Analysis of Contact Stresses in High Speed Sheet Metal Forming Processes

R. Ibrahim[1], S. Golovashchenko[2], A. Mamutov[1], J. Bonnen[2], A. Gillard[2], L. Smith[1]

Oakland University, Rochester, USA
Ford Research & Advanced Engineering, Dearborn, USA

April 24th – 26th, 2012 in Dortmund, Germany

Outline

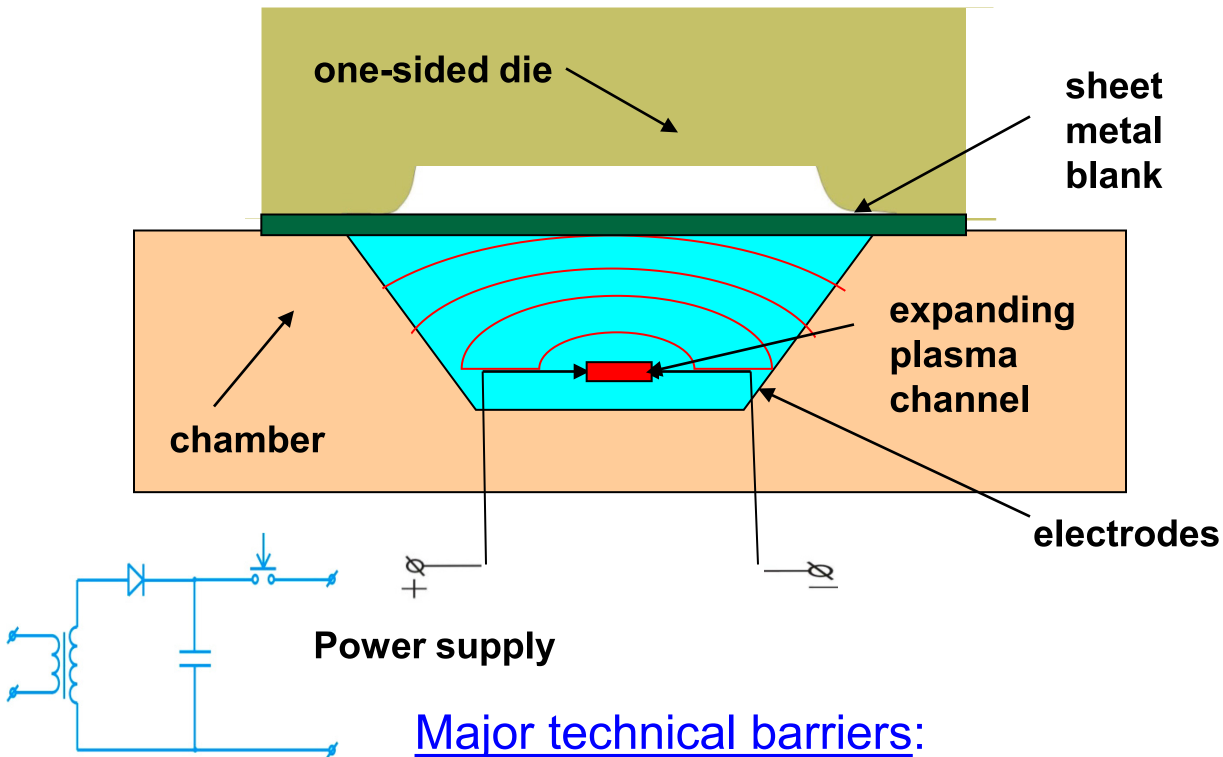
- Introduction
- Problem Statement
- Limiting Stress in High Rate Forming Impact
- Impact Stress values in FEA simulations
- Conclusion

Electrohydraulic Forming

Technology:

High voltage discharge of capacitors through a pair of electrodes in a liquid filled chamber creates a plasma channel.

Quick expansion of high temp. plasma channel creates a shockwave which propagates through the liquid and causes the blank to be deformed into a one-sided die cavity.



Advantages of EHF:

- Increased formability at room temperatures;
- Minimized springback;
- Low cost one-sided die;
- Adjustable pressure distribution; requires smaller presses;
- Operations can be combined.

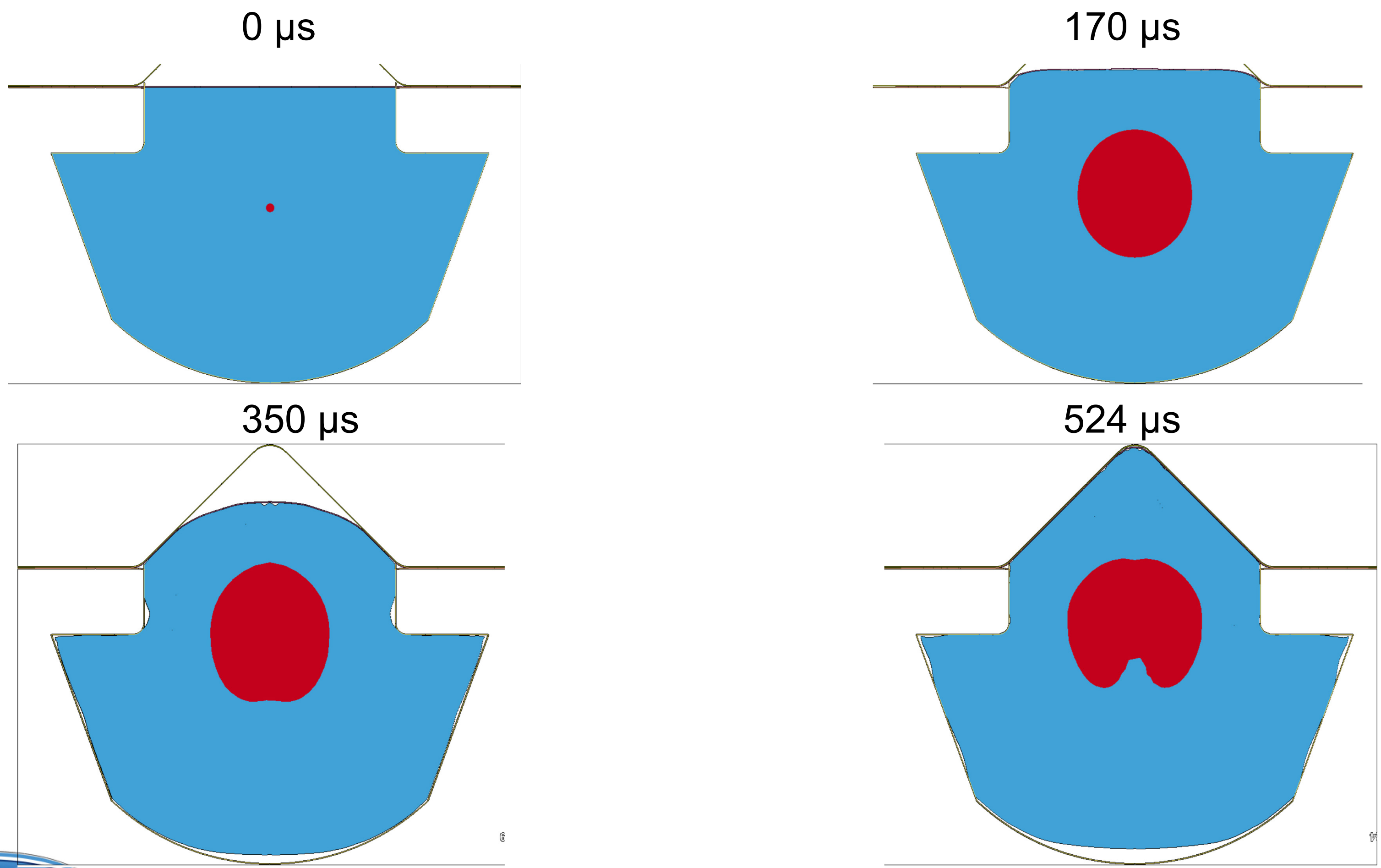
Major technical barriers:

- Lack of design methodology;
- Various die failure modes, reduced durability;
- Low electrode durability;
- Long cycle time;
- Lack of commercially available equipment;
- Previously used only for small parts.

Simulation of EHF forming process into 45º conical die

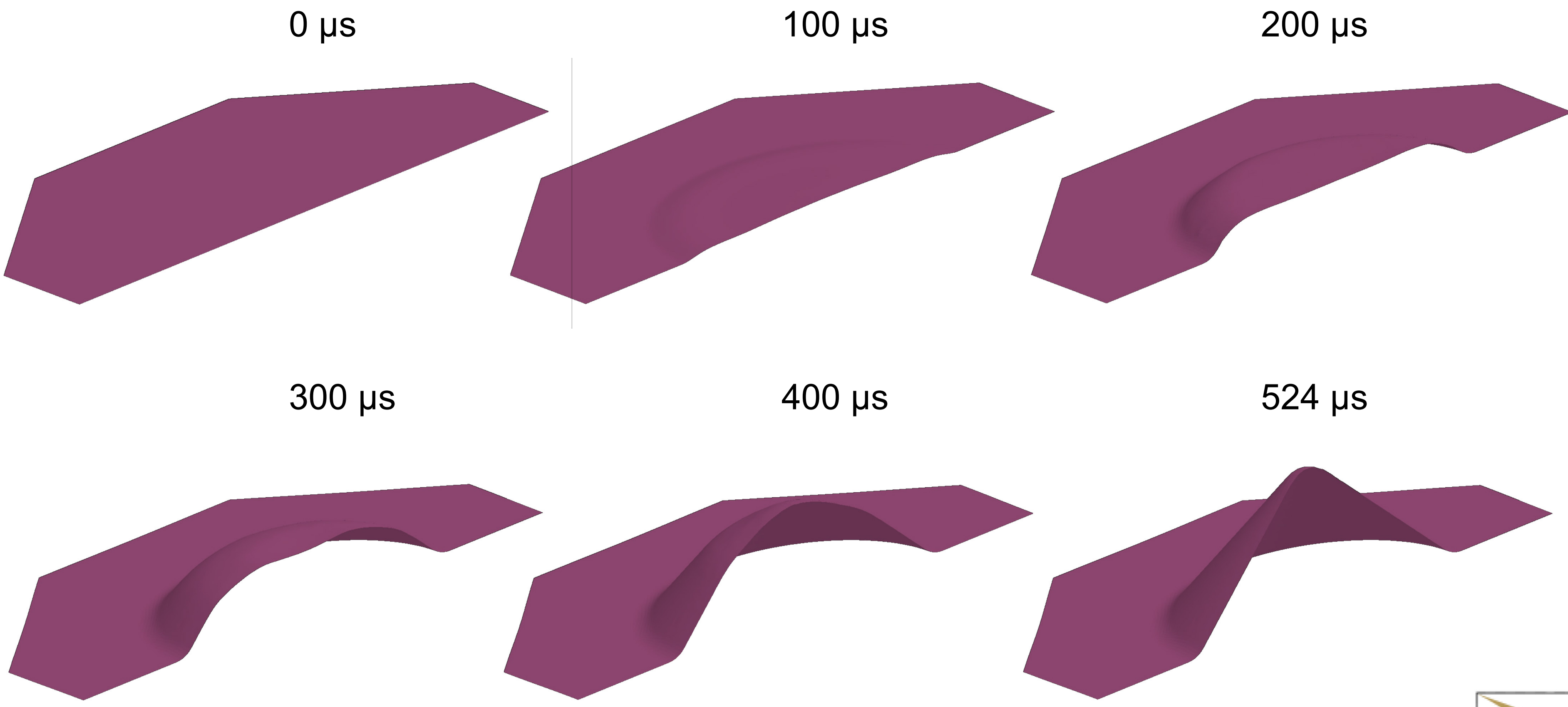
T_0 = 55 µs, N_0 =1.8*10^8 W

Plasma cavity expansion and blank deformation



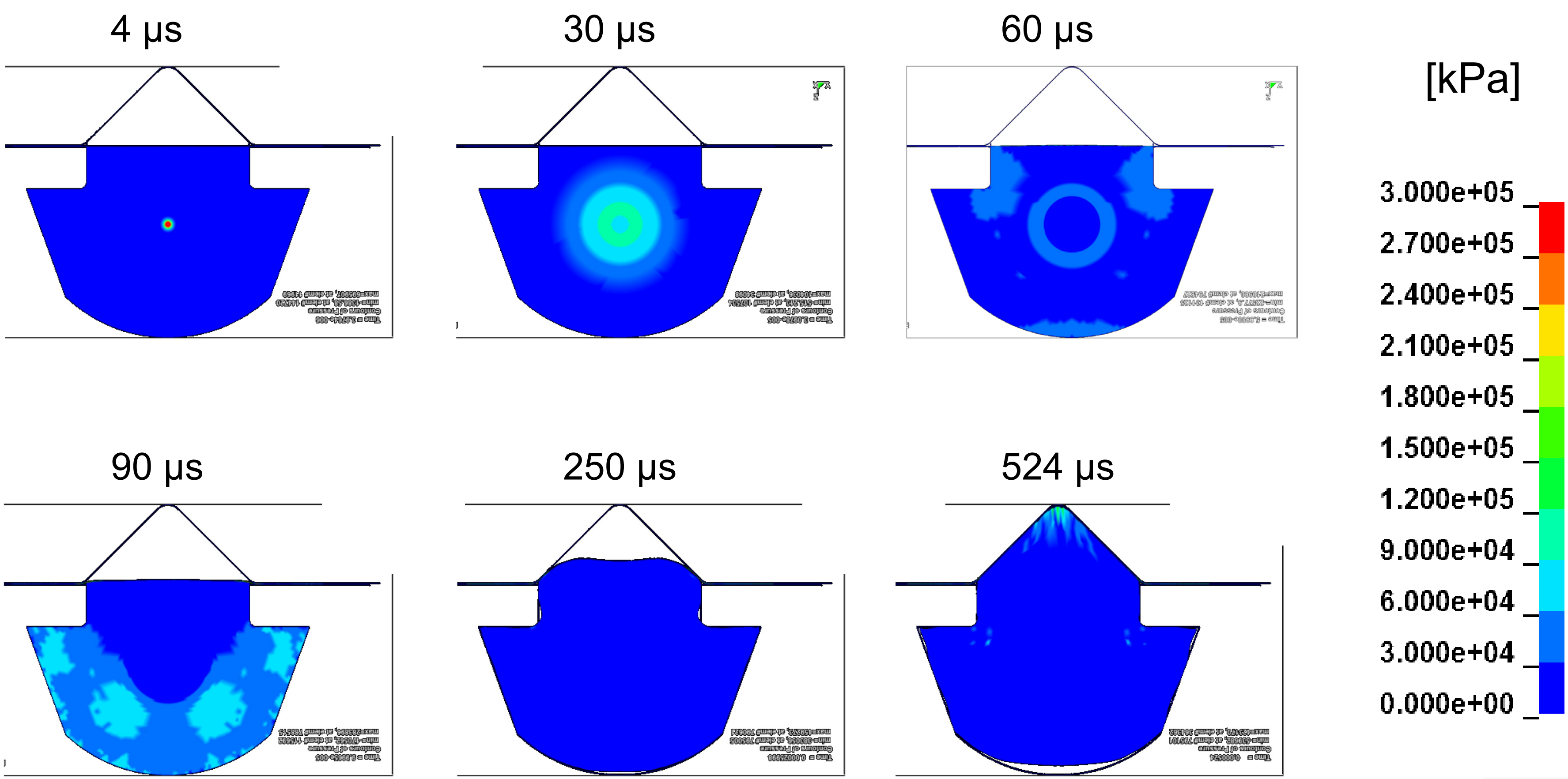
Simulation of EHF forming process into 45º conical die

Blank deformation



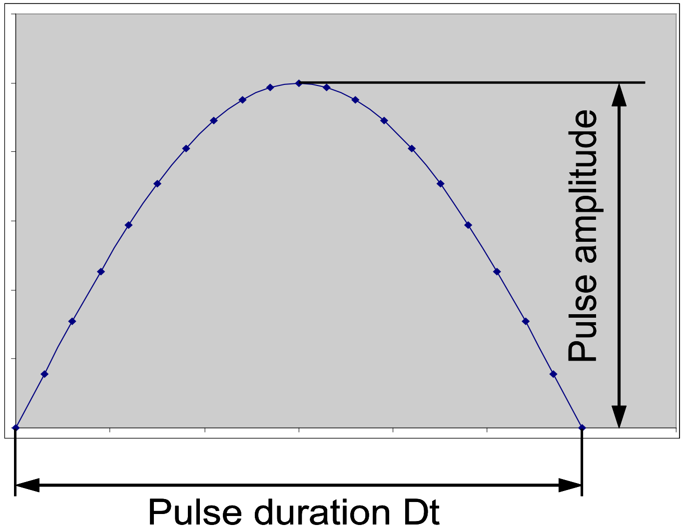
Simulation of EHF forming process into 45º conical die

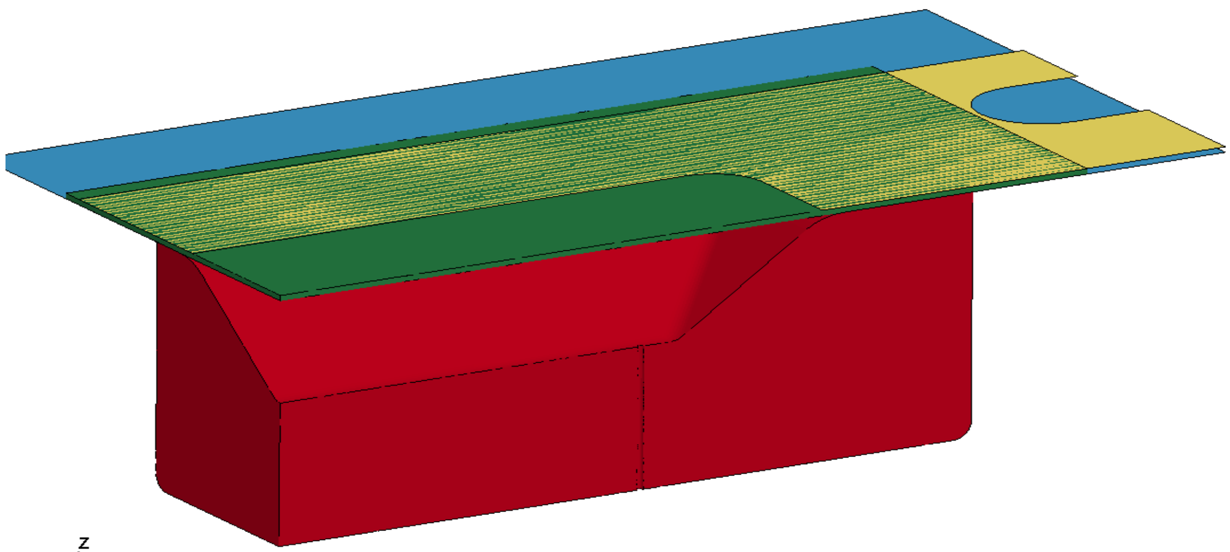
Pressure distribution



Simplified FEA model of EHF

- EHF pulse was modeled by pressure applied to exposed elements of the blank.
- The pressure variation in time was assumed a form of a half of the sine wave
- All other components of the process, such as chamber walls, water, plasma channel, electrodes and their interactions were not included in the simulation.

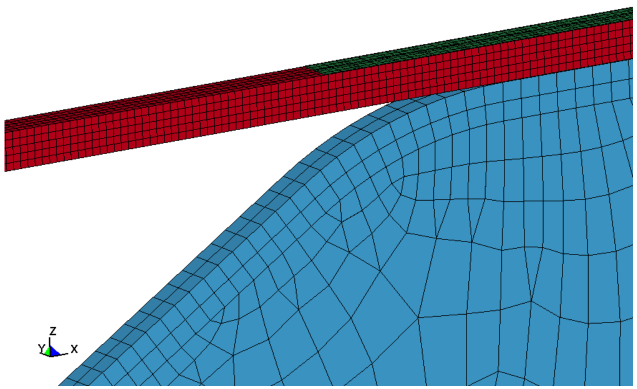


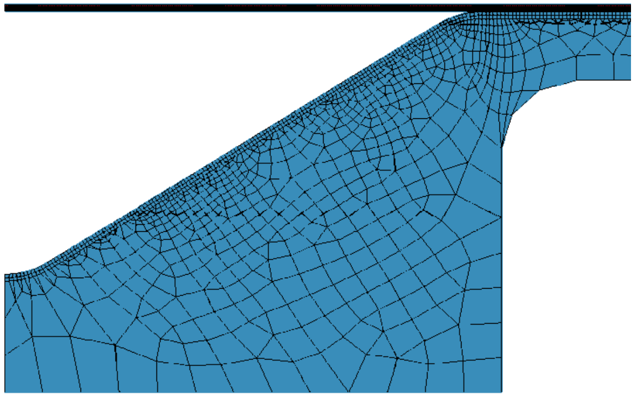


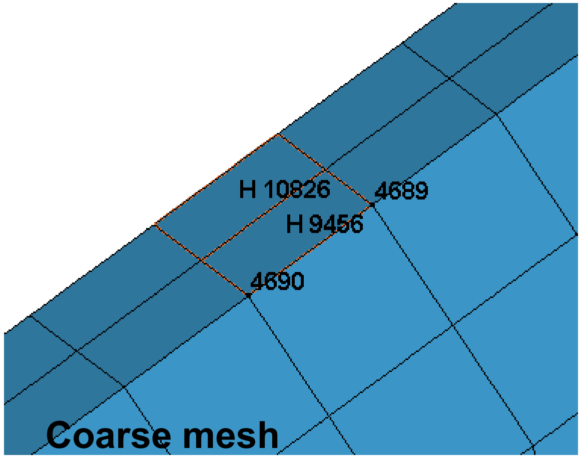
Coarse vs. Fine Mesh

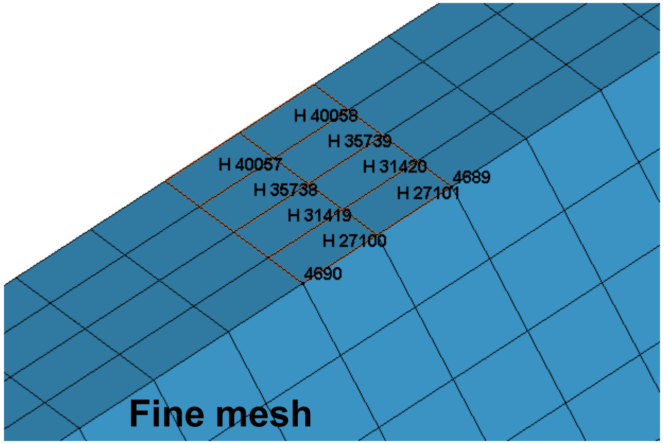
Contact Pressure MPa

blank mesh - die mesh	penopt				Constraint Contact
	1	2	3	4	
coarse - coarse	497	487	520	485	475
coarse - fine	817	813	839	811	816
fine - coarse	494	488	495	488	476
fine - fine	828	838	859	839	803



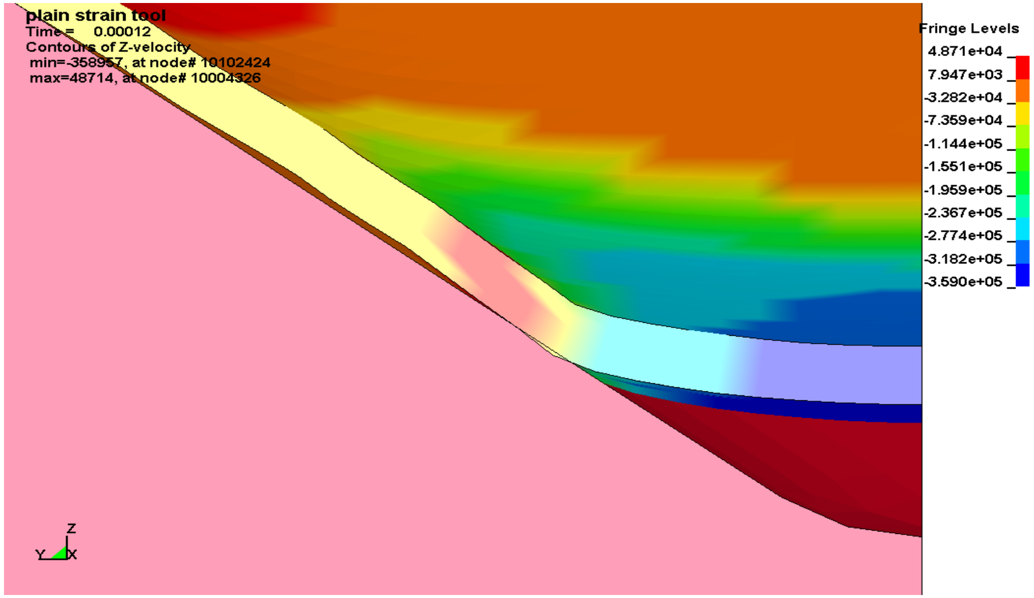




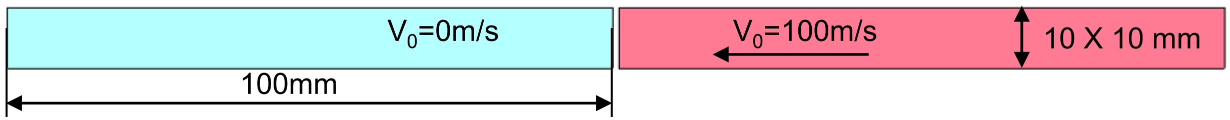


Stress value is Mesh dependent V-die

- Large penetrations in the bottom of the die were observed in this simulation regardless of the contact settings.
- Unphysical stress of 8000 MPa observed close to the corner



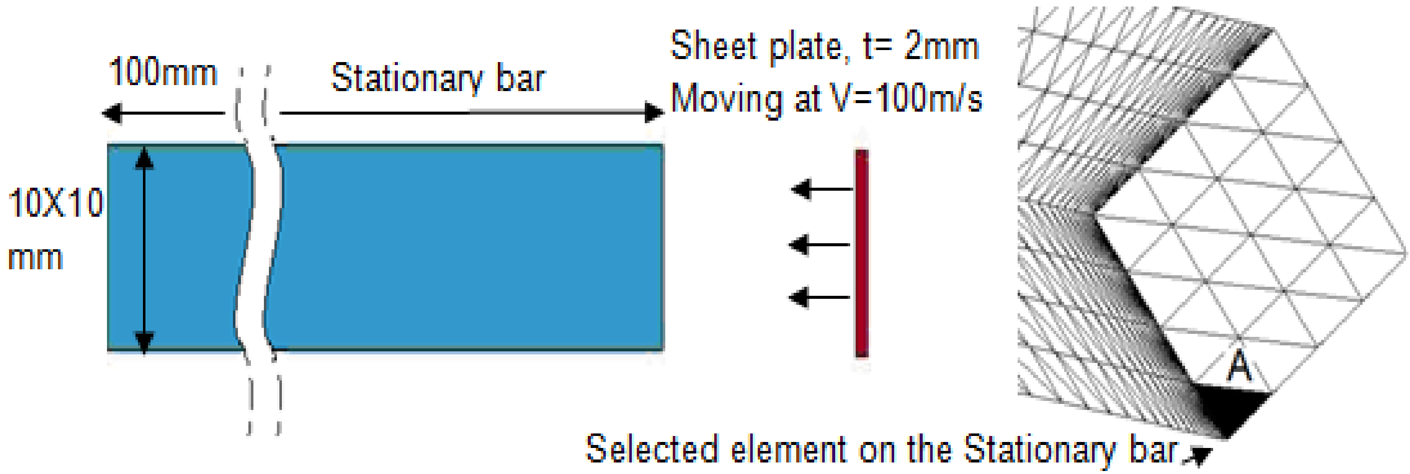
Elastic bar to bar Impact



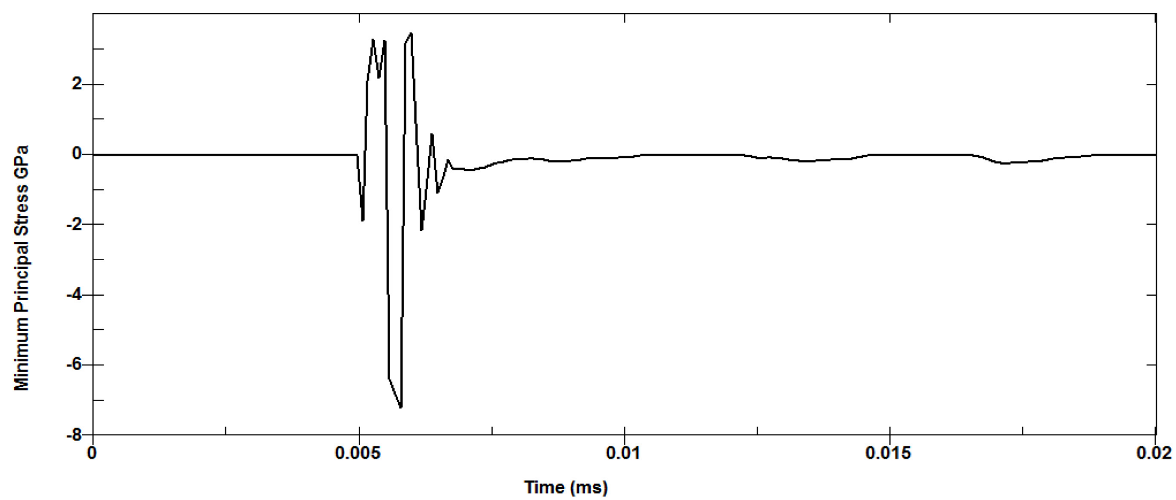
$$\sigma = \frac{\rho c v}{2} = 1975\ MPa \sim 2000\ MPa$$

mesh	V, m/s	Contact type (soft)	Stiffness scale factor (slsfac)	Max penetration depth, mm	coarse side			fine side		
					Min Z-stress, MPa	Avg Z-stress, MPa	Max Z-stress, MPa	Min Z-stress, MPa	Avg Z-stress, MPa	Max Z-stress, MPa
2.5mm brick - 2.5mm brick	100	0	0.01	2.19	-3465	-1203	-217			
2.5mm brick - 2.5mm brick	100	0	0.1	0.5	-5064	-1704	-358			
2.5mm brick - 2.5mm brick	100	0	0.5	unstable						
2.5mm brick - 1mm brick	100	0	0.1	unstable						
2.5mm tetra - 1mm tetra	100	0	0.1	unstable						
1mm brick - 1mm brick	100	0	0.1	0.17	-4230	-2010	-192			
2.5mm brick - 2.5mm brick	100	1	0.1	0.82	-5237	-1961	-299			
2.5mm brick - 2.5mm brick	100	2	0.01	2.05	-2262	-1393	-186			
2.5mm brick - 2.5mm brick	100	2	0.1	0.49	-3243	-1979	-859			
2.5mm brick - 2.5mm brick	100	2	0.2	0.38	-4789	-3674	-2521			
2.5mm brick - 2.5mm brick	100	2	0.5	unstable						
2.5mm brick - 1mm brick	100	2	0.1	0.13	-2716	-2057	-1436	-2931	-2026	-987
2.5mm tetra - 1mm tetra	100	2	0.1	0.06	-2776	-2044	-1472	-3444	-2062	-886
1mm brick - 1mm brick	100	2	0.1	0.24	-4336	-2386	-1051			
2.5mm brick - 2mm brick	100	2	0.1	0.17	-2630	-2073	-1514	-2530	-2030	-1473
2.5mm tetra - 2mm brick	100	2	0.1	0.47	-3369	-2016	-1471	-2922	-2017	-1080
2.5mm tetra - 2mm tetra	100	2	0.1	0.11	-3052	-2020	-1422	-2811	-2025	-1261
2.5mm tetra - 2mm tetra	10	2	0.1	0.01	-296	-202	-157	-270	-202	-138
1mm tetra - 0.33mm tetra	100	2	0.1	0.037	-3292	-2155	-1832	-4400	-2000	-950

Limiting Stress in High Rate Forming Impact

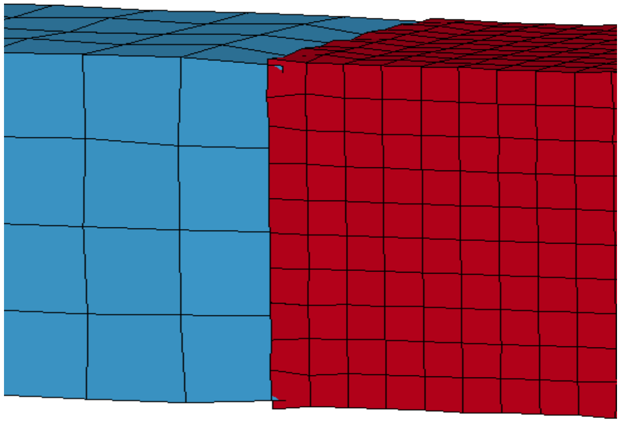


Unphysical peak in contact pressure in element A of the impacted bar

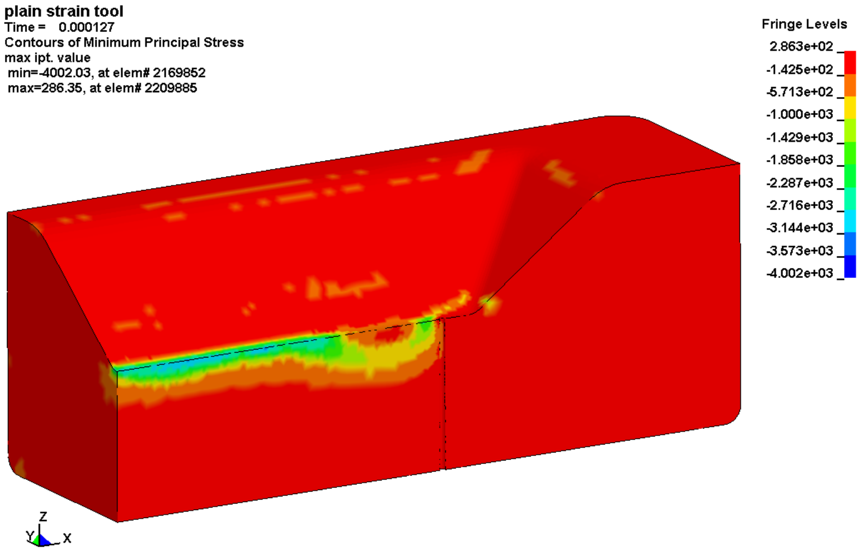


Determination of Correct Impact Stresses

- Incorrect reported values cannot be carried over for further design steps.
- User must be sure to use an appropriate mesh that should provide converging solution.
- Appropriate artificial viscosity should be selected to avoid damping the solution and artificial ringing.



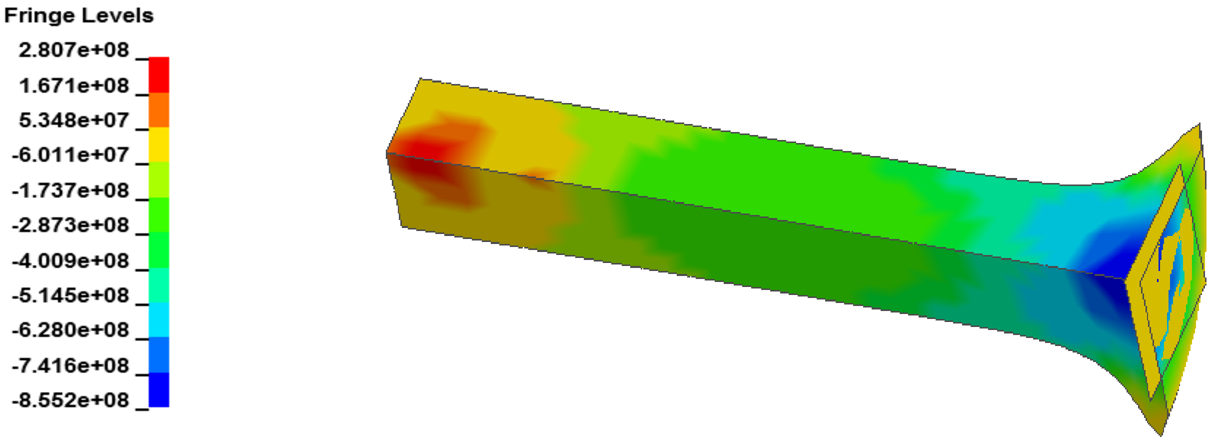
- In dynamic calculations, the location of the stress or pressure gradient is a function of time as well as the space.
- In many instances wave propagation and their reflection from material interfaces and geometric boundaries control the response.



Modelling of Dynamic Problems

Two important factors:

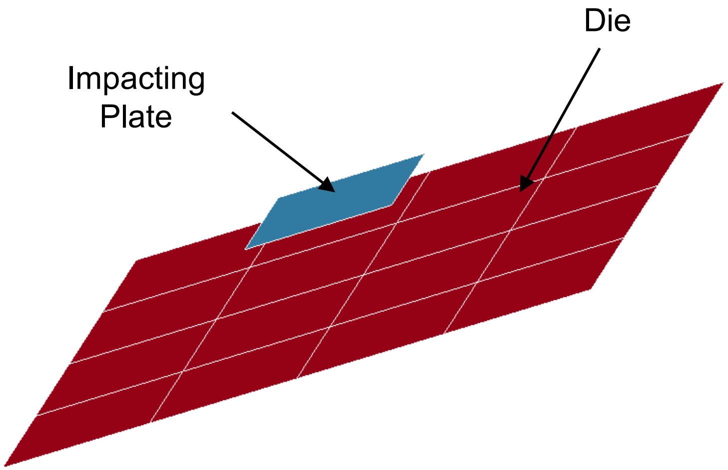
- The rate at which the observed phenomenon changes;
- The fact that information is propagated at a finite speed



- Waves in rods and rod-like structures have been considered to create a state of uniaxial stress.
- In this configuration, however it is impossible to reach very high tri-axiality stress states. With velocity increases, 2D and 3D effects begin to dominate the rod deformation. Plasticity and material failure govern the magnitude of the stress the rod can carry.

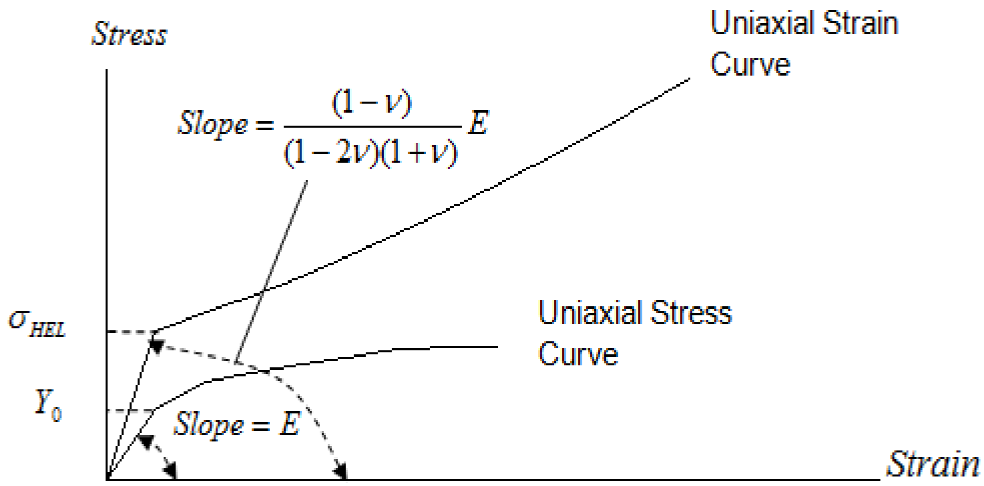
Modelling of Dynamic Problems

- To examine other possible states of die material in pulsed forming conditions, we need to achieve higher level of stresses using a thin plate, known as the flyer striking a thicker plate.
- Until the reflecting waves from the lateral boundary return to the centre, a state of uniaxial strain (but 3D stress) will exist.



Shock Waves in Solids

- Uniaxial strain state can be visualized where the deformation is restricted to one dimension such as in the case of plane waves propagating through a material dimensions, and constraints are such that the lateral strains are equal to zero



Shock Waves in Solids-Analysis

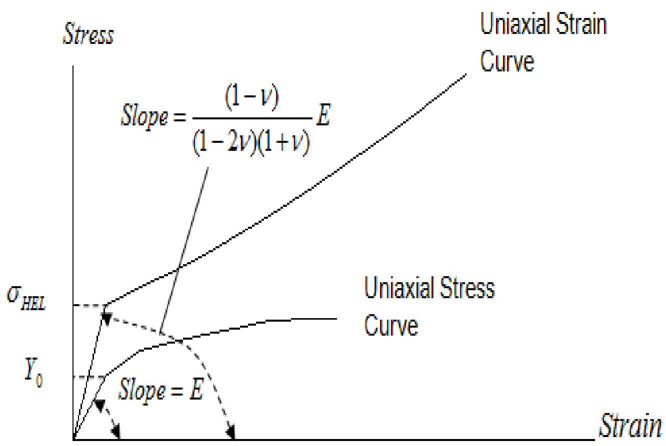
In the uniaxial strain loading the following expression can be obtained for σ_1

$$\sigma_1 = \frac{E}{3(1-2\nu)}\varepsilon_1 + \frac{2}{3}Y_0 = K\varepsilon_1 + \frac{2}{3}Y_0$$

where $K = \frac{E}{3(1-2\nu)}$ is the bulk modulus, σ_1 is the max principal stress, ε_1 is the corresponding principal strain and Y_0 is the static yield strength. In terms of pressure the above equation is expressed as

$$\sigma_1 = P + \frac{4}{3}Y_0$$

This is the stress-strain relation for the uniaxial strain loading. For uniaxial stress state, stress-strain relation is $\sigma_1 = E\varepsilon_1$ with the relation taking the form reported in a typical uniaxial tensile test. *The most important difference between the uniaxial stress and uniaxial strain states is the bulk compressibility. In this case the stress continues to increase regardless of the yield stress or strain hardening.*

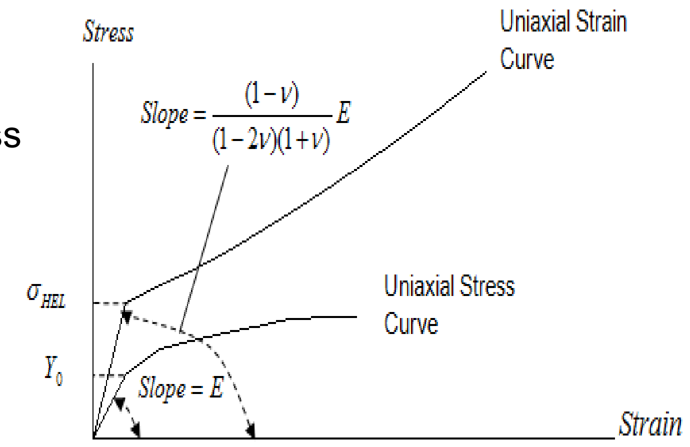


Shock Waves in Solids-Analysis

For the case of elastic 1 D strain we obtain

$$\sigma_1 = \frac{(1-\nu)}{(1-2\nu)(1+\nu)} E\varepsilon_1$$

we notice an increase in modulus by $\frac{(1-\nu)}{(1-2\nu)(1+\nu)}$

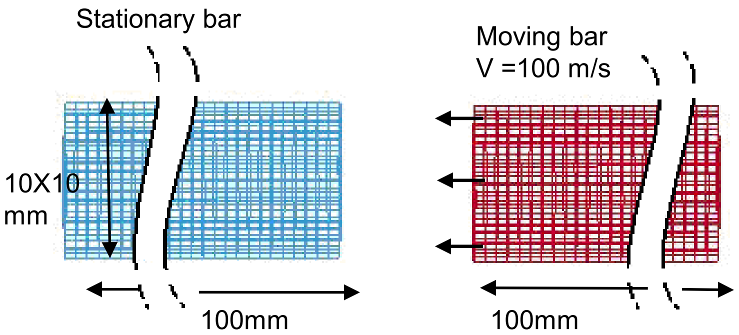


- The the yield point for the uniaxial strain is referred to as the Hugoniot Elastic Limit, σ_{HEL},which represents the maximum stress for 1D elastic wave propagation.
- For a strenghtless material ($Y_0 = 0$) the curve would be the hydrostat and characterized by P α ΔV/V
- If the material hardens with increasing strain, the difference between the Hugoniot and hydrostat curves increases.
- maximum stress in an elastic/plastic impact will have a slope less than

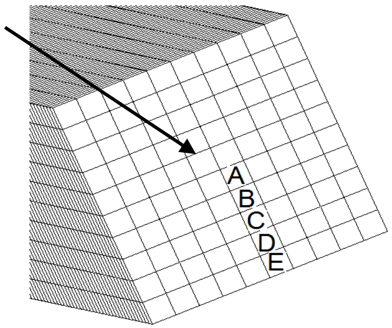
$$\frac{(1-\nu)}{(1-2\nu)(1+\nu)}$$

Impact Stress values in FEA simulations

- The previous discussion sets the boundaries for the limiting stress in impact of deformable solids. This can be used to identify the unphysical high stress values which can be obtained in impact simulations.
- This is necessary in the die design process for EHF because using of artificially high stress values in die design can be prohibiting to this technology or lead to excessively high cost of die material and its surface treatment.

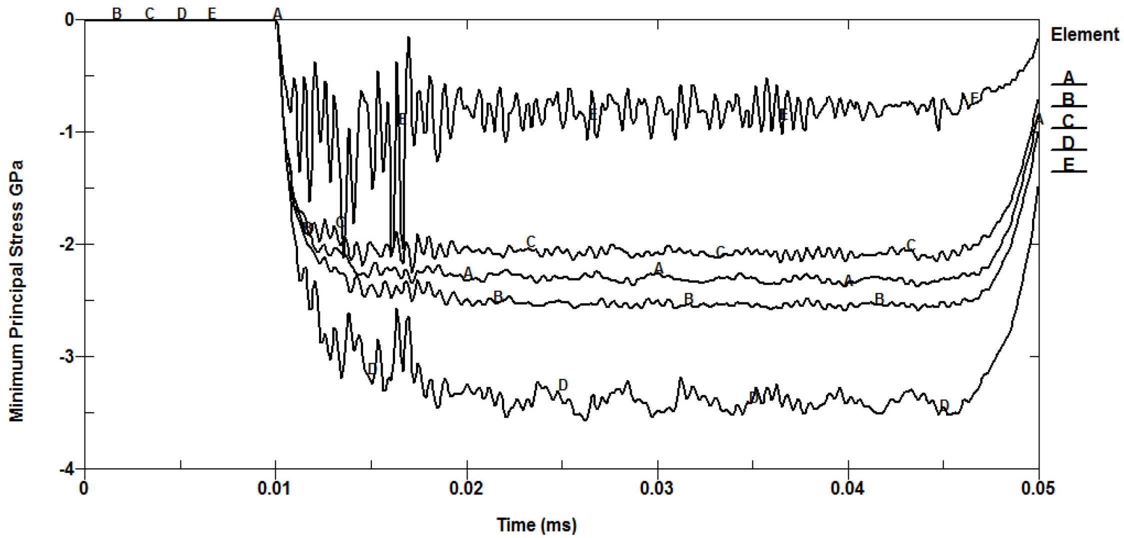


The elements A, B, C, D, and E, where the stresses are evaluated



Impact Stress values in FEA simulations

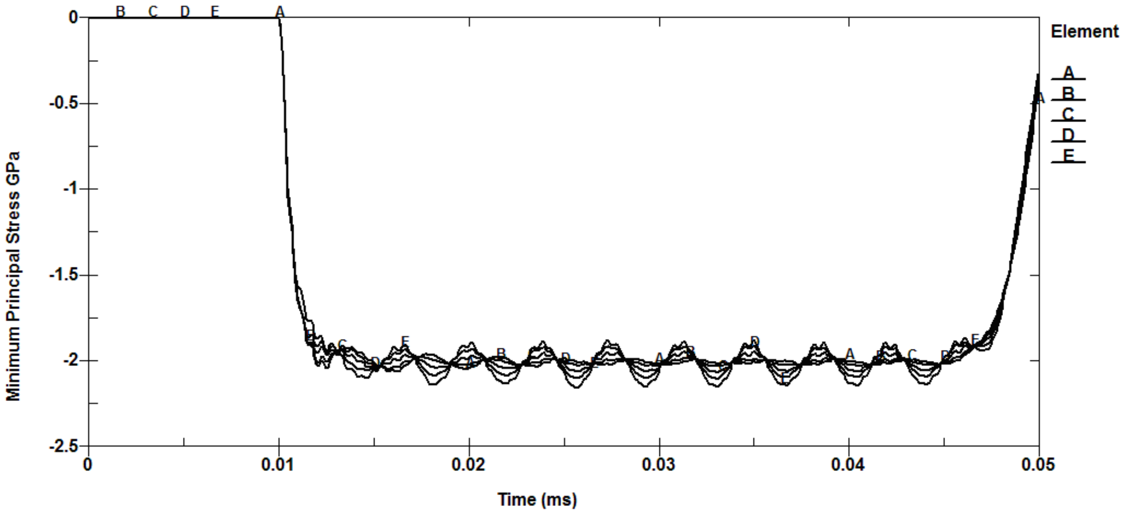
- Simulation was run on elastic steel bar to bar impact at velocity of 100 m/s in LS Dyna with the standard penalty formulation [Soft = 0]
- *CONTACT_SURFACE_TO_SURFACE contact with the SSTYP = MSTYP = 3, SLSFAC = 0.1, no artificial viscosity applied and the default values used for all other parameters] with bars meshed into 1 mm hexahedra solid elements



- The pattern of the stresses doesn't agree with the analytical solution of 2 GPa contact stress. A maximum stress appeared near the edges. It should be emphasized that the solution was very sensitive to contact type used.

Impact Stress: Consistent stress values

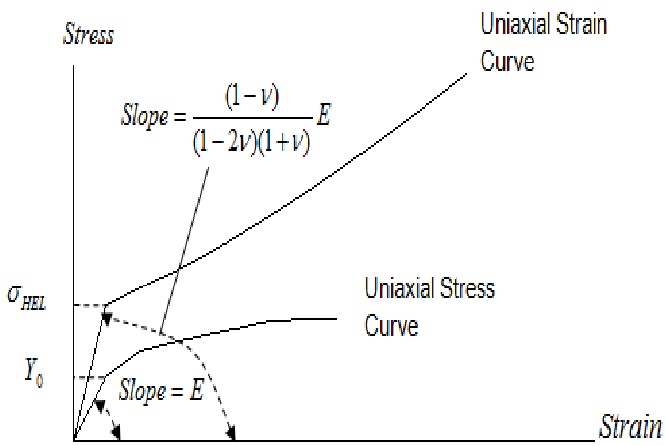
- One side of contact formulated into segments SSTYP = 0 and the other as a part type MSTYP = 3.
- Searching for the penetrating nodes and contact force update were required to be at high frequency.
- In LS Dyna bucket sorting identifies the nearest segment for each slave node. Number of cycles between bucket sorts was set to 1.
- For the same reason, the number of cycles between contact force update for penalty formulation was also set to 1. Those options help to keep penetration at the minimum level.

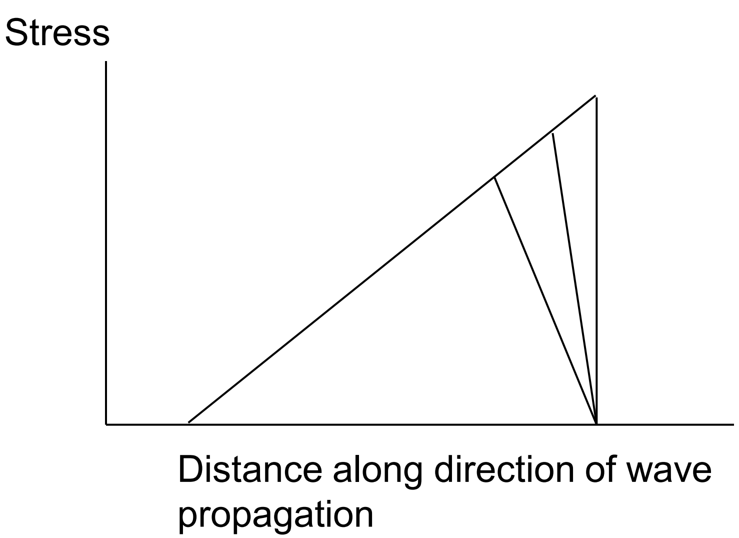


bulk viscosity TYPE 1 was used with coefficients Q1= 1.5, Q2= 0.06. Soft= 1 penalty formulation was used that takes into account the nodal masses and global time step size in contact stiffness calculations to achieve better stability.

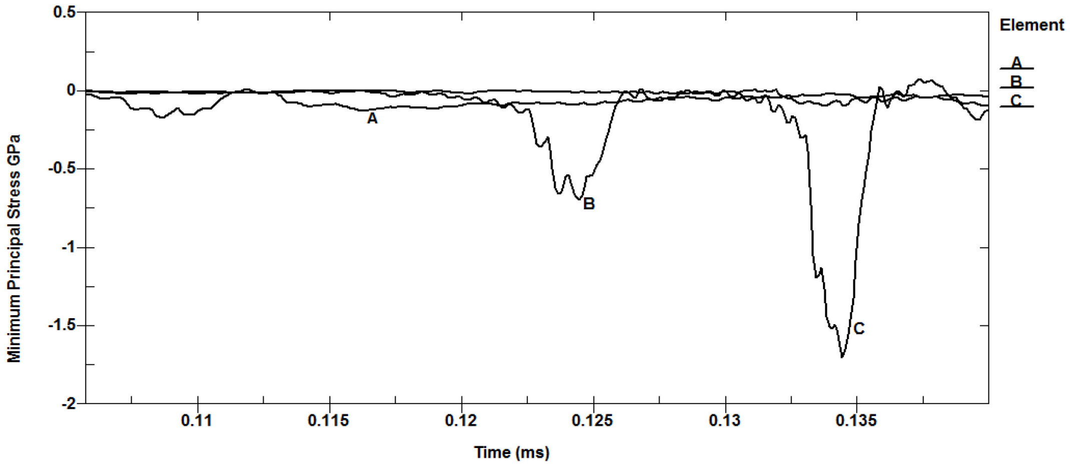
Impact Stress: Consistent stress values

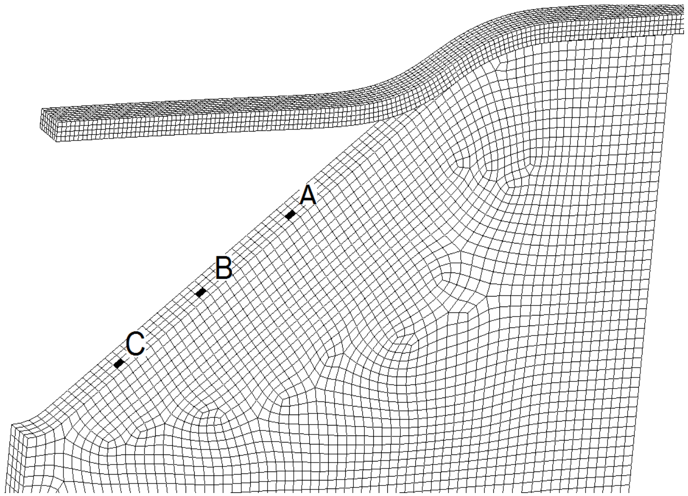
- Artificial viscosity is included in Euler and Lagrange codes to allow the code to handle the shock waves which are mathematically discontinuous, and to provide grid stabilization for quadrilateral and hexahedral elements which use one point (reduced) evaluation element formulation as indicated in.





Impact Stress: Consistent stress values





Theoretically, the ideal mesh should be uniform in all directions and get convergence for the critical values of the problem. However, it should be fine enough to give accurate results so that further refinement dramatically runs up the cost of computing with negligible improvement in accuracy

Contact algorithm

- The standard penalty formulation used in the above simulation with LS Dyna has an influence on the solution stability.

$$k_i = \frac{f_{si} K_i A_i^2}{V_i}$$

- coupling between the element dimensions with the penalty force calculation does not lend itself to solution stability with volume and area continuously changing during impact.
- Penetration can be completely avoided and contact forces calculations decoupled from the element dimensions by using the contact formulation

$$F = \begin{cases} K\left(\frac{1}{h} - \frac{1}{h_0}\right) & at \quad h < h_0 \\ 0 \quad at \quad h \geq h_0 \end{cases},$$

Conclusions

- The used contact algorithm in impact simulations substantially affects the accuracy of the contact stress.
- The user has to take great care to assure that the solution reflect the true physics of the problem.
- Analysis of contact stresses was conducted in blank impact simulations with different contact algorithms to avoid the so called mesh sensitivity.
- Inter-penetration was minimized along with better control over artificial viscosity and hour glassing to assure the stresses are closest to experimental results.