the CertaSim SOLUTION™

Featuring:
Explosive Formed Projectiles

2019

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CertaSIM, LLC is the official distributor of the IMPETUS Afea Solver® in North, Central and South America and provides technical support and training for the IMPETUS suite of software.

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News and Events

DoD Computational Human Body Modeling Performer Workshop

CertaSIM, LLC was represented at the "DoD Working Group on Computational Modeling of Human Lethality, Injury, and Impairment from Blast-related Threats" in Virginia, 05-06 February 2019. There were a little under 100 attendees discussing different aspects of modeling these applications. The two day workshop had many interesting presentations, one of them given by Professor Milan Toma, NYIT, about modeling the Human Brain with Fluid-Structure Interaction in the IMPETUS Afea Solver®. The workshop was a great success and CertaSIM, LLC obtained new valuable knowledge and expanded our network in this field. Thanks goes to DoD Blast Injury Research Program Coordinating Office, Fort Detrick and MITRE Corporation for hosting the event.

NVIDIA GTC 2019 Conference

The NVIDIA GTC2019 Conference was held March 17th-21st at the San Jose Convention Center. This is the 8th year that CertaSIM attended the conference and participated in the technical session. Mr. Kshitiz Khanna, Mechanical Engineer at CertaSIM presented a paper entitled “Modeling Fluid Structure Interaction with Multi-GPU Enabled Software”. The presentation is available from CertaSIM and NVIDIA also recorded the audio from the presentation and made it available to hear online. GPU technology is at the essence of the IMPETUS Afea Solver® massively parallel processing capabilities.

BMES 2019: Frontiers in Medical Device Conference

CertaSIM LLC, partnered with csimsoft, as a silver sponsor at the “Frontiers in Medical Devices Conference: The Role of Digital Evidence to Support Personalized Patient Healthcare” conference co-sponsored by the Biomedical Engineering Society (BMES) and the US Food and Drug Administration (FDA), held at the University of Maryland, Washington DC March 19th-21st, 2019. Many attendees were very interested in the IMPETUS Brain Impact Model video that we displayed at our booth. The model was developed by Professor Milan Toma at NYIT and couples the IMPETUS AsetTM High Order solid elements with the revolutionary ÐSPH™ algorithm. There were many interesting presentations and posters leading to good discussions with researchers and engineers that are interested in our Next Generation Solver technology. This is the conference to attend for the medical devices industry and we value the time spent with current IMPETUS users as well the chance to meet new customers.

Hypervelocity Impact Symposium (HVIS) 2019

CertaSIM, LLC had the pleasure of participating in the 15th Hypervelocity Impact Symposium (HVIS) held in Destin, Florida, USA. CertaSIM displayed its new booth with dual projectors that showcased the capabilities of the IMPETUS Afea Solver® with special emphasis on simulations performed with the γSPH™ Solver. Our booth was positioned just outside the main conference doors which made for the perfect spot to display IMPETUS capabilities and resulted in many of the attendees stopping by to ask questions. The conference was well planned and executed – much thanks to the organizers for this fantastic conference where we really expanded our network.

IMPETUS User Conference 2019

The IMPETUS Afea User's meeting in Flekkefjord Norway was a great success as the attendees shared their experiences. Attendance included IMPETUS users from many countries in Europe. Areas of interest focused on Defense related applications, such as ballistics, blast simulations, material modeling of high strength steels, modeling concrete under hypervelocity impact, etc. The IMPETUS development team gave presentations about new features in the solver and new GUI features such as object libraries and templates that provide increased productivity and allow for an easy but secure way to work on collaborative projects with other companies.

Pressure Vessels and Piping Conference (PVP) 2019

CertaSIM, LLC attended the ASME Pressure Vessels and Piping Conference (PVP) held from July 14th-19th, 2019 in San Antonio, Texas, USA. This Conference is an international technical forum to discuss and expand the knowledge on the topics related to Pressure Vessel and Piping technologies for the Power and Process Industries. There were people from over 40 countries in Europe, Africa, the Middle East, Asia, the Americas, and the Oceania islands. Some of the topics included Design & Analysis, Fluid-Structure Interaction, High Pressure Technology, and Seismic Engineering which are of great interest for our customers.

Ground Vehicle Systems Engineering and Technology Symposium (GVSETS) 2019

For the 6th Consecutive year CertaSIM, LLC attended the 11th annual Ground Vehicle Systems Engineering and Technology Symposium (GVSETS) & Advanced Planning Briefings for Industry (APBI) conference held August 13th-15th in Novi, Michigan, USA. Some of the technical tracks of the conference focused on Modeling & Simulation, Testing & Validation and Autonomous Ground Systems, areas that CertaSIM currently supports or conducts research in. It was a great opportunity for us to meet many of our customers in the Military Vehicle Industry and discuss new features in the IMPETUS Afea Solver®.

1st International Orbital Debris Conference

NASA held its first International Orbital Debris Conference on December 9-12, 2019 in Sugar Land, Texas. It was a great conference where many space related topics were discussed. The "Father of Orbital Debris", Don Kessler, gave a very inspiring Keynote on the History of the NASA Space Debris Program. Dr. Jensen represented CertaSIM, LLC discussing with customers and potential customers how the IMPETUS Afea Solver® is used for simulating Hypervelocity Impact as it relates to space debris.

Latest Scientific Articles that rely on the IMPETUS Afea Solver®.

The IMPETUS Afea Solver® provides scientists all over the world an accurate and robust tool for simulation. This is evidenced by conference papers and published articles from both Industry and Academia.

Characterization of Anisotropic Behavior of Extruded Aluminum – Experimental Work.

Reference: *M. Bondy, W. Altenhof, J. Magliaro and M. R. Jensen: "Experimental characterization of anisotropic mechanical properties of extruded AA6061-T6". Proceedings of The Joint Canadian Society for Mechanical Engineering and CFD Society of Canada International Congress 2019, CSME-CFDSC Congress 2019, June 2-5, 2019, London, Ontario, Canada.*

CertaSIM, LLC believes in combining numerical and experimental work as foundation for good solid engineering. Predictive numerical results should be supported by experimental verification. This article considers extruded AA6061-T6 profiles commonly used in the automotive industry. Uni-axial tensile tests and VDA plate bending tests for specimens in 0°, 45° and 90° to the extrusion direction are carried out and documented. Furthermore, three point bending as well as axial bending experiments are described. The influence on the material and process behavior from the anisotropic directions is discussed.

Fragmentation under Hypervelocity Impact using γSPH Algorithm

Reference: *A. Collé, J. Limido, T. Unfer and J.-P.Vilab: "An Accurate SPH Scheme for Hypervelocity Impact Modeling". Proceedings of the 2019 Hypervelocity Impact Symposium, HVIS2019, April 14-19, 2019, Destin, FL, USA, HVIS2019-078.*

In this paper the theory, background and the algorithms behind the newly developed ÐSPH is described. The algorithms have been applied for Barotropic Flows as published in previous articles. It shows how the formulation is extended to solid dynamics and how it can reproduce strain localization in adiabatic shear bands which is important to predict failure. Also shown is how tensile instability is prevented which increases accuracy and stability compared to classic SPH approaches. A Hypervelocity Impact experiment is compared with numerical results using the ÐSPH algorithm and good agreement is obtained.

Development of Accurate Smooth Particle Hydrodynamics Algorithms

Reference: *A. Collé, J. Limido, J.-P.Vilab: "An Accurate Multi-Regime SPH Scheme for Barotropic Flows", Journal of Computational Physics 388 (2019) 561–600".*

The presented work discusses the theoretical aspects behind the development of γSPH applied for solving Barotropic Fluid Flows. It is shown how the accuracy in the pressure field is drastically improved. As verification of the algorithms four academic test cases are showcased those being; isentropic shock tube, rotating square patch of fluid, oscillating drop and finally a dam break model. It is mentioned that the new development increases stability and accuracy in the solution as well as reduces the computational time.

Fracture and Fragmentation of Laminated Glass due to Blast Loading

Reference: *K. Osnes, J. K. Holmen, O. S. Hopperstad and T. Børvik: "Fracture and Fragmentation of Blast-loaded Laminated Glass: An Experimental and Numerical Study", International Journal of Impact Engineering 132 (2019) 103334.*

The Aset™ higher order elements combined with the Node-Splitting Algorithm is applied in this paper to investigate fragmentation and fracture of laminated glass. Features include fine cracking of glass plates, delamination and separation between the glass and the polymer interlayer. 15 glass specimens were tested at different pressure levels in a shock tube. Good agreement and highly comparable response to the experiments was obtained and the numerical models were able to describe cracking, formation of large fragments and free-flying fragments.

Modeling the Behavior of the Tricuspid Valve with Real Fluid-Structure Coupling

Reference: *S. Singh-Gryzbon, V. Sadri, M. Toma, E. L. Pierce, Z. A. Wei and A. P. Yoganathan: "Development of a Computational Method for Simulating Tricuspid Valve Dynamics", Annals of Biomedical Engineering, 2019, https://doi.org/10.1007/s10439-019-02243-y.*

The γSPH approach is in this work applied to perform a Fluid-Structure coupling in simulating the Tricuspid Valve. A computational model was developed based on high resolution microcomputed tomography (μCT) images. Material properties were found by studying valve closure. The computationally obtained leaflet coaptation zone was validated against μCT images. It is stated that the FSI model captured realistic leaflet dynamic deformation and in fact comparing with only a FE model it was concluded that FSI is required to capture the valve dynamics.

Applying IMPETUS for Modeling Brain Damage

Reference: *Milan Toma and P. D. H. Nguyen: "Coup-contrecoup Brain Injury: Fluid–Structure Interaction Simulations", International Journal if Crashworthiness, https://doi.org/10.1080/13588265.2018.1550910.*

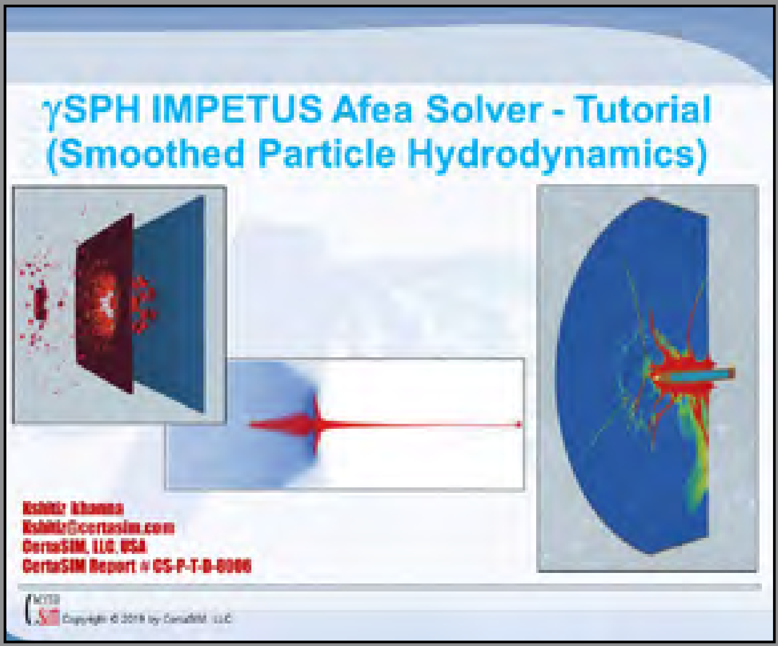
Damage can happen to the brain without any fracture of the skull and this research covers this scenario. A complex model of the human brain is used to study injuries due to shifting of the brain inside the skull, both at impact points and opposite non-impact points named Coup and Contrecoup injuries, respectively. The Cerebrospinal fluid flow is modeled with ĐSPH and the numerical approach is validated against Cadaveric experiments. It was concluded that the IMPETUS model provides realistic results.

Modeling Real IEDs and Soil Bed Conditions

Reference: *M. R. Jensen and W. Smith: "Numerical Parameter Characterization of a Buried Mine Blast Event with Emphasis on IED Shapes and Soil Bed Conditions", International Journal of Vehicle Performance, Vol. 5, No. 4, 2019.*

The paper illustrates the advantage of IMPETUS DEFENSE for modeling real mine blast scenarios and a large numerical parameter study was conducted. Furthermore, modeling of real IED shapes and soil bed conditions was performed. One example considered was a soil bed with random rocks and its influence on the total blast impulse on a real structure.

Training Material from CertaSIM



A new tutorial was developed for CertaSIM's γSPH users - "γSPH IMPETUS Afea - Tutorial". This tutorial will help CertaSIM's customers get started using the ĐSPH Solver. It lists the input commands along with the detailed descriptions. It also provides three working examples which will be beneficial for developing the different application-based models. First example is based on "γSPH structure interacting with a Lagrangian structure". Second example represents the modeling of "the impact of two ĐSPH structures". And the third example describes "How to build a complex γSPH structure". The package consists of a tutorial PDF file along with the IMPETUS command files. Please contact support@certasim.com to get the latest version of this tutorial package.

Questions on this feature can be sent to support@certasim.com

New Option in the IMPETUS AFEA Solver Engine

The IMPETUS development team is constantly working on adding useful and cutting edge features. New implementations also cover well known material models that are used extensively for specific applications.
A new command is *OUTPUT_SENSOR_THICKNESS which is used to sample the thickness of a part.

```
*OUTPUT_SENSOR_THICKNESS
"Optional title"
coid, pid, x0, y0, z0, fixed, tbeg, tend
nx, ny, nz
```

Output is written to the sensor_thickness.out file and the thickness can be accessed during the simulation by using *FUNCTION with the call *thicks(coid)*.

The online manual for IMPETUS has a detailed description of the parameters and a rolling example is provided where the vertical motion of the rolls are adjusted to reach a target thickness for the slab. Further information can be obtained by contacting *support@certasim.com*.

Experimental and Numerical Study of Cell Phones

San Jose State University and CertaSIM, LLC has a collaboration in which they offer joint projects to graduate students. These projects apply the IMPETUS Afea Solver® as a numerical tool and offer the student an opportunity to work with the CertaSIM Staff at the Saratoga office. This article describes briefly one of these projects, a drop test simulation of a cell phone.

Mr. Raghuvamshi Chilukuri Leela is a graduate student in Mechanical Engineering at San Jose State University, Department of Mechanical Engineering. We have asked him to describe his project and its current status to our readers. The project is numerical and experimental investigation of cell phone drop tests.

The objectives of my graduate project:

- To perform a drop test to evaluate the structural integrity of a cell phone.
- To draw parallels between experimental and simulation results obtained from drop tests.
- To quantify the effect of impact force on structural integrity of the cell phone.
- To optimize the design of the cell phone housing to maintain structural integrity and reduce impact damage.

A three-dimensional Finite Element model of a cell phone (LG Rebel 4) was developed in a CAD software (Pre-Processor) and analyzed in the IMPETUS Afea Solver®. Test models were simulated with IMPETUS to understand and learn the full extent of software. The IMPETUS FE module (IMPETUS BASIC) is used to perform the stress and damage analysis. The mesh obtained in the Pre-Processor is transformed into higher order elements (linear to quadratic or cubic) to obtain more accurate results. Aluminum alloy of density 2700 kg/m3 for the cover(case) and glass of alloy of density 2000 kg/m3 for the screen are used to run the analysis.

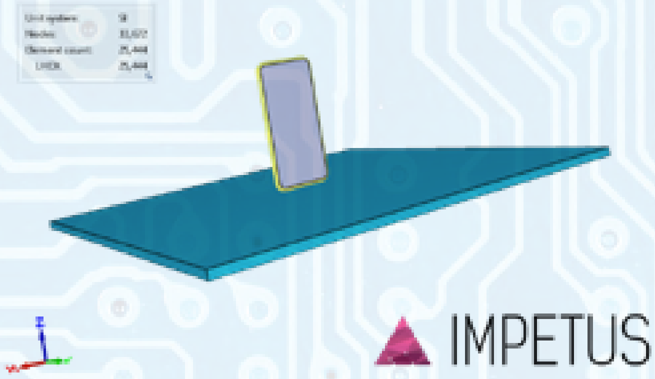


Figure 1 shows the model I analyzed in IMPETUS.

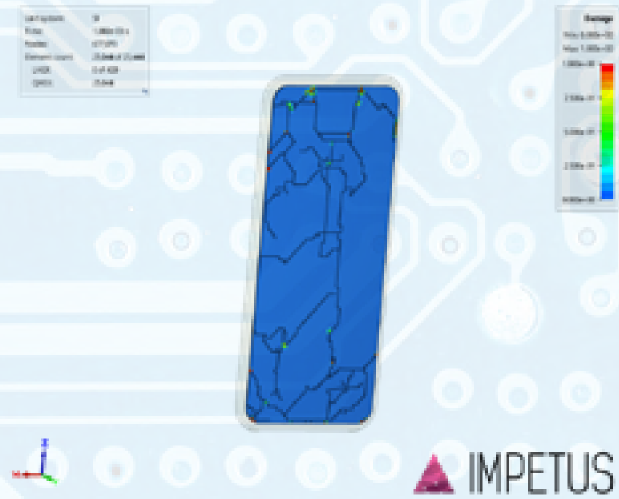


Figure 2 shows the crack propagation after impact.

Damage can be observed in the impact zone (bottom of the cell phone) resulted in maximum impact force of 20kN which induced maximum stress of 383.7MPa. IMPETUS replicated damage areas as predicted. It also shows the node splitting of the screen because of impact.

I am currently working on the experimental part of the project, I will be able to wrap up the project by end of March 2020.

Involved Project Partners:

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Professor and Associate Chair
Director of Product Design Lab
Mechanical Engineering Department
San Jose State University

M. R. Jensen, Ph. D
CTO
CertaSIM, LLC

New Partnership for High Energy Impact Research Between Missouri University of Science & Technology and CertaSIM, LLC

CertaSIM, LLC believes strongly in partnerships with research institutions and companies to gain knowledge in different engineering disciplines and exchange of experience. Thus, a large effort is made in order to find and approach the most "cutting edge" research centers in North America. In this article such a partnership is described, the recently formed partnership with the Rock Mechanics and Explosives Research Center at Missouri University of Science and Technology.

A new research partnership has been formed between Research Assistant Professor P. Mulligan, Ph.D., Missouri University of Science and Technology and CertaSIM, LLC. Missouri University of Science and Technology (Missouri S&T) was founded in 1870 as one of the first technological institutions west of the Mississippi. In 1964 the Rock Mechanics and Explosives Research Center (RMERC) was established to meet the research needs of the mining, petroleum and geological industries. Since RMERC's founding, the explosive research program has evolved to include three separate testing facilities. Testing capabilities include indoor testing facilities (up to 8-pound charge weight limit), an underground research mine (17-pound charge weight limit) and an above-ground test facility (10-pound charge weight limit). The Explosive Research Group at Missouri S&T also houses a 40-millimeter powder gun and shock tunnel that can produce pressure vs. time waveforms similar to large-scale arena tests. The explosive research faculty investigates a wide range of explosive and dynamic related subjects ranging from blast-induced traumatic brain injuries to demolition and mining to predictive system performance. The RMERC also offers geological testing, water jetting, and 3D printing services.

The goal for the partnership is to apply the IMPETUS Afea Solver® for the simulations needs of complex energetic events experimentally performed at RMERC. These events include Explosive Formed Projectiles, Shaped Charge, Air Blast, industrial mining blast and many other applications. With the partnership RMERC will have access to a very advanced numerical tool with Aset™, Node Splitting, iDPM and γSPH functionality and many other features. Additionally, the computational simulation time will be significantly reduced due to the utilization of GPU technology compared with the current Legacy Finite Element Codes and Government Eulerian Codes used at RMERC. CertaSIM will gain further experimental knowledge as well as introduce IMPETUS to the next generation of Explosives Engineers, in the Mining as well as in the Defense Industry. In fact, during the last visit to RMERC Dr. Mindle and Dr. Jensen attended Plate Dent Blast Experiments.

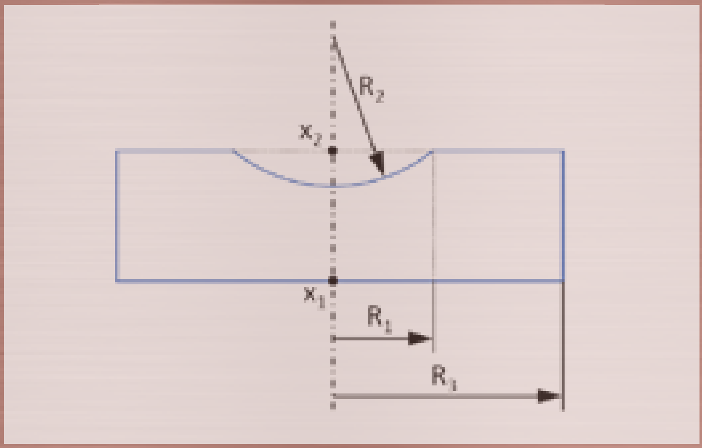
Please visit https://rockmech.mst.edu/ for more information about the Research Center.

Easy Creation of Explosively Formed Projectile Model

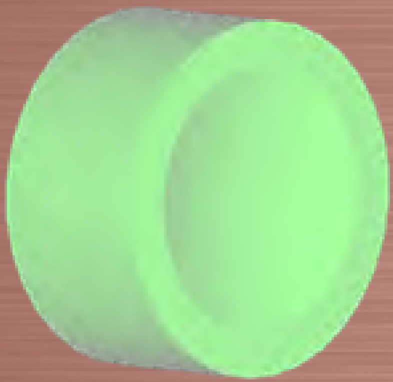
*This article presents the command to use in the Editor Mode in order to create geometric design of the charge in an Explosively Formed Projectile. This is done with the *GEOMETRY_EFP command that makes the specification of the EFP charge very simple and efficient.*

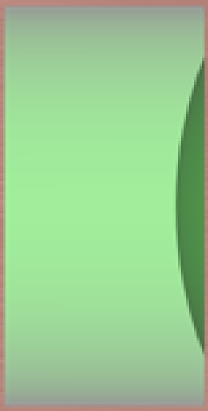
When applying the iDPM algorithm to model High Explosive one need a geometry that describes the shape of the HE. In the case of Explosively Formed Projectile, which often has a cylindrical shape, the *GEOMETRY_EFP option makes this specification very easy.

```
*GEOMETRY_EFP
"Optional title"
gid, csysid
x1, y1, z1, x2, y2, z2, R1, R2
R3
```



Two, point locations are giving which are the back and front faces and thus determines the thickness of the charge. Furthermore, three geometric radii can be given where the third, R3, is optional. If not given, R3 has the value of R1.
In the IMPETUS Afea Solver GUI the geometry can be shown in the Assemble Mode and it can be verified that the input is correct. The command makes modeling the EFP charge very efficient and easy, just by a few command lines it is very easy to change the geometry.





Explosive Formed Projectiles – A Literature Review

This article is a result of a Literature Review carried out at CertaSIM, LLC over the last year in order to obtain in-depth knowledge about Explosively Formed Projectiles. The goal was to obtain knowledge about the EFPs process and the influence of the Design Parameters on flight behavior and penetration characteristics. EFPs are a relatively simple weapon where an explosive in a container detonates to form a disk into a highspeed projectile. Due to their simplicity and low cost they have been used extensively by insurgents in modern day warfare. Using Finite Element modeling of EFPs will help to design new and improve existing vehicles that will provide for more protection of our warfighters.

The Explosively Formed Projectile (EFP) is designed to penetrate armor at high velocity and at long distances. A container, typically cylindrical in design, is filled with High Explosive (HE) and a disk closes the geometry. This disk called the Liner is slightly concave and in direct contact with the HE. When detonated the HE collapses the Liner and forms a projectile with a very high velocity which can exceed 1000 m/s. The process is illustrated in Figure 1 and an initial Liner together with the resulting heavily deformed EFP is illustrated in Figure 2.

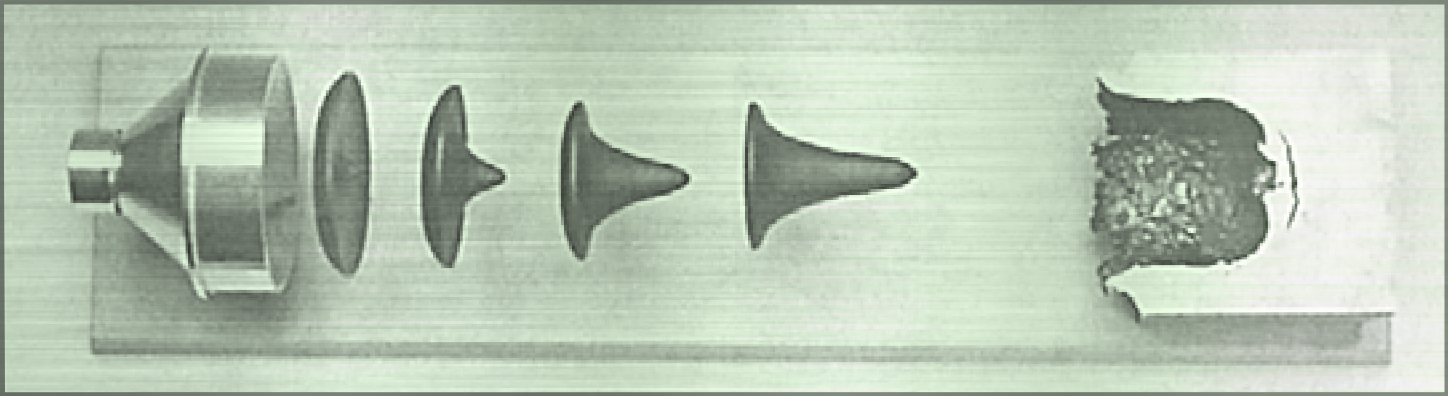


Figure 1: Development of an EFP starting with initial configuration from left and the resulting impact to the right [Zukas, 1998].

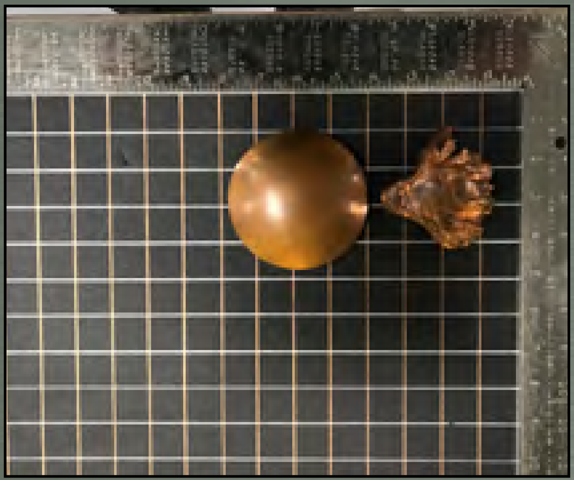


Figure 2: An example of an initial Liner and the resulting EFP. Items are from Rock Mechanics and Explosives Research Center, Missouri S&T [Jensen, 2019].

According to [Cardoso, 2016] the first publication on this weapon were seen in 1935 so it is definitely not a new process, however significant studies were first shown in the 1970s. Carleone [Carleone, 1993] gives a list of the historical developments on this topic, starting in 1936. EFPs are fairly simple in design and have been used by insurgents both in Iraq and Afghanistan as lethal roadside bombs [Fahim, 2017]. In Morrison [Morrison, 2007] it is mentioned that EFPs has been seen used in the Iraq conflict and that the major wounding mechanism is from fragmentation and burns. Past experience has shown that Ballistic injury accounts for around 75% of all injuries.

These circumstances have led to a need for research into the effect of impact of EFPs on military vehicles in order to improve their design for survivability. If the forming and behavior of the projectile can be captured with numerical simulations as well as the impact with various target materials, a safer environment for our warfighters can be obtained. However, to do that one must first develop the knowledge base for EFPs which includes understanding the Process and Design Parameters as well as performance of this type of weapon.

Through time, different designs and types of EFPs have been developed, but first consider the traditional single Liner cylindrical EFP as shown in Figure 2. There are several design and process parameters to consider. In [Randers-Pehrson, 1978] it is mentioned that the explosive impulse should form a slug that has a very low velocity gradient else it will be pulled apart. EFPs can be used for very long stand-off distances since air drag only causes a slight loss in velocity. It can have a trajectory of over 100 meters and even reach velocities of 3000 m/s. Alternatively, a Shaped Charge is designed for smaller stand-off distances but reaches a much higher velocity at the Jet Tip than is the case for an EFP.

Parameters influencing the performance of an EFP are well described in the 1993 paper by Weimann [Weimann, 1993]. Many parameters that affect the projectile shape and velocity are described, among them the explosive, casing material, Liner material and dimensions. As an example, the charge length is found to be a very important design parameter, where increased charge length gives additional stretching of the EFP, higher velocity and kinetic energy. When the casing thickness was increased, an increased velocity was found, even when the outer diameter was kept constant and hence a smaller explosive charge was applied. Another important parameter that influences the performance, as has been observed for Shaped Charges, is the initial position of the detonation point. The closer to the backend of the casing, further away from the Liner, the higher is the velocity of the projectile.
One aspect of EFP research is the forming, shape and velocity of the projectile, another is the penetration performance for impacting the target. In [Zukas, 1998] it is mentioned that the penetration depth is typically 0.8-1 times the charge diameter which is much less than for a Shaped Charge. In [Mulligan, 2011] a large experimental study was carried out on performance where the EFPs performance is defined as penetration of the target. Five physical parameters are tested leading to a total of eighteen different designs. The parameters investigated are Charge Weight, Container Geometry, Liner Thickness (called Flyer in the report), Liner radius of curvature and finally the type of HE used. Results indicated that there is an optimal charge weight for the penetration since for the larger charges the projectiles broke apart and the penetration got smaller, though the measured velocity increased with the heavier weight. One design had a nearly flat Liner that gave similar velocity as one with a typical curvature, however the flat design had half the penetration depth. Furthermore, it was concluded that the Liner can also be too thick, relative to the charge diameter, to give good performance when compared to thinner Liners. In [Carleone, 1993] the important L/D ratio is mentioned, where L is the length of the charge and D is the charge diameter. Often this ratio is limited due to the overall constraint of the system, but it is mentioned that for increased ratio the kinetic energy is increased until it flattens, indicating an optimal design for the EFP. Research on the effect of the type of HE used is shown in [Miao, 2011] where five different types of explosive were investigated, two of them being TNT and PETN. They found that increase of explosive density, detonation velocity and detonation pressure in general increased the velocity and L/D ratio. An X-ray image from one of the experiments showed the velocity difference between the tip and back of the EFP, having the highest velocity at the tip as expected.

The flight characteristic of an EFP has been found to influence the impact performance. A stable aerodynamically EFP [Bender, 2001] means a more accurate impact which is measured by distance from the target point and angle of impact. A way to secure a stable flight is to have the EFP develop fins on the projectile. In [Bender, 2001] this is obtained by using an initial shape of the Liner similar to a pin-wheel at the outer rim, whereas in [Liu, 2014] this is done by the use of multiple detonation points. A total of three detonation points is used, leading to improved aerodynamic stability of the projectile.

Different designs have been developed over time, e.g., the Multiple Explosive Formed Projectile (MEFP) which is seen as a collection of EFPs. There are different types of MEFPs, e.g., Liners with individual charges as in an array, integral type with one charge and multiple Liners or one charge with one formed Liner. Figure 3 shows a formed Liner with multiple imprints (left) and an example of an integral MEFP (right).

Figure 3: Different types of MEFPs. Left: Multiple imprints in one Liner plate [Fong, 2005]. Right: Integral MEFP [Liu, 2017].

The MEFP will generate a spray of multiple fragments to impact the target. Of special interest for research is the spatial dispersion patterns and penetration properties [Liu, 2017]. In their set-up there is a center Liner and six radial placed surrounding Liners. It is mentioned that the radial Liners travel with the same velocity and are distorted due to unsymmetrical detonation pressure. However, the velocity of these and the center EFP are on the same level, around 2500 m/s. It is also seen that the damage area increases with larger stand-off distance.
Different numbers of Liners can be applied as shown in Figure 3 where [Liu, 2017] used seven individual Liners. The same number of Liners was used in [Koch, 2017] but formed into one single piece Liner. They used different geometries, some with deeper imprints and other configurations with more distance between each EFP, etc. Three different materials were tested and very different projectile formations were observed. For a Liner made of a two-phase tungsten-nickel-iron alloy each penetrator fractured down their center into two pieces. Resulting shapes for the three materials are shown in Figure 4.

Figure 4: Soft Recovered penetrators for three different materials tested in [Koch, 2017].

Other variations have been developed over time in order to improve the efficiency of this type of weapon. One is a Non-AxiSymmetric Explosively Formed Penetrator which is called NAS EFP. The concept is to create more volume, increasing the mass of the High Explosive and then generate a more lethal design as described in [Fong, 1998]. It was mentioned that the first testing of NAS EFP warheads started in 1979. Another concept is to use two Liners, an inner and outer one [Xu, 2018] and [Arnold, 2014] where the later also describes the concept of an Axially Switchable Modes Warhead.

One of the challenges in experimental investigation of EFPs is the recovery of the projectile. If studies of the final formed projectile are of interest, how can this be done without damaging the shape when stopping it? This topic has been researched at the Air Force Research Laboratory where water and sand has been applied to make a Soft-Recovery as shown in [Lambert, 2005]. Soft-Recovery studies have also been done at Missouri S&T where a series of impact materials have an increasing density gradient as one method and other tests were done with water barrels [Bookout, 2013]. There are differences between the two methods, the pros and cons are described but if an accurate projectile geometry is the highest priority then the first method should be used.

Any questions about the referenced documents can be directed to CertaSIM, LLC by contacting support@certasim.com.

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[Arnold, 2014] W. Arnorld, E. Rottenkolber and T. Hartmann, "Axially Switchable Modes Warheads", 28th International Symposium on Ballistics, Atlanta, GA, September 22-26, 2014.

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[Jensen, 2019] Photo taken by M. R. Jensen of parts investigated during visit at Rock Mechanics and Explosives Research Center, Missouri S&T. The parts were used in: P. R. Mulligan, "The Effects Select Physical Parameters Have on An Explosively Formed Projectile's Performance", Master Thesis, 2011, Missouri S&T.

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Numerical Modeling of Explosive Formed Projectiles

This article describes research that was performed related to numerical simulation of Explosive Formed Projectiles. It is critical to be able to accurately model an EFP to understand the threat that faces our soldiers in order to develop better protection for them. Various numerical methods have been applied to this problem in the past which shows how difficult this problem is to solve.

If numerical modeling can be applied to the design of Explosive Formed Projectiles (EFPs) this can lead to a much better weapon design with better efficiency. On the other hand, when the EFPs are used as an IED against our soldiers, better knowledge can be used in developing Protective Armor and vehicle design resulting in a safer environment for our warfighters. This article focuses on research done with simulation in this area using the open literature, acknowledging that a much larger amount and better research is not publicly accessible. This review highlights the methods and problems as well as showcases results from many resources.

Some of the potential problems in modeling EFPs are related to the extreme pressure generated by the detonation of the High Explosive (HE) which drives the process, see [Jensen, 2019] for more information on EFPs. The HE is laid against the casing and the Liner which creates very large deformation of the Lagrangian elements that are used and the resulting problems with hourglassing if hexahedral constant stress elements are chosen as the element type. Deformation and high pressure will also create large problems with the Lagrangian contact, a penalty contact would typically experience large penetration with the need to use a high penalty factor to avoid numerical instability. If simulating the flight trajectory is of interest this can involve a long distance and hence be computationally expensive, especially if aerodynamic effects are to be considered.

Trying to apply numerical tools for this application is not a new approach, it was investigated in the past by Randers-Pehrson in 1978 [Randers-Pehrson, 1978] using a 2D model in the HEMP code from Lawrence Livermore National Laboratory (LLNL). The model illustrates some of the problems with very distorted elements in a Lagrangian code, leading to a need for eroding elements and thus loss of mass. The thinning was especially a problem at the outer edge of the Liner. It is discussed that in real examples it could be that the "dropping of elements" should be done 2-3 times during the simulation. This suggestion is what today is widely used in Legacy Solvers and referred to as "Element Erosion", an ad-hoc method that is used to get the numerical model to run to completion. It is also mentioned in [Zukas, 2004]. [Zukas, 1993] an interesting point of view related to modeling this very difficult dynamic event. They point to the fact that the Legacy Codes all have about the same features so any divergence can be attributed to the skill and experience of the engineering analyst. They suggest that a minimum of 6 months to two years of experience of the software is required and an in-depth knowledge of warheads is also required. At the same time the engineer cannot be a junior level due to the lack of knowledge. In their paper they use the ZeuS code, a two-dimensional Finite Element Code. They looked at how the projectile's material parameters and mesh density influence the penetration of a multi-layered steel target. The initial configuration is shown in Figure 1.

They used an already formed EFP for the impact with a simple

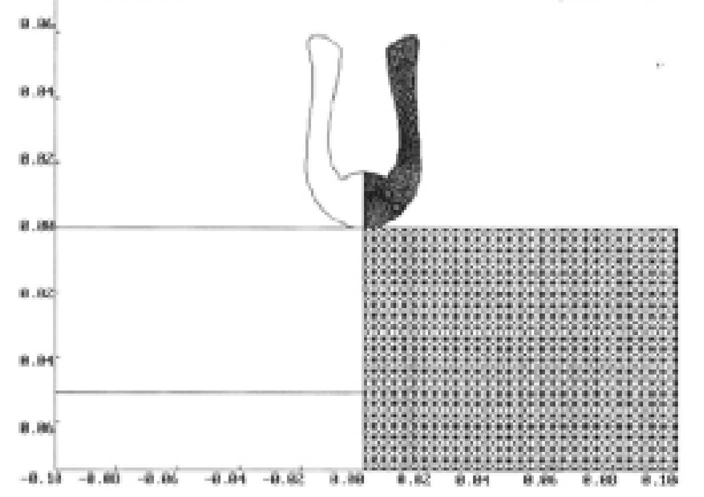

Figure 1: Finite Element model of EFP penetration using the ZeuS code [Zukas, 1993].

Elastic-Perfectly Plastic Model. Applying different strength values for the projectile had very little effect on the hole profile. For a coarser mesh they obtained a v-shaped hole profile that didn't match experimental results, finer meshes were found to have better agreement. It was believed that the coarse mesh could not capture the pressure gradient and had a tendency to pressure lock since triangular elements were used. Mesh generation and element types for simulations of EFPs is also discussed in [Johnson, 2006] where three topics are mentioned as challenges for this type of simulation: contact interfaces, type and arrangement of elements and generation of the mesh. Discussion about contact leads to adding thickness for the slave nodes and for the applied constant stress element they discuss the use of tetrahedron versus hexahedron elements, though for the later they never discussed in detail the many problems with applying hourglass control. As we know hourglassing is a numerical instability that is introduced by using under integrated elements. Controlling hourglassing involves numerical tricks which is difficult to validate unless results are compared with experiments leading to a model which can have limited prediction capabilities. A discussion of a symmetric versus non-symmetric mesh was also presented which was based upon the set-up shown in Figure 2.

Different types of meshes gave very different results,

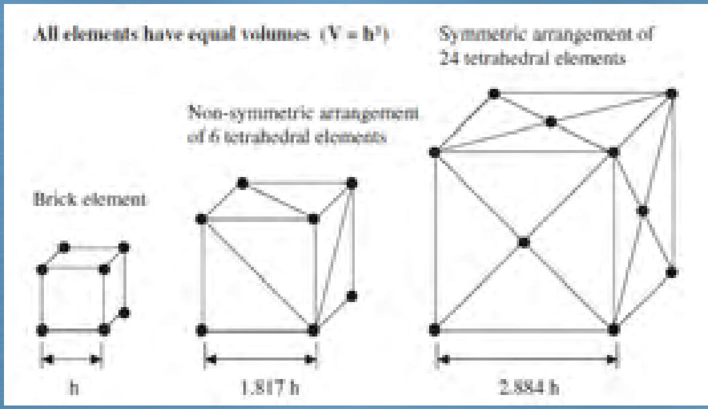

Figure 2: Element types and arrangements [Johnson, 2006].

even some with very strange deformation patterns. It was concluded that a symmetric mesh gave the best results. An example is shown where tetrahedron elements that get highly distorted are automatically converted to particles. It is not explicitly mentioned but the author of this article believes that the EPIC Code has been applied in this research which is a Finite Element Code originally developed back in the mid 1970's at Honeywell.

Many different software packages have been applied to model EFPs as will be mentioned throughout this article and in the earlier research two-dimensional models were used. In [Fong, 1998] both DYNA2D and DYNA3D were applied and it was noted that "3D hydrocode tools are needed for the design process". DYNA2D and DYNA3D are Government Codes developed at Lawrence Livermore National Laboratory starting in 1976.

Yet another Code that has been used to model EFPs is the Eulerian Code CTH developed at Sandia National Laboratories also making it Government controlled software with limited access for industry. In 1992, Hertel [Hertel, 1992] published a Sandia report with four experiments to be compared with CTH, one of them was an EFP experiment, in fact one of the few somewhat detailed experiments available in the open literature. A 2D Axis-symmetric model was used and it was stated that CTH captures the "gross features" of the experiment. It was also mentioned that the simulation is sensitive to small changes in numerical treatment and models. Two other papers have tried to reproduce these results using LS-DYNA® [Van Dorsselar, 2010], [Puryear, 2018] by developing an Axisymmetric ALE model. ALE is Arbitrary Lagrangian Eulerian, see [Belytschko, 2000]. In [Van Dorsselar, 2010] the values for velocity, length and diameter of the EFP was close to the experiment but reviewing the results it appears that the shape seems somewhat off although the authors in [Van Dorsselar, 2010] claim it is "very close". The geometry obtained with CTH at 200 μsec is shown Figure 3, which is a typical shape for this type of EFP.

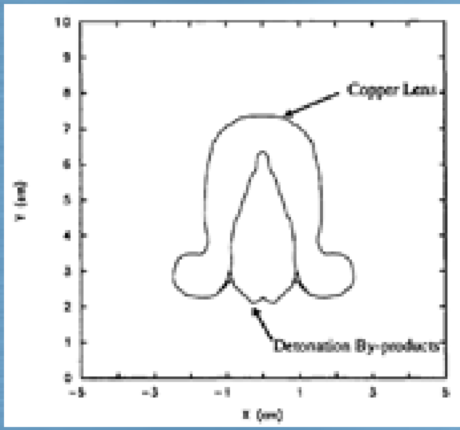

Figure 3: EFP Terminal Shape obtained with CTH [Hertel, 1992].

However, the picture from the experiment is not of high quality so it is somewhat difficult to judge the experimental shape. No real 3D models were developed and it is mentioned that "... sometimes this necessary very small element size is unreachable with a 3D model". Eight years later, Puryear and colleagues repeated the study and they found good agreement between numerical and experimental data for the peak velocity. However, they couldn't reproduce the agreement for the shape of the EFP and noticed that the longer the model continued running, the longer became the projectile indicating that it never stabilized. They show a long list of possible causes for the inconsistency, e.g., Element Size, Geometry, EOS, etc.

Aeroballistic studies are important when developing EFPs and in [Bender, 2001] it was shown how LS-DYNA was used to simulate the formation of the EFP and the TRASTA code applied for aerodynamic analyses. This research used numerical models to design canted finned EFPs leading to stable flight conditions, which is beneficial for impact performance with the target. EFPs can fly a long distance before hitting the target which means that it first forms and then flies in air at stabilization. Distance to target is in [Wu, 2007] 48 meters which is a very long travel to simulate. Thus, they scaled it to a flight distance of 0.5 m using empirical velocity equations and numerically model the 0.5 m flight and impact with LS-DYNA applying ALE in 3D. Results of the experiment in [Wu, 2007] is used by Cardoso et al. in 2016 as a reference verification example for a numerical Base Model that is used for numerical sensitivity studies [Cardoso, 2016]. They verify the velocity profile from their Base Model with the experimental band and study afterwards, element formulation, discretization, Liner material, high explosive, etc. It is never mentioned what software tool is used, only that it is a Finite Element based numerical model but it seems to be Lagrangian. Some the findings are that thickness of the Liner is one of the most important parameters together with the off-center distance of the detonator. It is stated that it is beneficial to have a smaller thickness closer to the center of the Liner since this gives a higher velocity. As seen in Figure 4, interesting and very different shapes are obtained with different numbers and placement of the detonation points, up to five are used.

Figure 4: Very different shapes of the projectiles are seen with variation in location and number of detonation points [Cardoso, 2016].

Number of detonation points was also studied in [Li, 2010] where LS-DYNA was applied with the ALE approach. Seven different configurations were tested with a minimum of three detonation points up to a maximum of 36. Three dimensional models were used with either half or quarter symmetry. Compared to experimental data some differences are seen though nothing is mentioned about classic ALE numerical issues like leaking or problems with advection. Observations are that the number of detonation points influences velocity and length-diameter ratio and that a velocity gradient across the Liner is the main reason for bending of the penetrator. Similar work related to number of detonation points and use of LS-DYNA ALE was done in [Liu, 2013] where two different configurations were modeled, one with 36 and one with 72 points.

Similar to [Cardoso, 2016] the Lagrangian approach was used in [Liu, 2017] to simulate Multiple Explosively Formed Penetrators (MEFPs) and compared with experimental work. Due to symmetry, half a model was used and it should be noted that the HE was deleted after 30 μsec. It is not mentioned why that is the case but it could indicate numerical instability in the HE Lagrangian mesh and a need for deletion to continue the simulation. The MEFP consisted of 7 penetrators and impact pattern for FE and experiments were compared visually. Also considered was the Damage Area which shows the area that is covered by the penetrators. It was found that numerical results showed larger areas than the experiments and it is speculated that the lack of considering air resistance and other external factors in the numerical models are reasons for the differences [Liu, 2017]. Also [Zhao, 2015] applied the Lagrangian approach in LS-DYNA for MEFP modeling using half symmetry as illustrated in Figure 5.

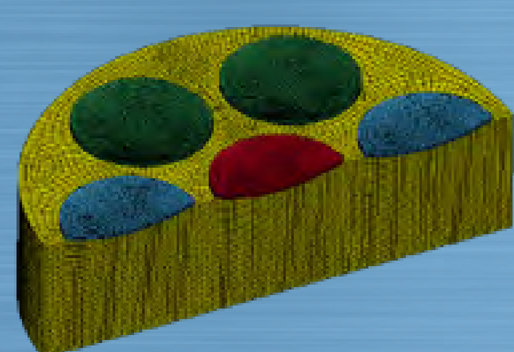

Figure 5: Numerical set-up for a MEFP using only Lagrangian formulation [Zhao-2015].

The paper is only numerical modeling, investigating what influence Liner material will have on shape and velocity of MEFPs, in this case a 7 Liner configuration. Five different Liner materials were tested and it was found that iron and copper were the best material. Furthermore, the simulations show that the density seriously affects the projectile formation. Increasing density leads to a decrease in velocity for all Liners. As in the major parts of all the research mentioned in this article, Zhao et al. used the JWL EOS for the HE and Johnson-Cook constitutive model for the Liner. The latter is often applied when the material experiences high strain rate and thermal effects. Influence of Liner material is studied in [Hussain, 2012] as well where Autodyn 2D is used as the numerical tool to model a single EFP. Different response parameters are shown for the three materials that were investigated but no deformed configurations are illustrated nor were any details provided about the formulation applied, e.g., ALE, SPH etc. SPH is Smoothed Particle Hydrodynamics, see e.g. [Liu, 2003]. Results showed that the internal energy of the EFPs was inversely proportional to the density of the material. Worth mentioning is that the Length over Diameter Ratio could not be reproduced. However, in another paper on the same topic of material for the Liner, Hussain and coworkers mention the use of an Autodyn 2D axisymmetric model using an Eulerian description of the HE and structural parts [Hussain, 2013]. It was shown how the Johnson-Cook constitutive model underestimated the projectile diameter and gave an unrealistic elongated projectile compared with experiments. However, increasing the hardening constant by 10% gave better results though both material models did not match the experimental velocity. This illustrates the sensitivity of material parameters in numerical modelling of EFPs.

So far several approaches and software codes have been presented and the majority chose the ALE approach. In [Castedo, 2018] the Lagrangian method in LS-DYNA was used and pros and cons for different simulation techniques were given. For the Lagrangian approach contact and large element distortion required the need for element erosion. For an ALE approach there were problems with Advection and resizing of a model was needed due to computational time. Finally, SPH is described as being computationally expensive and limited model size. These comments and observations are correct for Legacy Codes, however it is not the case for the IMPETUS Afea Solver®. The higher order Aset™ family of elements can withstand very large deformation and the tetrahedron elements do not suffer from the classic drawbacks as being too stiff and tendency to experience locking. EFPs have been modeled with the Lagrangian approach in IMPETUS, of course with use of limited element eroding at very large deformation. However, it is the author's experience that in modeling EFPs for weapon design very good results can be obtained with the ĐSPH algorithm in IMPETUS ADVANCED. Contrary to the classic SPH formulation, ĐSPH does not have high computational penalty and limitations in number of particles since GPU Technology allows for models with 10s to 100s of millions of particles. Furthermore, ĐSPH is very accurate and the classic tensile instability issue has been solved. In [Jensen, 2019a] examples of modeling EFPs with ĐSPH are showcased and compared with experiments.

Currently CertaSIM, LLC is extending our research into Explosive Reactive Armor combined with the performance of EFPs. This will supplement our successful modeling of EFPs as shown in [Jensen, 2019a] as well as our work on Shaped Charge modeling.
Any questions about the references or the IMPETUS Afea Solver® can be directed to CertaSIM, LLC by contacting support@certasim.com.

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EFPs in the IMPETUS Afea Solver® – Case Studies

Numerical modeling of the Explosive Formed Projectiles is very difficult and requires significant knowledge about the process and use of advanced simulation software. In this article the IMPETUS Afea Solver® has been applied to a verification example from Sandia National Laboratories and very good agreement has been obtained with use of the γSPH algorithm in IMPETUS ADVANCED for this Case Study. An extension of this study to Multiple Explosive Formed Projectiles is done next, taking the geometry and measurements from open literature. Also, in this case, IMPETUS successfully managed to deliver the expected results.

There is limited publicly available experimental data for Explosively Formed Projectiles (EFPs) due to the nature of this application and use thereof. One reference is [Hertel, 1992] where an experiment performed at Sandia National Laboratories is described. This experiment is also investigated numerically with more or less success in [Van Dorsselaer, 2010] and [Puryear, 2018], where 2D models in LS-DYNA® were developed. The experiment is an AISI 4340 steel case with an OFHC copper Liner and around 1 kg LX-14 High Explosive. The set-up for the EFP is shown in Figure 1.
Response Parameters are Terminal Velocity, Length and Diameter of the EFP. A model was developed in the IMPETUS Afea Solver® using the γSPH module (IMPETUS ADVANCED). The parts were created in Trelis with shell elements and at RUNTIME the volumes were filled with γSPH particles. A total of 1 million particles were used which were applied for the High Explosive, the Casing and the Liner. The initial IMPETUS model is shown in Figure 2.

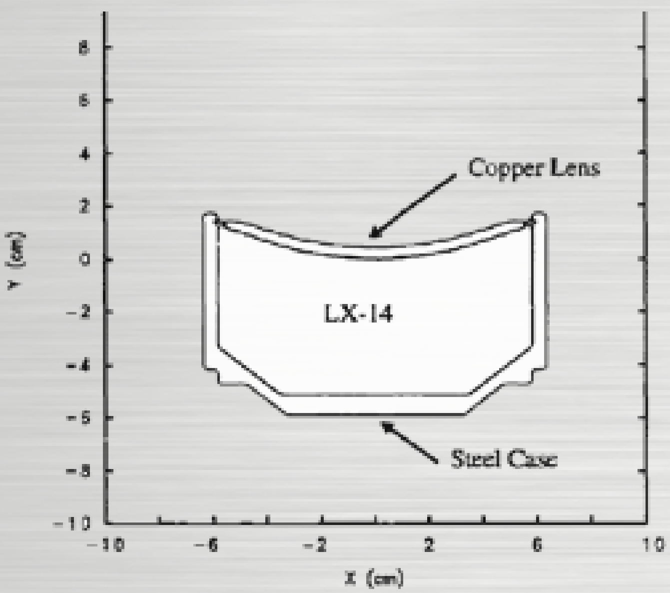

Figure 1: Set-up for EFP experiment [Hertel, 1992].

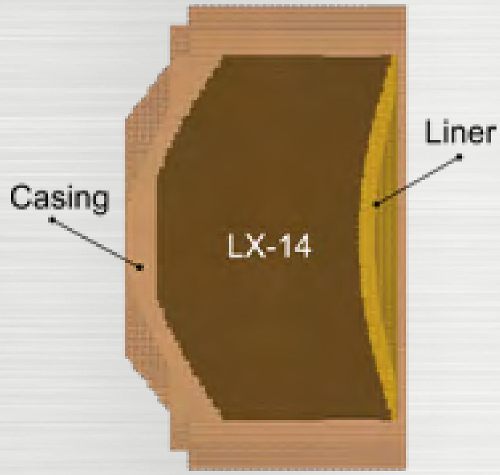

Figure 2: The initial set-up in IMPETUS ADVANCED using γSPH particles for all components of the EFP. Only half model is shown.

The model ran successfully to normal termination on a NVIDIA RTX 8000 GPU with a computational time of 16 minutes, illustrating the computational advantages of the GPU processing for particle based methods. In [Hertel, 1992] 200 μsec was used as the simulation time, which is also applied here, though it is believed that it could have been shorter, especially when looking at the velocity curve and observing the stabilization zone. Simulation results of the EFP forming phase is seen in Figure 3.


Figure 3: IMPETUS Results: Development of the EFP's forming phase. Half model shown to increase visibility.

As mentioned earlier Hertel lists the EFP length of 5.46 cm as one of the experimental findings. The IMPETUS model computed the length as 5.49 cm which matched the experimental results. The paper also lists the diameter of the EFP to be 4.95 cm but never mentions where that is measured. As Figure 4 reveals the EFP is not uniformly cylindrical but if one studies the results in Hertel it seems as the diameter value is taken at the bottom of the EFP, the flattened end. Even when looking at this one may wonder where to measure the diameter, in fact it is a range. The IMPETUS approximate average is around 5 cm so definitely the shape is matched.

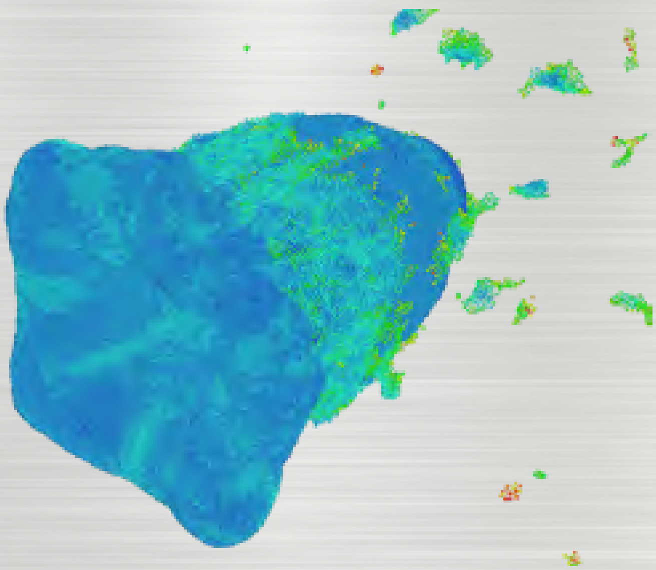

Figure 4: The simulated EFP is not homogenous, the shape is so unique that the diameter can't be determined.

Matching the shape is also verified by comparing the IMPETUS projectile with X-rays from experiments. This is shown in Figure 5.

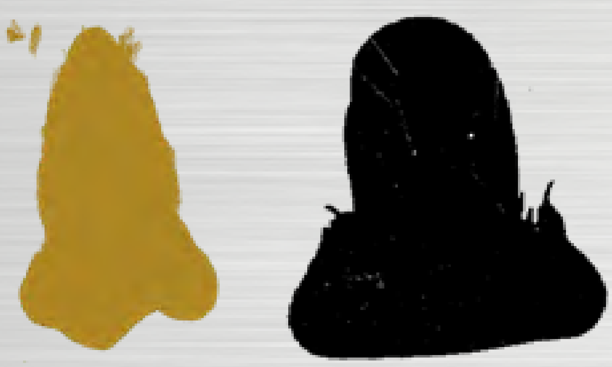

Figure 5: The simulated EFP (left) matches the shape seen in experiments (right) [Hertel, 1992].

As a last response parameter consider the Terminal Velocity which was found to be 2280 m/s [Hertel, 1992]. IMPETUS found this to be approximately 2142 m/s which is only a 6% difference and thus in very good agreement. The development of the rigid body velocity of the EFP is plotted in Figure 6 together with the experimental results.

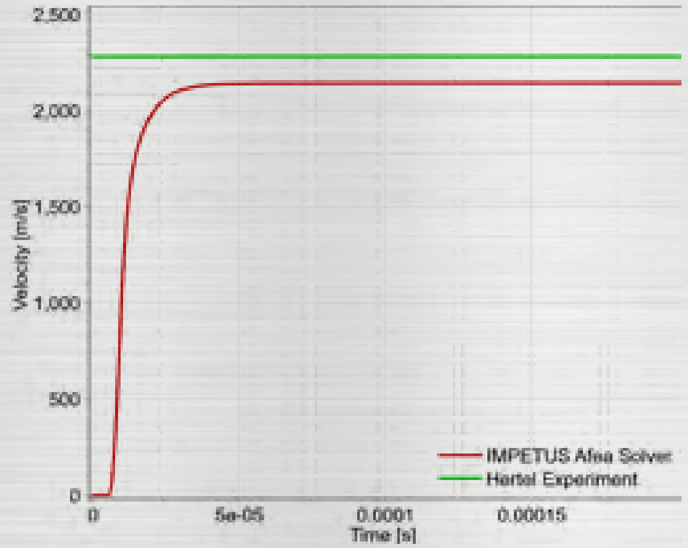

Figure 6: Rigid body velocity of the simulated EFP compared with the experimentally obtained velocity, showing very good correlation.

It has been described how the γSPH Solver in IMPETUS ADVANCED was successfully applied to match experiments obtained for Explosively Formed Projectiles. Response Parameters considered were overall shape, length, diameter and Terminal Velocity. This is especially impressive as no tuning of parameters was done in the simulations. Because increasing the particle resolution is easy, just changing one parameter in the input command file, the accuracy of the model can be improved even more.

Matching the experimental data gives confidence in modeling of EFPs using IMPETUS and thus numerical test cases can be developed to study the behavior of different scenarios involving this type of weapon. As mentioned in [Jensen, 2019] Multiple Explosively Formed Penetrations (MEFPs) can be seen as a collection of EFPs which results in a large Damage Impact Area. A numerical model has been developed in IMPETUS ADVANCED to see how this can be modeled. Geometry and measurements are taken from [Liu, 2017]. Figure 7 shows the experimental set-up and the IMPETUS Model.

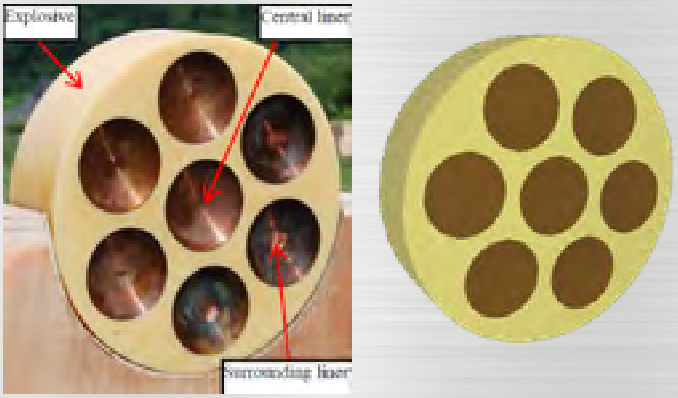

Figure 7: Experimental [Liu, 2017] and Numerical set-up of the MEFP. This is a seven Liner weapon based on a simple design.

It is seen that the MEFP consists of seven Liners that are integrated into a cylindrical charge. Detonation point is located on the backside. IMPETUS used a termination time of 20 msec which was enough time for forming of the projectiles. The shapes of the EFPs at termination time is illustrated in Figure 8. It should also be mentioned that there were no numerical problems running this model, even with the very large deformation that occurs in the process. An NVIDIA RTX 8000 GPU was also used for this simulation resulting in approximately a 25 minutes runtime for 2.5 million γSPH particles. All parts of the model are represented by γSPH particles.

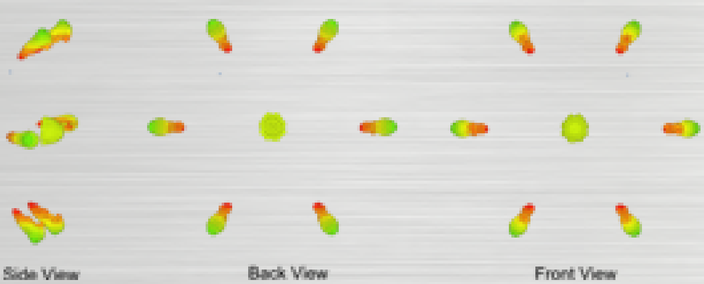

Figure 8: Deformation of the seven Liners at the termination time (IMPETUS model).

Formation of the projectiles are visually very similar to experimental pictures in [Liu, 2017] but details are missing in the paper to directly compare the results. [Liu, 2017] also shows that the center Liner has a slightly higher velocity than the surrounding projectiles which have very similar velocities. The IMPETUS model reflects exactly that as well when the rigid body velocity profiles are plotted. It is the hope of the author that in the near future it will be possible to obtain reliable experimental data to be used as an additional public verification example.

Two Case Studies have been described, one with a single EFP where experimental data matched and hence the IMPETUS Afea Solver® is verified for this type of application. Secondly, a MEFP test case was developed showing that IMPETUS indeed can handle this test case. Both models ran extremely fast utilizing GPU Technology and once again showcased the speed and robustness of the γSPH algorithm. This research work also illustrated the ease of use when applying IMPETUS ADVANCED for complex events.

The models presented are available from CertaSIM, LLC by contacting support@certasim.com.

Acknowledgement:
The help developing the model in γSPH from Dr. Jérôme Limido and Dr. Anthony Collé, both IMPETUS Afea SAS, France is greatly appreciated.

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Dr. Mulligan is Assistant Research Professor at Missouri University of Science and Technology, Rolla, Missouri, USA. His research is mainly focused on Explosives Engineering for the mining industry and military applications. We are pleased to present this discussion by Dr. Mulligan regarding "Experimental and Numerical Investigation of the Performance of EFPs"

The Explosively Formed Projectile (EFP) is a unique device that utilizes the energy of a chemical explosion to shape a metal liner into a projectile and simultaneously accelerate the projectile. This process is known as the Misznay-Schardin effect. Other devices that utilize the Misznay-Schardin effect are the well-known claymore mine and conical-shaped charge (CSC). There are currently many EFP designs. The basic concept for each is the same, in that the detonation wave inverts a flyer plate into a solid projectile, see Fig 1. However, the overall performance differs slightly with different designs. Some EFP designs are rather complicated, capable of spinning the projectile and producing fins on the projectile. Others use devices inside the EFP known as "wave shapers," where a device placed into the explosive, manipulates the detonation wave, thereby causing a projectile not obtainable with cylindrical charge.

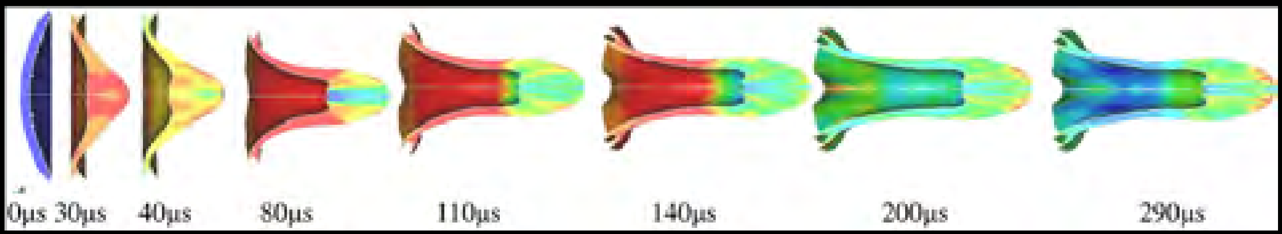


Figure 1: The Transformation of the Flyer Plate (0µs) to the Explosively Formed Projectile (290 µs) [1].

When an explosive is detonated (the chemical reaction is occurring at supersonic speeds) the rapid chemical reaction results in the generation of large quantities of gaseous by-products. The speed of the reaction is such that it can assume to be instantaneous [1]. The rapid production of gaseous by-products is known as Chapman Jouguet (CJ) pressure or detonation pressure and commonly results in pressures in the Gigapascals (GPa). For example C4 has a detonation pressure of 30 GPa [2]. Doubling the distance from the point of chemical reaction results in a quarter of the pressure.

With the metal plate in intimate contact with the explosive, the high detonation pressure and instantaneous loading cause the material to flow and deform as if it were in a fluid-like state. It is the fluid-like state that enables the projectile to form, rather than spall and fail under the dynamic loading condition. Note most EFP designs use a high ductile material for the metal plate, also known as the flyer plate, and there are conditions and other design parameters that influence the projectile shape and velocity.

Modeling and simulation coupled with experimental testing at Missouri University of Science and Technology (Missouri S&T), illustrates the deformation process and some of the challenges that accompany modeling the projectile formation. The testing was carried out at one of three explosive research sites at Missouri S&T. The EFP shown in Fig 2 was collected using a soft recovery catch system of four incremental density increases from polystyrene to water.

Figure 2: The original flyer plate geometry (a), the projectile from an EFP (b) and the cross-section highlighting the material deformation (c).

The process involves very large deformation, which presents a challenge when attempting to examine an EFP's performance via modeling and simulation with high-fidelity computational physics solvers. When using Eulerian solvers the material deformation can be recognized, but the material loses strength late in time resulting in unrealistic elongation of the projectile. Lagrangian solvers present a different challenge in that most elements are limited on the deformation before the element either fails, skews and significantly increases computation time, or the node locking occurs preventing the element from further deformation. Figure 3 highlights how node locking prevented the material from flowing, resulting in a geometry that does not equal the empirical testing.

Figure 3: Predicted projectile geometry from a high-fidelity computational physics solver (a) compared to the recovered projectile geometry from empirical testing (b) of identical EFP designs.

Persons who are skilled with a given solver can overcome most of the challenges associated with modeling EFP formation by turning the proverbial "nobs and dials" of the Solver. However, as the "nobs and dials" are turned in the setup process to capture the EFP formation the method becomes highly specific to a given design and may not be representative of other EFP design variants. Some of the "nobs and dials" that can be tweaked to improve the predictive capabilities of a model include but are not limited to: adjusting the material model and equation of state, meshing schemas, element failure and deletion criteria, and re-meshing. Figure 4 illustrates a meshing schema that utilizes gradient elements, placing larger elements in the center of the flyer plate and smaller elements near the edges. Additionally, gradient elements are placed through the thickness of the flyer plate to allow for greater deformation of the element before node locking occurred. The gradient meshing schema enabled the material to flow to a greater extent than uniform elements, but the projectile formation was eventually inhibited by node locking.

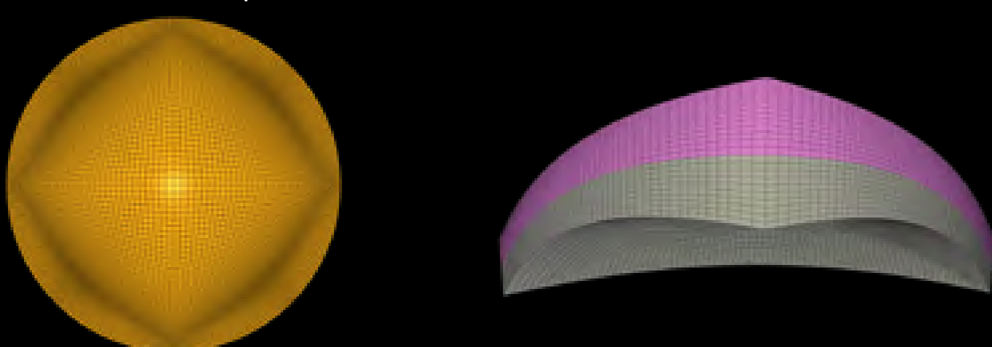


Figure 4: Gradient meshing schemas showing a gradient mesh from the center of the flyer plate (a) and a gradient mesh through the thickness (b) both have an average element size of 0.6 mm.

Advanced Element Technology, Aset™ is a feature of the IMPETUS Afea Solver® that has been identified to work well for modeling high deformation formation of a projectile, while maintaining accuracy across different EFP design variants. With high order cubic element (Aset™) offered in IMPETUS, 64 nodes are used to capture the high deformation of a single element without minimizing the element failures due to deformation and node locking. The use of Aset™ in IMPETUS has enabled Missouri S&T to explore EFP design variants for ongoing projects, as well as other projects that utilize explosively driven material flow. In addition to these features the γSPH, an advanced Smooth Particle Hydrodynamics Module, can be used to model Hypervelociγty events as e.g. Shape Charges which also are experimentally done at Missouri S&T. The γSPH formulation has the benefit of a very accurate pressure field, no tensile instability and is very computational fast compared with classic SPH.

References:

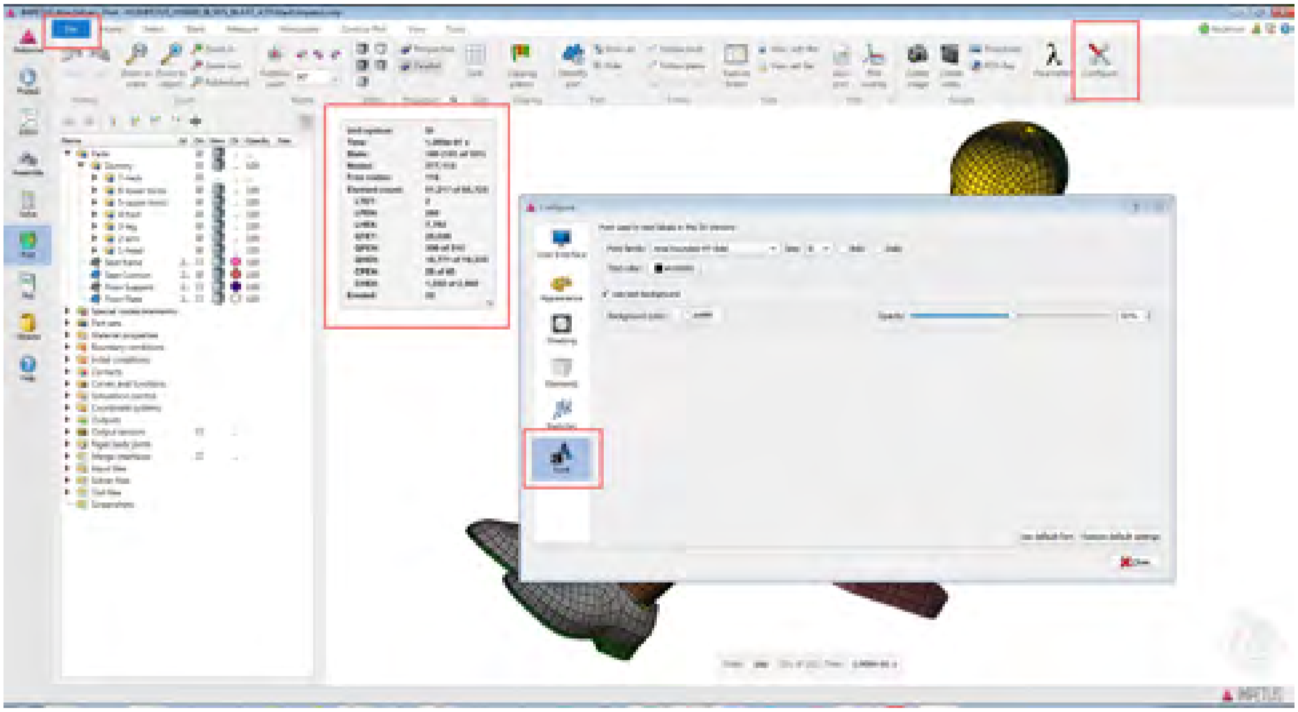
[1] J. Wu et al., "Experimental and Numerical Study on the Flight and Penetration Properties of Explosively-Formed Projectile", International Journal of Impact Engineering (34), pp. 1147-1162, 2007.

[2] P. W. Cooper, "Explosives Engineering", Wiley-VCH, 1996, p. 387, ISBN-13: 978-0471186366.

New Features in the IMPETUS Afea Solver GUI

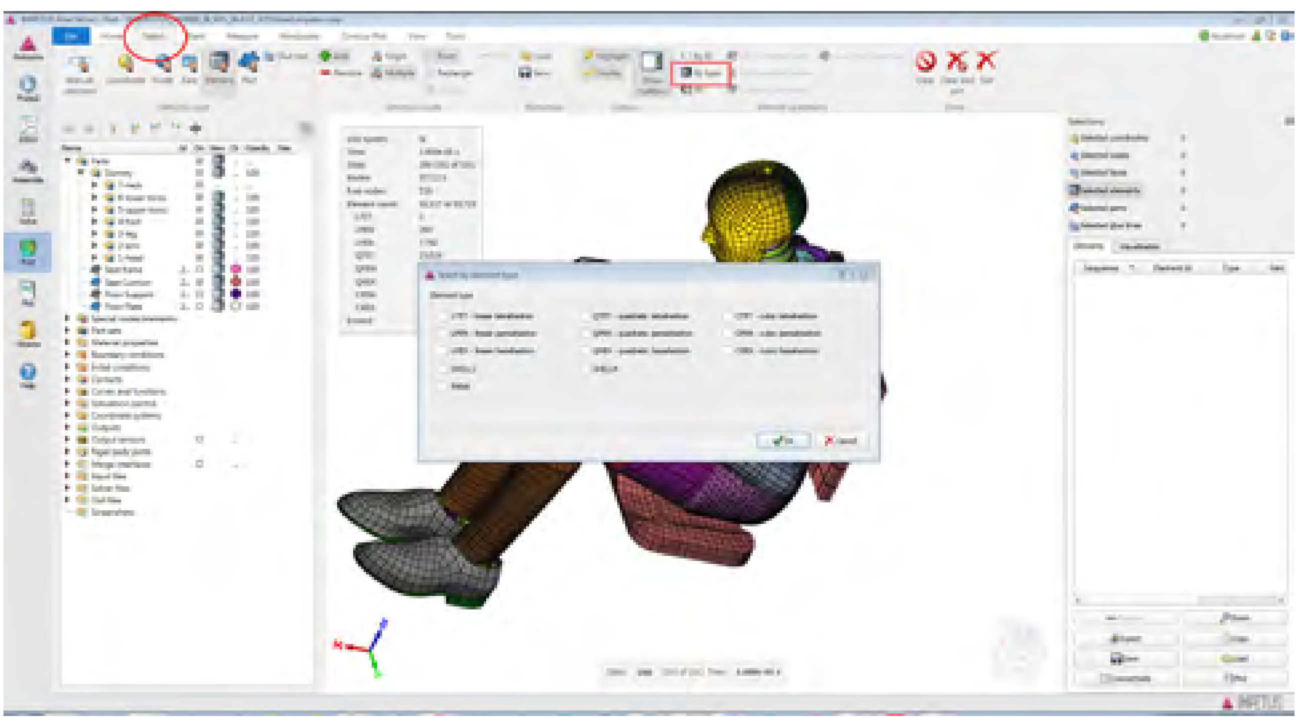
Change Font used in Information Textbox.

It is now possible to change the font for the textbox located in the 3D graphic Window. Many different fonts are available. The feature is found from the File tab – Configure – Font.

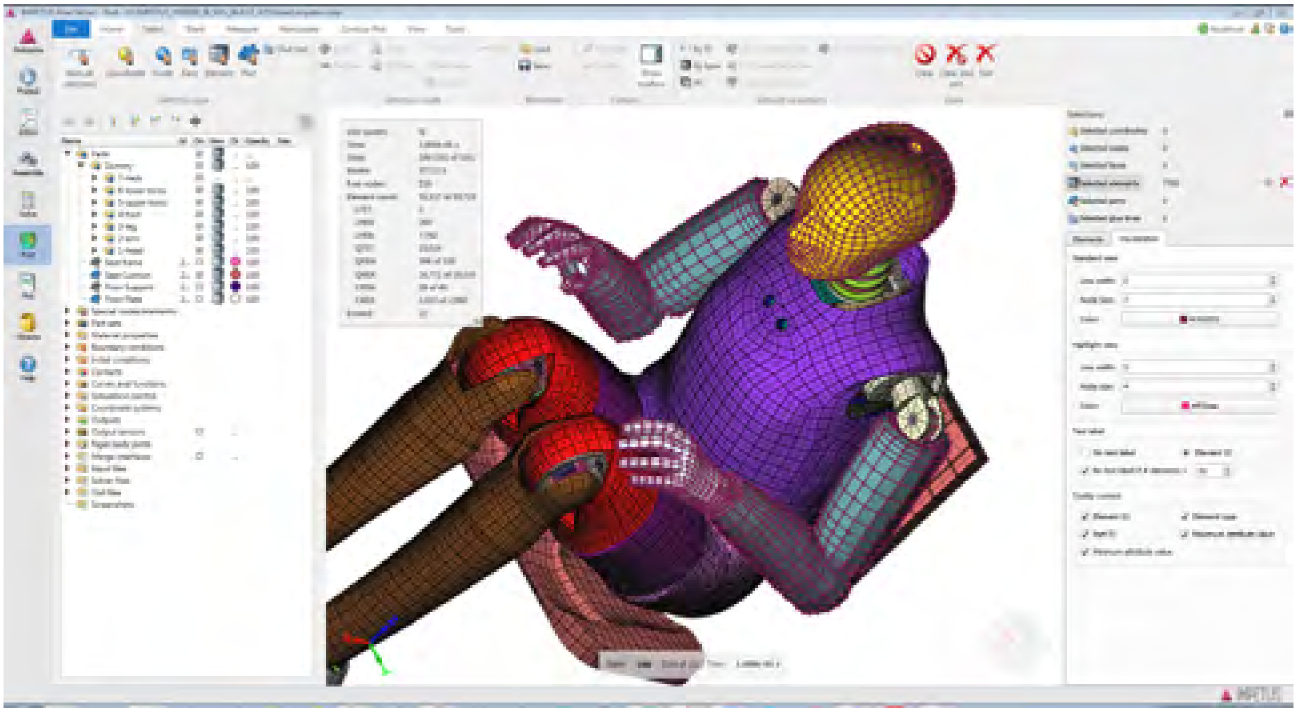


Select Element by Type.

Many models use a mix of element types some parts are linear hexahedron, others are cubic or quadratic as well as tetrahedron. In later versions of the IMPETUS Afea Solver GUI one can now select elements based on the type of element so only these are selected. This can be done using File – Select – By type. A selection box will appear where the type of element can be checked.



After the selection, the requested element types are highlighted as normally done when using the Select option.



Toggle on/off Coordinate System, Information Textbox and Orientation Cube.

Sometimes it is beneficial to just have the graphic in the 3D Graphical window and thus not showing the Information Textbox nor Coordinate System or Orientation Cube. This is useful if for example, a screen dump is to be used without access to the features in the normal image interface. This is controlled under File – View.