

Modeling of High-Rate Ballistic Impact of Brittle Armors with Abaqus/Explicit

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Abstract: Accurate modeling and simulation of brittle armor panels under projectile impact is a challenging problem involving costly experimental characterization of material properties and verification of ballistic impact response with actual test data. The nature of impact of brittle armors, specifically those made of cementitious materials, is a problem of much complexity, due to high-rate fragmentation caused by strong compressive shock waves followed by reflected tensile waves. Traditional Lagrangian finite element modeling (FEM) of these problems can introduce errors and issues of convergence as a direct result of the resulting large deformations of free surfaces. Introducing element erosion can resolve some of the issues related to excessive distortion of elements, but presents new problems involving conservation of mass. Regardless, traditional FEM cannot account well for secondary contact of spalled fragments from these panels. Smoothed particle hydrodynamics (SPH) is a more recent addition to Abaqus/CAE and resolves many of these issues. However, SPH is less accurate in general than traditional Lagrangian finite element analyses when the deformations are not too large. The main focus of the paper is to deal with these modeling issues related to high-rate impact of projectiles on high-strength cementitious composite panels, as well as to evaluate the situations in which a particular method would be more appropriate. A dynamic user-defined material model is used to accurately represent the complex behavior of this high-strength cementitious composite. The simulations of several example problems are validated with experimental results.

Keywords: Abaqus, Cementitious, Experiment, Impact, Material, SPH

1. Introduction

The performance of brittle, cementitious armor panel under high-rate impact is contingent upon a wide array of variables including but not limited to projectile and target geometry, impact velocity, type of projectile material, and angle of attack of the projectile. Due to comparatively low cost, ease of rapid on-site manufacture, and high early strength, the use of ultra-high performance concrete (UHPC) as an armor material for protection against small arms fire and mortar fragments has been found to be very attractive. Understanding the performance of such armors to high-rate ballistic impact is vital to ensure safety of military personnel in war zones. Under ballistic impact, UHPC panels experience various stress states that lead to complex failure modes. In the worst case scenario for a single projectile impact event, which corresponds to an impact orientation normal to the surface, a crater is formed in the front surface followed by a strong compressive shock wave. This wave weakens as it traverses through the plate thickness and is eventually reflected off the free back surface (Nordendale, 2012). This compressive shock wave reflection generates a tensile

shock wave, which if large enough in magnitude, can lead to fracture on the rear face of the panel accompanied by spalling of the material behind the point of impact. Since the speed of shock waves propagating through the material can approach speeds of over 4000 m/s, this fracture takes place before a projectile can even penetrate through the target panel. Such fracture and spalling phenomena in brittle materials becomes problematic when using the traditional Lagrangian finite elements available in Abaqus. By using a dynamic user-defined material (VUMAT) model and coupling it with an element deletion scheme, these elements can easily handle the large strains and large strain rates without computational impediments. However, it has been found that to efficiently use an element deletion scheme without loss of accuracy or increased in computational time, very large strains can still be experienced in the model (Nordendale, 2013). This, however, leads to a model that can accurately predict the exit velocity of the penetrating projectile, but cannot track the fragmented pieces of the target once they become free-flying fragments. The SPH numerical method has received considerable theoretical support since its inception. Using the same material model and model parameters as for a traditional finite element model, an SPH model can easily handle the complex failure states that occur during an impact event, and more accurately handle the fragmentation process in a more natural way (SIMULIA, 2012).

Significant advancements in phenomenological and experimental characterization of complex materials, numerical simulation techniques, and computer speed, is enabling finite element analysts to more accurately predict the dynamic effects of structures subjected to high-rate ballistic impact. Accurate simulation of the structural response of armor panels to such dynamic loads is a convenient way to radically decrease the cost of R&D efforts related to new materials and applications. The availability of the powerful general purpose finite element modeling code, Abaqus/CAE, with the ability to incorporate new material models developed by the user have given added boost to this effort.

1.1 Nature of Impact of Cementitious Targets

Problems of material failure near a free surface that is at some distance from the localized area of application of an impulsive load have been studied extensively. In the case of highly brittle materials with very high compressive strengths but relatively weak tensile strengths, spalling and fragmentation at the free surfaces is a phenomenon to be expected due to the reflection of incident-compressive impulses generated by high-velocity ballistic impact (Reinhart, 1999). This study focuses on the impact of relatively thin panels. In the first few microseconds of a high-velocity impact event, local material cratering takes place. Directly in front of the projectile path, the material then undergoes local material compaction. Due to the extremely high rate of loading, Poisson's effect does not have time to get mobilized, which would normally allow for some of the material in front of the projectile to expand outward radially in the plane of the panel. This phenomenon, thus, creates a radially confined compression zone. This high-rate loading also temporarily increases the intrinsic strength of the material. Additionally, the instant the projectile comes into contact with the panel, a compressive shock wave traverses the panel in the thickness direction, reflects off the free surface on the back causing a tensile shock wave to form, and thereby causing cracking and fragmentation (or spalling) of the material (Nordendale, 2013). Figure 1 illustrates these progressive effects.

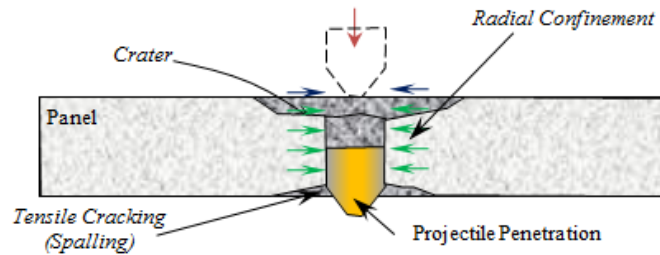


Figure 1. Progressive effects of high-velocity penetration of brittle panel.

1.2 SPH vs. Traditional Element Models

SPH is a numerical method that is part of the larger family of meshless methods. Instead of defining nodes and elements, one only needs a collection of points to represent a given body. In SPH, these points are commonly referred to as particles. The SPH capability in Abaqus is a fully Lagrangian modeling scheme that permits the discretization of a prescribed set of continuum equations by interpolating the properties directly at a discrete set of points distributed over the solution domain without the need of a traditional spatial mesh. The difficulties associated with fragmentation and free-flying motion of spalled particles coupled with very large deformations of free surfaces are resolved in a comparatively natural way. Moreover, in a case where there is interest in the secondary impact of fragmented particles against some second target a certain distance away from the first target, SPH has no additional computational cost associated with tracking these fragments through a large empty volume (as would be prohibitively expensive with a coupled Eulerian-Lagrangian scheme). The SPH scheme incorporated in Abaqus includes a tool known as the “domain.” This is a rectangular region computed at the beginning of the analysis as the bounding box within which the particles are tracked. This fixed rectangular box is 10% larger than the overall dimensions of the whole model and is centered at the geometric center of the model. As the analysis progresses, if a particle moves outside the domain, then it behaves like a free-flying point mass and no longer contributes to the SPH calculations. As mentioned earlier, SPH interpolates the properties of each particle. This is done using what is called a “smoothing length calculation”. Even though particle elements are defined in each model using one node per element, the SPH method computes contributions from each element based on adjacent particles that are within a sphere of influence. This smoothing length governs the interpolation basis of the method. For every increment, this local connectivity is recalculated internally and the kinematic quantities like normal and shear strains as well as deformation gradients are computed (SIMULIA, 2012).

However there are some limitations inherent with SPH models that are not present in traditional finite element models. In regions of the model where deformations are not too large and elements are not highly distorted, the SPH analyses are found to be less accurate in general than Lagrangian finite element analyses. A large problem that has been identified is that of tensile instability. When the material is in a state of tensile stress, the particle motion may become unstable. This instability is strictly related to the interpolation technique of the standard smoothed particle dynamic method. Because of this instability, particles tend to clump together and show numerical fracture-like behavior and artificial voids. The underlying cause has been shown to be a lack of formal consistency in SPH. It cannot reproduce exactly any class of function on a defined set of points.

Because of this drawback, a numerical clumping instability manifests itself when nodes are mutually attracted. More specifically, the SPH kernel function is unable to keep the nodes apart once they are sufficiently close to each other (Mehra, 2012).

Another limitation inherent to the SPH functionality currently implemented in Abaqus is that bodies modeled with particles that were not defined with the same section cannot interact with each other. Therefore, SPH cannot be used to model the mixing of bodies with dissimilar materials. This limits one to model only the brittle target panel with particles; whereas, the projectile model must use traditional finite elements. The new functionality of Abaqus version 6.12 has incorporated the automatic conversion of finite elements to SPH particles. This eliminated many of the limitations associated with applying loads directly to bodies that could, eventually, become particles. But this functionality has the limitation that once the elements are converted to particles, whether by time-, stress-, or strain-based criterion, they are free-flying particles which no longer obey symmetric boundary conditions. This leads to inaccurate fragmentation patterns if a user wishes to take advantage of the symmetry in the problem.

2. Material Model

The constitutive model used in this study has four basic elements: (1) an equation of state (EOS) for the pressure-volume relation that includes the nonlinear effects of compaction, (2) a representation of the deviatoric strength of the intact and fractured material in the form of a pressure-dependent yield surface, (3) a damage model that transitions the material from the intact state to the fractured state, and (4) a strain-rate law that is coupled with the failure surface. The model builds upon the initial efforts of Adley and coworkers on the Advanced Fundamental Concrete (AFC) model (Adley, 2010). Further improvements and developments were made by the authors and were shown to have excellent performance (Nordendale, 2013). This model accounts for processes like irreversible hydrostatic crushing, material yielding, plastic flow, and damage evolution. The model is based upon a non-linear pressure-volume relationship, a linear shear relationship (constant shear modulus, G), and incorporates a failure surface that is strain-rate dependent. As with most of the simplistic models for geomaterials, the proposed model uncouples the hydrostatic and deviatoric responses, so that no volumetric strain due to purely deviatoric loading may develop. A full description of each of the four components is illustrated in Figure 4.

2.1 Pressure

The pressure-volume behavior of the model characterizes a non-linear bulk modulus and irreversible volumetric crushing contributing to material damage. The compressive pressure behavior can be separated into three distinct zones: (1) an initial elastic zone followed by (2) an irreversible crushing response zone, where air voids begin to collapse, and finally (3) an elastic locking zone corresponding to a fully packed material where all air voids have been crushed out. Additionally, this model treats initial loading, unloading, and reloading differently. An illustration of pressure-volume behavior is given in Figure 2. In the equation shown for the crushing response zone, K_1 , K_2 , and K_3 are material constants, P is the mean normal stress (pressure), and μ is the measure of volumetric strain that is equal to the ratio of the initial volume minus the current volume to the current volume.

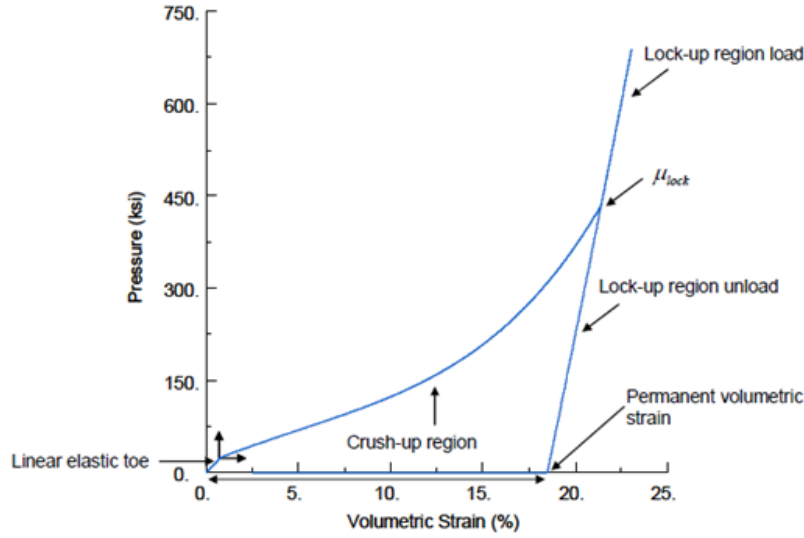


Figure 2. Pressure-volume model (Adley, 2010).

2.2 Strength

Shear or distortional behavior of the model is characterized by plastic flow, material yielding, and damage initiation as well as evolution. Following the sign convention of continuum mechanics, the mean normal stress values less than zero denote compression. Here, the yield surface is represented by two equations, depending on whether the state of stress is in compression or tension, where C_1 , C_2 , C_4 , and A_n are constants that are greater than zero, D is the scalar damage parameter that varies between 0 (intact) and 1 (damaged), $\dot{\epsilon}$ is the strain rate, $T_{\max}$ is the maximum allowable tensile pressure, and the value of $\sigma_{\max}$ is restricted to values that are greater than or equal to zero. The failure surface for rock-like materials is dependent on the third invariant of the stress tensor. Specifically, the ultimate compressive strength for a given pressure is greater than the ultimate extension (tensile strength) at the same pressure. This yields a failure surface that is non-axisymmetric in the octahedral plane, as illustrated in Figure 3 where $\zeta = (\sigma_1 + \sigma_2 + \sigma_3)/\sqrt{3}$ is the hydrostatic axis, θ is the Lode angle which is a function of the second and third invariants of the deviatoric stress tensor, and ρ_c and ρ_t are the maximum values of deviatoric stress components in compression and tension, respectively.

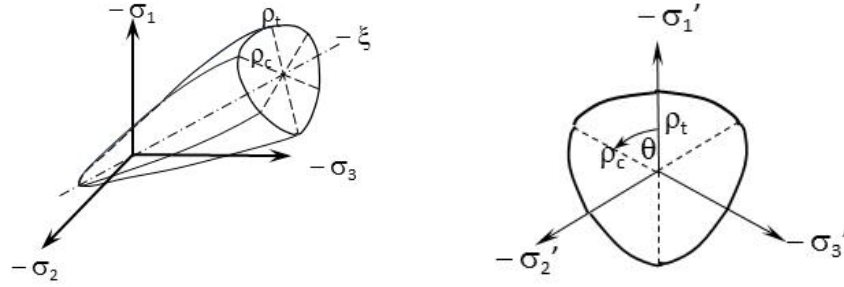


Figure 3. Failure surface for material model.

2.3 Damage

This model also accounts for material damage that develops incrementally during the course of stress loading histories. This material damage effectively provides a reduced failure surface due to excessive plastic shear strain as well as hydrostatic crushing. The value of material damage is quantified using a scalar damage parameter, D , that is computed from the equation shown in Figure 4, where D_I is an input parameter that is greater than zero with the values of $-I_1 D_I$ restricted to greater than 0.01, $\Delta \varepsilon_p$ is an increment in the effective deviatoric plastic strain, $\Delta \mu_p$ is an increment of volumetric plastic strain, and μ_{lock} is the locking volumetric strain.

2.4 Strain-Rate Law

The original AFC model proposed a generic Johnson-Cook strain rate law in the failure surface, but it has been shown that many materials, including concrete, show nonlinear behavior in the log-scale of the strain rate (Schwer, 2007). In contrast, the Huh-Kang strain rate law, used in this study, provides a significant improvement with no appreciable decrease in computational efficiency (Huh, 2002). The equation for the Huh-Kang strain rate law, as shown below in Figure 4, has two non-zero constants, C_3 and C_{11} .

3. Applications

For this study, an ultra-high performance geopolymer (UHP-GP) target was used to validate our modeling schemes. This UPH-GP had a compressive strength of $f_c = 239$ MPa. Twenty actual ballistic impact laboratory experiments to determine the ballistic limit were undertaken for comparison of traditional element models to SPH models. Here the ballistic limit is the velocity required for a particular projectile to have a 50% chance of penetrating a particular target. In other words, a given projectile will not penetrate a given target when the projectile velocity is below the ballistic limit. The panels tested were of size 305 mm x 305 mm x 27 mm and clamped on all four sides as shown in Figure 5. The projectile was a 12.7 mm diameter sphere made of AISI Type S2 Tool Steel and was fired at the target panels at speeds between 350 m/s to 500 m/s, the range of ballistic limit for this panel material.

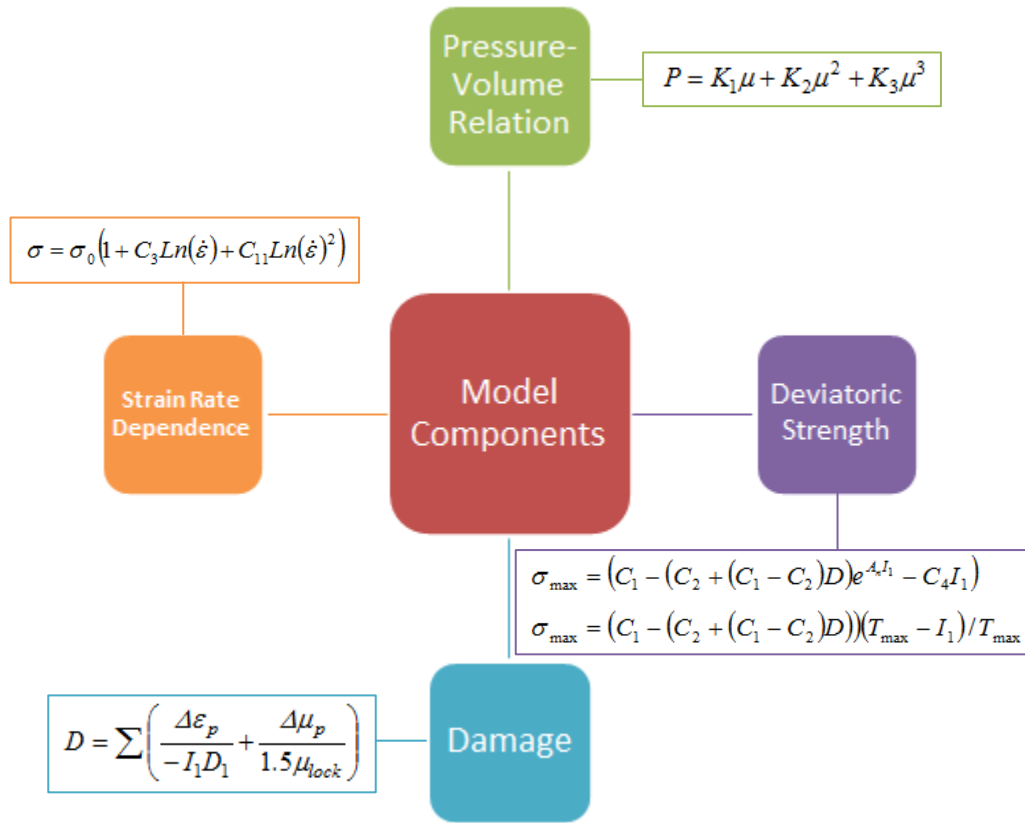


Figure 4. Components for the constitutive model.

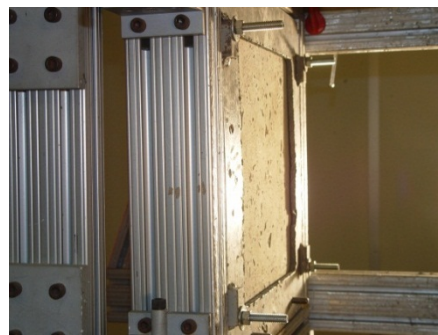


Figure 5. Target panel in test setup (exit side, before impact).

Many tests were performed to accurately characterize the material. A model fitting algorithm developed by the authors was used to determine the material constants used in the VUMAT. The material constants for the UHP-GP are shown in Table 1 and the material constants for the steel projectile are shown in Table 2. To model this experiment, two-way symmetry was utilized requiring only one quarter of the panel and projectile to be simulated. Appropriate symmetric boundary conditions were implemented and the periphery of the panel enforced fixed boundary conditions. Figure 6 shows an isometric view of the model configuration and mesh. The projectile, as shown in the enlarged view on the right, initiated with a predefined field to induce an initial velocity of $V_i = 483$ m/s at the instant of impact in the positive Z direction. A summary of the mesh details of both of the models is given in Table 3 and a summary of the CPU times for both models to run on an AMD Phenom™ II X6 1075T Processor (3.00 GHz) are given in Table 4.

Table 1. UHP-GP Material Constants for VUMAT (Target Panel).

Variable	Description	Value	Units
ρ	Density of Material	2.56E-09	Tonne/mm ³
G	Shear Modulus	18457	MPa
C_1	Failure Surface Constant	1016.3	MPa
C_2	Failure Surface Constant	908.65	MPa
C_3	H-K Strain Rate Constant	0.012089	
C_4	Failure Surface Constant	0.10382	
C_{11}	H-K Strain Rate Constant	-0.000627	
A_n	Failure Surface Constant	0.0017345	
T_{max}	Maximum Allowable Tensile Pressure	6.8946	MPa
K_1	Equation of State Constant	7919.2	MPa
K_2	Equation of State Constant	-29206	MPa
K_3	Equation of State Constant	187100	MPa
μ_{lock}	Equation of State Constant	0.10094	mm/mm
D_1	Damage Constant	0.000406	

Table 2. Tool Steel Material Constants (Projectile).

Variable	Description	Value	Units
ρ	Density of Material	7.79E-09	Tonne/mm ³
E	Young's Modulus	190,000	MPa
ν	Poisson's Ratio	0.25	
σ_y	Yield Stress	2,000	MPa
ϵ_{pl}	Plastic Strain	0.0105	

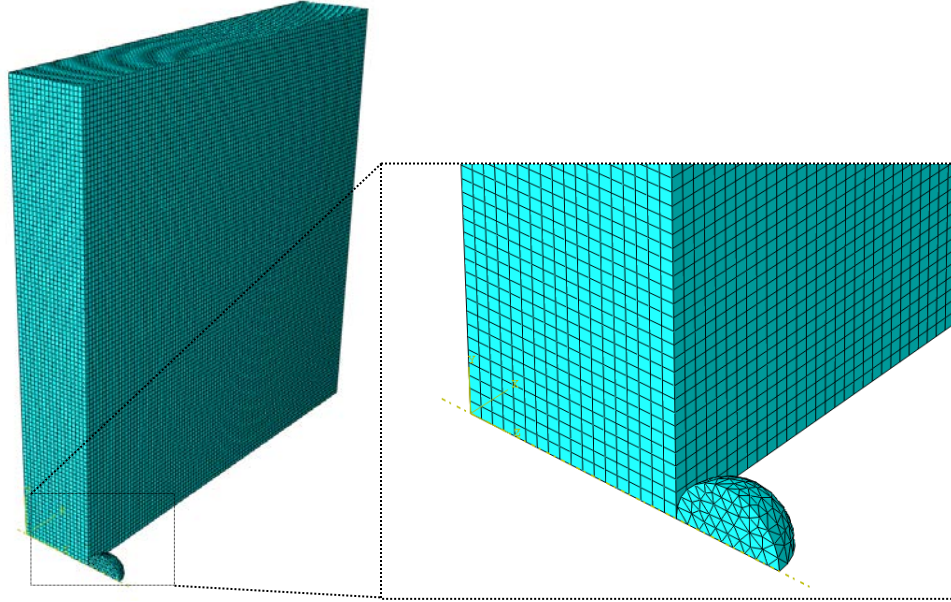


Figure 6. Abaqus assembly and mesh of model.

Table 3. Summary of mesh details.

Part	Element Type	Element Designation	Number of Elements
Projectile	Linear Tetrahedral Elements	C3D4	848
Panel (FEA)	Linear Hexahedral Elements	C3D8R	187,272
Panel (SPH)	Particle Elements	PC3D	187,272

Table 4. Time to complete analyses.

Model	CPU Time
FEA	0:22:21
SPH	1:40:20

3.1 Experimental Results

Twenty ballistic impact experiments were undertaken to validate the models built for this purpose. Views from one such experiment is shown in Figure 7. As seen on the left (the front side of the panel), the hole created by the projectile is only slightly larger than the diameter of the projectile itself (13 mm). However, the crater formed is approximately five times that size (63 mm). It is noted that for some of the experiments, a few large cracks emanated from the impact site and followed the shortest path to the periphery. But in majority of the experiments, damage was found to be highly localized and no significant cracking occurred away from the damaged region. The exit velocities for all experiments are shown at the end of the section for comparison with the FEA and SPH model results. For the experiment shown in Figure 7, the residual velocity was 88 m/s.

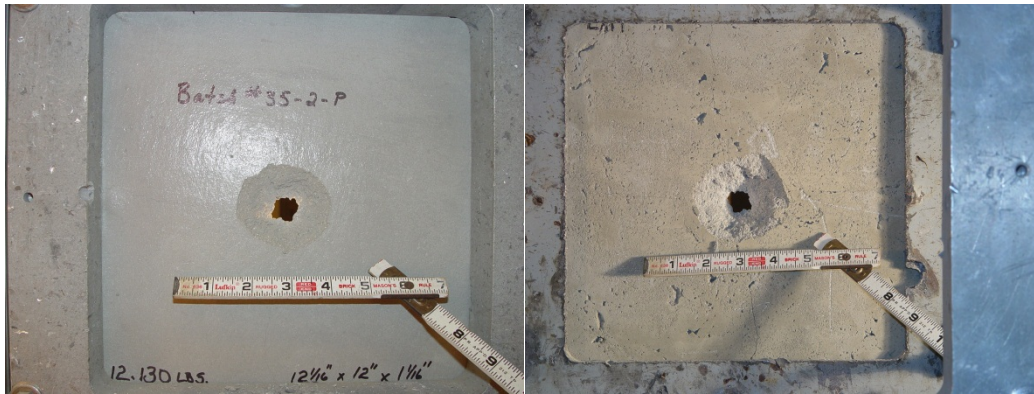


Figure 7. Target panel in test setup (front side and exit side, after impact).

3.2 FEA Model Results

The model presented relies heavily on the calculation of plastic strain for use in the damage evolution model. Figure 8 below shows the results of the model once a constant velocity is achieved, signifying that the projectile continues penetrating the panel with no further resistance. The residual velocity of the projectile for the FEA model was 92 m/s. The FEA model was found to be very good at predicting the exit velocity as well as the approximate failure pattern, but as shown by the cross sectional view of the panel, the elements in front of the projectile path were heavily distorted. Eventually the analysis stopped due to excessive distortion. A study has been undertaken by the authors incorporating the element deletion option using effective plastic strain as a metric for removing excessively distorted elements from the mesh. It was found that using a value below $\epsilon_{pl}^{max} = 1.5$ (150% strain) added to the computation time drastically as well as changed the velocity response of the projectile over time (Nordendale, 2013).

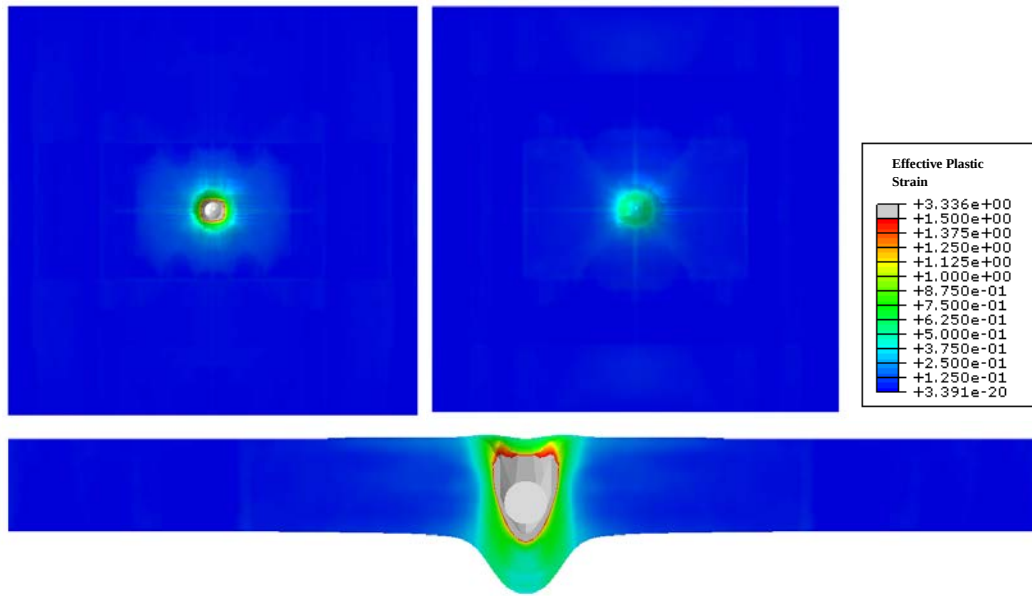


Figure 8. Effective plastic strain contours of FEA model.

3.3 SPH Model Results

An identical model to the FEA model shown in Figure 6 was created, but particle elements were used instead. The same VUMAT, material properties, boundary conditions, and number of elements as the FEA model were used. This allowed for a direct comparison of the performance of FEA and SPH models. Figure 9 illustrates the results of the SPH model. The residual velocity of the projectile from the SPH model was 138 m/s. This is significantly higher than the velocity predicted by the FEA model as well as the experimental results. Moreover, as shown in Table 4, the analysis time was more than four times what the FEA model took to run. This can be attributed to the smoothing length calculation that is undertaken at each increment, for each particle. However, the capability of the excessively strained particles to become free-flying point masses is highly useful. This eliminates the complications associated with excessive distortion, element deletion, and secondary impact. The failure pattern predicted by the SPH model is highly accurate as is the spalled behavior of the fragmented UHS-GP material directly in front of the projectile.

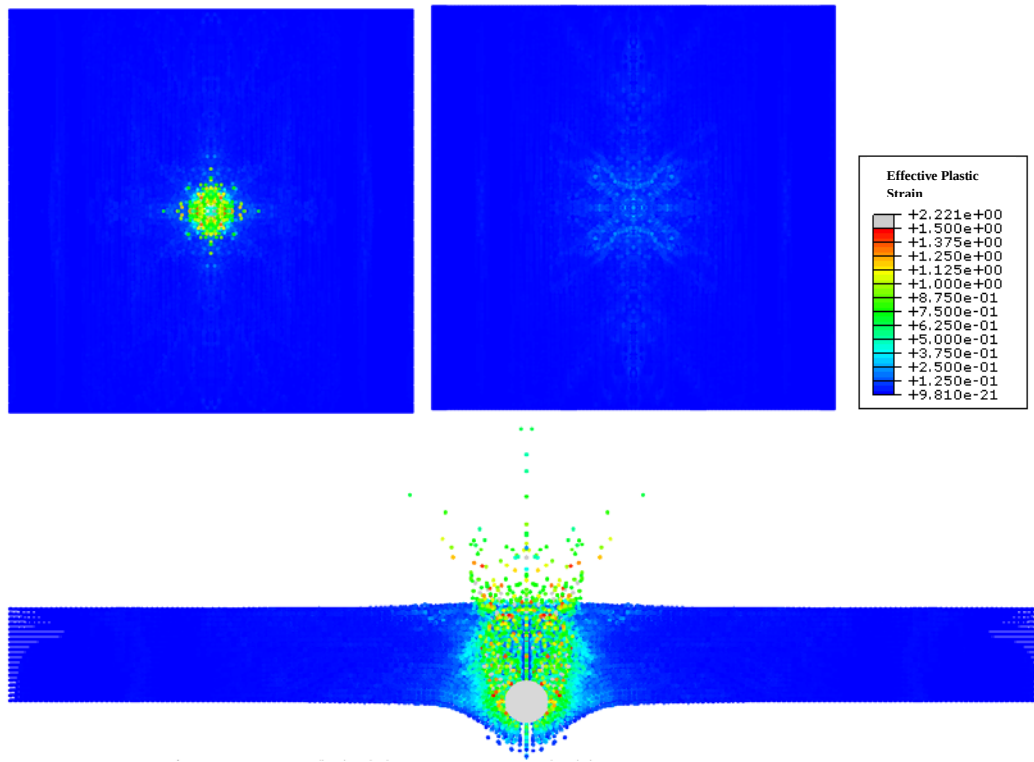


Figure 9. Effective plastic strain contours of SPH model.

4. Discussion

The traditional FEA model shown is significantly better at predicting the exit velocities of the projectile than a comparable SPH model. The FEA model is also faster to run. Figure 10 shows the impact velocity vs. the residual velocity of the twenty experiments, the FEA model, and the SPH model. Figure 11 shows the velocity vs. time for both models compared to the experimental value. These results suggest that the SPH model simulates a relatively weaker panel than the equivalent FEA model without element deletion.

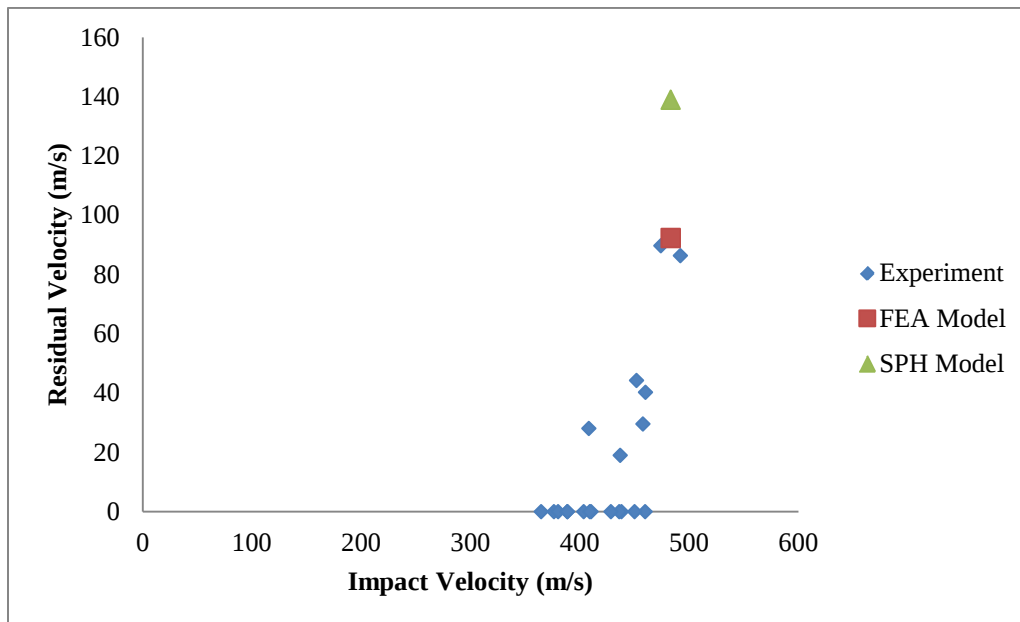


Figure 10. Impact vs. residual velocity of ballistic limit experiment and models.

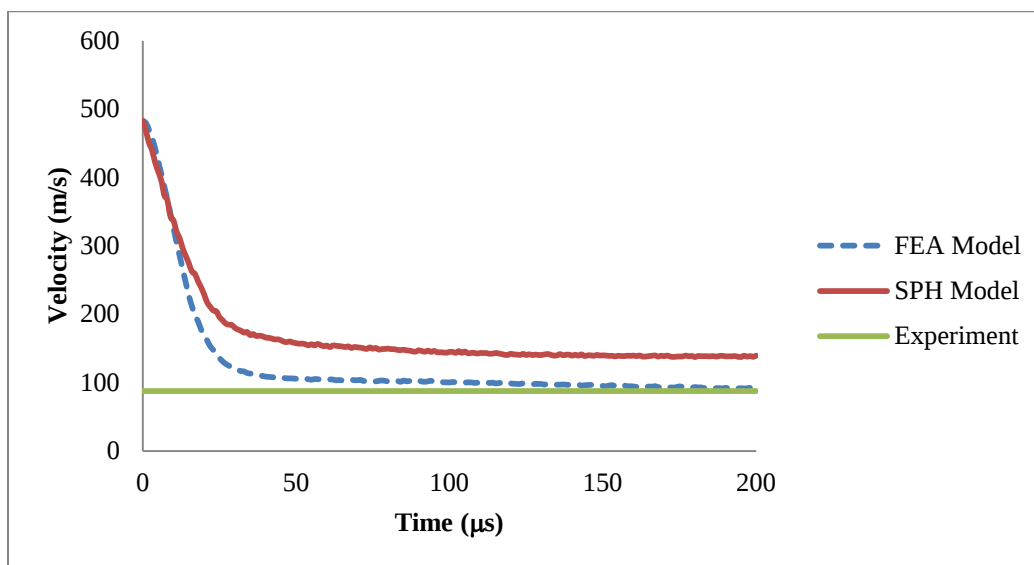


Figure 11. Velocity vs. time of FEA and SPH models compared to experiment.

5. Conclusions

An accurate modeling and simulation model of brittle armor panels under projectile impact has been presented. The results of a traditional Lagrangian finite element model has been compared with the results of a smoothed particle hydrodynamic model as well as actual laboratory experiments of a ballistic limit test. The results suggest that for the purpose of predicting exit velocities, a traditional finite element model is significantly more accurate. This is likely due to the smoothing length calculation as well as tensile instability that is possibly occurring at the rear face of the panel. If tensile instability occurs, further study into the tensile behavior of an SPH model must be undertaken. It has also been found that for the purposes of secondary impact as well as dealing with issues related to distortion, the SPH models are highly useful and easily implemented. The authors are currently working on studying both FEA and SPH models applied to higher rate impact of alternative high-strength cementitious materials.

6. References

1. Adley, M., Frank, A., Danielson, K., Akers, S., & O'Daniel, J. (2010). *The Advanced Fundamental Concrete (AFC) Model: TR-10-X*. Vicksburg, MS: U.S. Army Engineer Research and Development Center.
2. Huh, H., & Kang, W. (2002). Crash-Worthiness Assessment of Thin-Walled Structures with the High-Strength Steel Sheet". *International Journal of Vehicle Design*.
3. Mehra, V., CD, S., Mishra, V., & Chaturvedi, S. (2012). Tensile Instability and Artificial Stresses in Impact Problems in SPH. *Journal of Physics*, 1-5.
4. Nordendale, N., Heard, W., Ahn, J., & Basu, P. (2012). Mixed-dimensional and Multi-scale Modeling in Computational Mechanics. *Proceedings of the 2012 Engineering Mechanics Institute Conference*. Notre Dame, TN.
5. Nordendale, N., Heard, W., Hickman, M., Zhang, B., & Basu, P. (2013). Cementitious Material Models for Simulating Projectile Impact Effects. *Journal of Computational Materials Science*.
6. Reinhart, W., Chhabildas, L., Kipp, M., & Wilson, L. (1999). Spall Strength Measurement of Concrete for Varying Aggregate Sizes. *15th US Army Symposium*, (pp. 1-12).
7. Schwer, L. (2007). Optional Strain-Rate Forms for the Johnson Cook Constitutive Model and the Role of the Parameter Epsilon_01. *6th European LS-DYNA Users' Conference* (pp. 1-17). Gothenburg, Sweden: ERAB.
8. SIMULIA. (2012). *Abaqus Analysis User's Manual*. Providence, RI: Dassault Systemes.