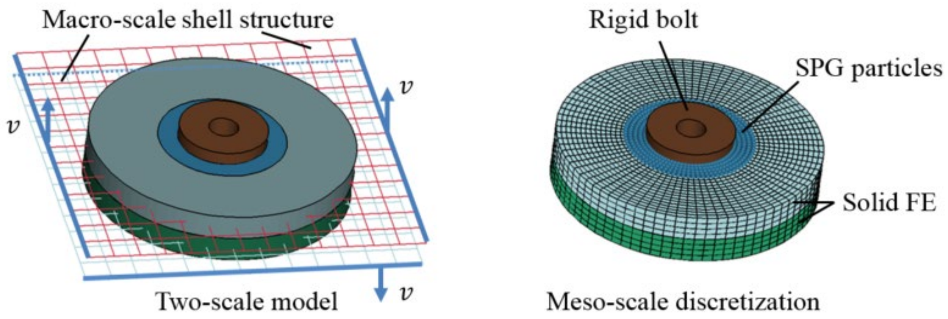


Figure 9. Single joint problem

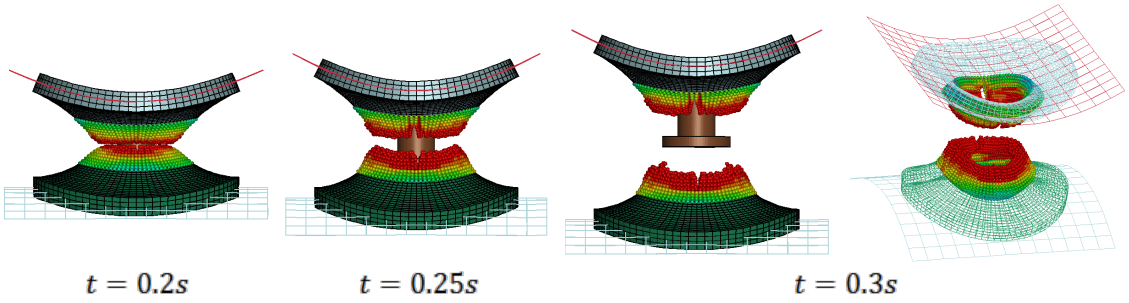
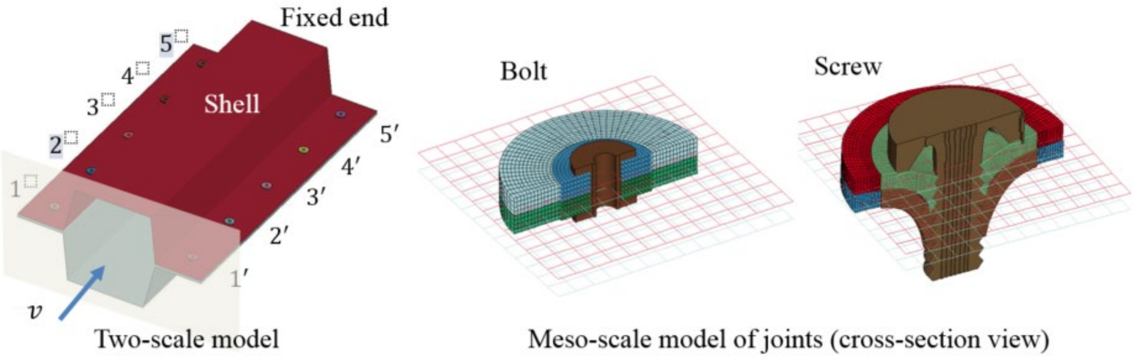


Figure 10. Progressive deformation profile and EPS contour (fringe level $0 \sim 0.4$)

The progressive plots in Fig. 10 show reasonable deformation in both macro and meso scales and the desirable material failure pattern captured by SPG in the meso scale. Note that the material failure can be simulated only in the meso-scale SPG solids not in the macro-scale shells. The matching of deformation profile at the coupling interface between the meso-scale solids and macro-scale shells in both translational and rotational degrees of freedom indicates that the through-thickness constraints are accurately imposed by the proposed two-scale coupling scheme.

4.3 Crush tube analysis

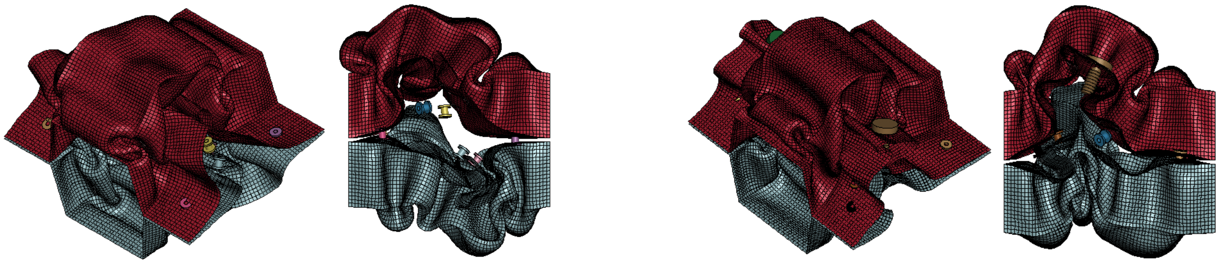
Consider a crush tube problem as shown in Fig. 11, where five pairs of joints fasten two layers of shell structure with $1mm$ thickness. The crush tube has one end fixed and the other subjected to a constant velocity $10mm/s$. Ten joints are rigid bolts in the design case I while two joints $3-3'$ are replaced by rigid screws in the case II. The modeling of meso scale joints including the material parameters are the same as the previous example in 4.2. The time step size of the macro-scale shell model varies in $(1.0{\sim}1.6)\times10^{-4}s$, and that of the meso-scale model falls into the range of $(1.3{\sim}3.2)\times10^{-5}s$ for the case I and $(1.1{\sim}1.7)\times10^{-5}s$ for the case II with smaller mesh size, where the variation of time step sizes is due to the mesh distortion of finite elements as the material deforms.



Two-scale model

Meso-scale model of joints (cross-section view)

Figure 11. Crush tube problem

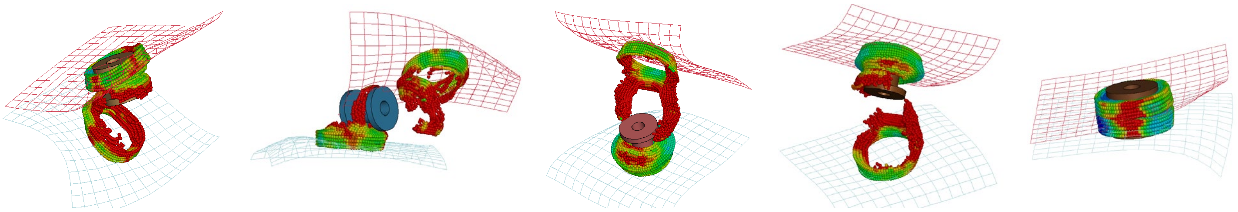


Case I

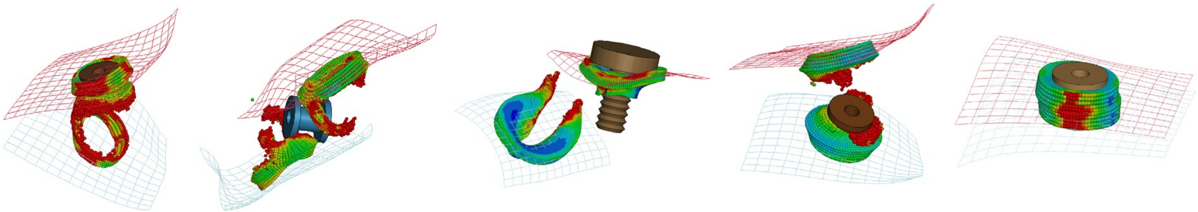
Case II

Figure 12. Final deformation profile of crush tube analyses (45° angle of view and side view)

Figure 12 shows the final deformation of the macro-scale shell structure for both cases, where the case II with stronger screw joints $3-3'$ has better energy-absorption shape. Note that the meso-scale solids including rigid bolts and screws can only interact with the macro-scale shells through the coupling interface, and there is no contact defined between the meso-scale solids and macro-scale shells. Figure 13 shows different failure pattern of joints $1{\sim}5$ for both cases, and the corresponding jointing force curves are plot in Fig. 14 where we can clearly see the highest peak force at the stronger screw joint 3 in the case II.



Case I



Case II

Figure 13. Connection failure with EPS contour (joint ID 1,2,3,4,5 from left to right)

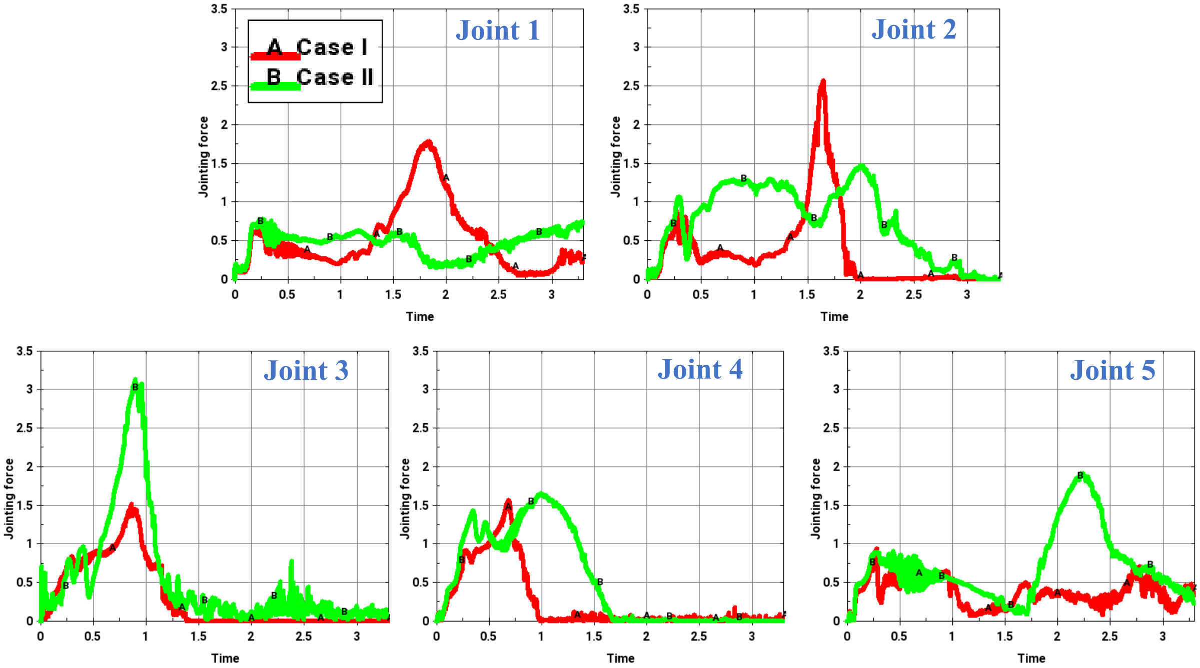


Figure 14. Jointing force curve

5. Conclusions

Today's vehicle engineers continue to search for ways to maximize performance and efficiency of new cars. One approach that has gained huge momentum in automotive industry is the light-weighting through advanced material design and fabrication. The integration of stronger, thinner, lighter and mixed materials in new cars has led to significant weight reductions as well as the new jointing technology. On the other hand, inappropriate joining method and unexpected joint failure detected in later stage of new car development cycle, have frequently resulted in design compromises that can adversely affect weight savings available by using advanced materials. Consequently, further light-weighting opportunities from optimized use of new materials will not be possible without improved joint modeling techniques for the crashworthiness analysis.

Modeling various joints and their failure in a full car finite element model using the tie-contact approach is very time consuming, expansive and error prone. From a vehicle engineer's viewpoint, it is always advantageous to adopt an effective computational model for the simulation of connection failure in crashworthiness analysis. In this study, we have introduced a concurrent two-scale method that is suitable for modeling various joint types and their failure analyses in component design level. Unlike the tie-contact approach where only very few joint models such as spot weld can be idealized to model certain connection failure modes, the present two-scale approach captures meso-structure evolution which is applicable for modeling most connection failures modes in different joint models. Although we have focused on the pullout rupture in this study, the consideration of interfacial rupture in the simulation is not limited by the proposed method. The numerical results in this study suggest that the present method is able to produce the desired pullout rupture mode in the connection failure analysis. Using this two-scale approach, vehicle engineers will be able to set up joint models easily in the finite element car assembly process. This nice feature of present method can minimize human interactions with software and enable more parallel and collaborating engineering work. It is also beneficial to vehicle engineers in analyzing the joining effect of car crash model and to improve the structure integrity during the vehicle virtual development stage. To the authors' best knowledge, other existing technology has not been able to demonstrate similar capability in automotive crash analysis.

Although the present method is studied exemplary in the component design level, its extension to the full car crashworthiness analysis will not be technically difficult. It requires the establishment of a comprehensive database containing all necessary information for a variety of meso-scale joint models. It also requires the design of scripting functionalities in a dedicated graphical user interface for pre- and post-processing. Those developments will be discussed in the near future.

References

[1] A. Haufe, M. Feucht, F. Neukamm, The challenge to predict material failure in crashworthiness applications: Simulation of producibility to serviceability. In: Hiermaier S. (eds) Predictive Modeling of Dynamic Process, Springer, Boston, MA, 2009.

[2] P.R. Marur, S. Srinivas, A reduced-order finite element model for the simulation of automotive side structure crash response, Int. J. Crashworthiness 13 (2008) 211-218.

[3] X. Pan, C.T. Wu, W. Hu, Y. Wu, A momentum-consistent stabilization algorithm for Lagrangian particle methods in the thermo-mechanical friction drilling analysis, Comput. Mech. 64 (2019) 625-644.

[4] C.K. Park, C.D. Kan, W.T. Hollowell, Evaluation of crashworthiness of a carbon-fiber-reinforced polymer (CFRP) ladder frame in a body-on-frame vehicle, Int. J. Crashworthiness 19 (2014) 27-41.

[5] F. Seeger, M. Feucht, T.H. Frank, B. Keding, A. Haufe, An investigation on spot welding modeling for crash simulation with LS-DYNA, Proceedings of the 2005 LS-DYNA Forum, Bamberg, Germany, 2005.

[6] C.T. Wu, Y. Guo, E. Askari, Numerical modeling of composite solids using an immersed meshfree Galerkin method, Compos. Part B: Eng. 45 (2013) 1397-1413.

[7] C.T. Wu, D.D. Wang, Y. Guo, An immersed particle modeling technique for the three-dimensional large strain simulation of particulated-reinforced metal-matrix composites, Appl. Math. Model. 40 (2016), 2500-2513.

[8] C.T. Wu, Y. Wu, J.E. Crawford, J.M. Magallanes, Three-dimensional concrete impact and penetration simulations using the smoothed particle Galerkin method, Int. J. Impact Engrg. 106 (2017) 1-17.

[9] C.T. Wu, T.Q. Bui, Y. Wu, T.L. Luo, M. Wang, C.C. Liao, P.Y. Chen, Y.S. Lai, Numerical and experimental validation of a particle Galerkin method for metal grinding simulation. Comp. Mech. 61 (2018) 365-383.

[10] C.T. Wu, Y. Wu, D. Lyu, X. Pan, W. Hu, The momentum-consistent smoothed particle Galerkin (MC-SPG) method for simulating the extreme thread forming in the follow drill screw-driving process, Comp. Part. Mech. 7 (2020) 177-191.