Workshop

Methods for modelling Air blast on structures in LS-DYNA

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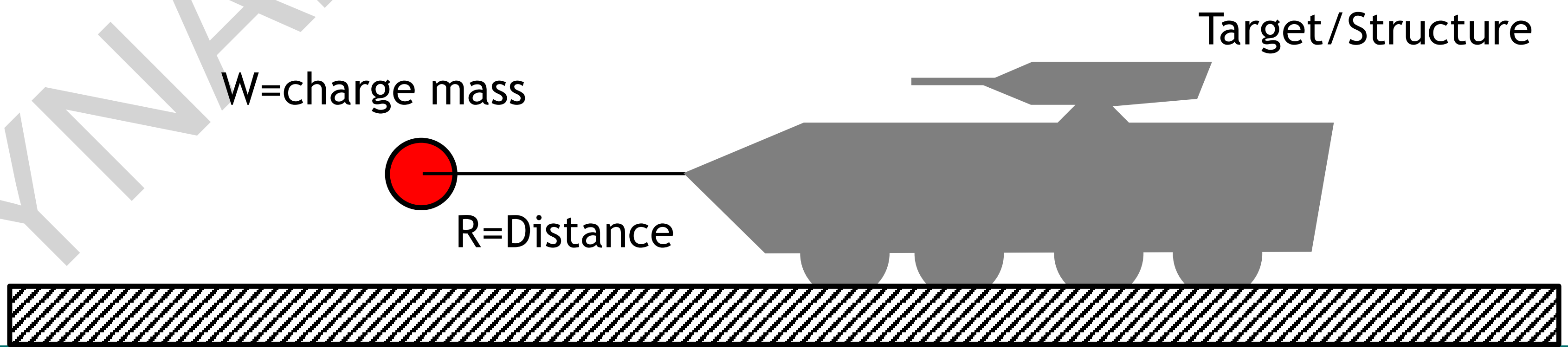
About the workshop

- An overview of available and upcoming methods in LS-DYNA to calculate explosive blast loads from conventional explosives on structures for structural engineering purposes.
- Audience – Knows about LS-DYNA & FEA but would like to learn about methods for blast & explosion simulation to be able to do strength/performance analysis of blast loaded structures.



Caution

- This workshop material only provides an overview of available methods and does not constitute a recommendation do use any particular method.
- Blast load/explosives simulation is inherently complicated, it requires know-how of both numerical methods, explosives, and blast effects.
- Perform QA of the method you intend to use using relevant experimental data or data from the literature. This is important to:
  - Quantify the accuracy.
  - Minimize the risk for undetected user errors.
  - Detecting any software errors or changes of solver behavior in new versions.

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LS-DYNA for defense

- The predecessor of LS-DYNA (DYNA3D) was developed starting around 1976 for defense applications at Lawrence-Livermore National Laboratory, CA, USA, by Dr. John O. Hallquist.
- Dr. John O. Hallquist founded Livermore Software Technology Corporation (LSTC) in 1989, which develops LS-DYNA.
- Today, LS-DYNA is a general high performance multi-physics and finite element solver that is widely used both in the civil and defense sectors.

LS-DYNA for defense - Applications

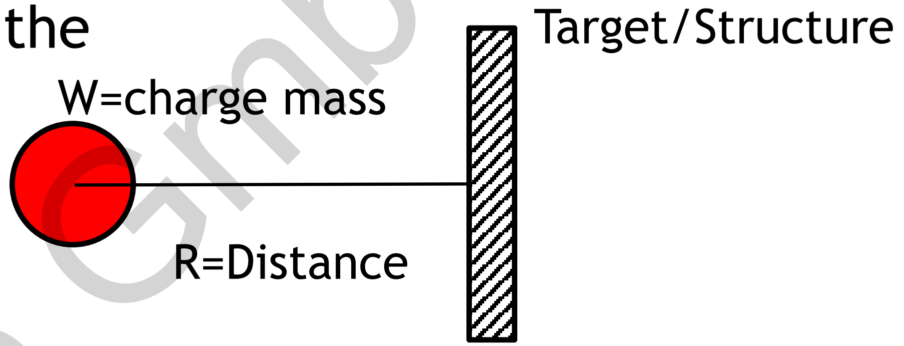
- Homeland security – blast loads on buildings & infrastructure
- Mine and IED (Improvised Explosive Device) blasts on vehicles and transported personnel.
- Penetration mechanics
- Warhead performance
- Explosively formed projectiles and shaped charges
- Munitions & guns/barrels
- Submarine and surface vessels underwater shock analysis using the USA Code (requires special license)

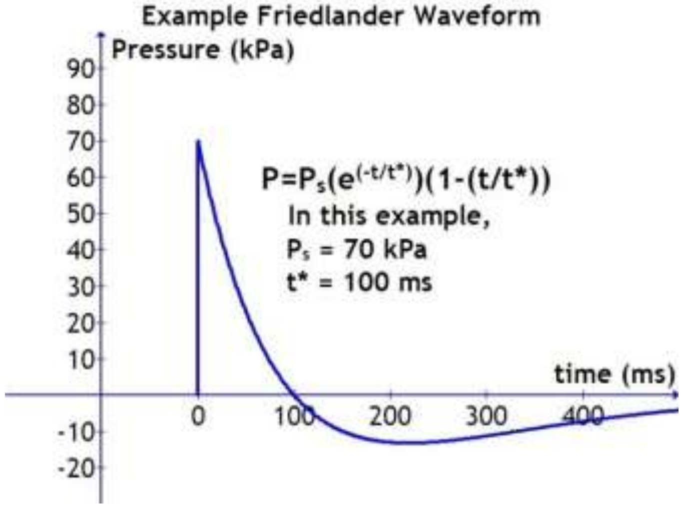
Software

- LS-DYNA R8.1.0 or R9.0.1 unless otherwise noted
- LS-PrePost 4.3, August 2016 or later

Spherical TNT charge in free air at normal temperature and pressure

- From theory and experiments it is known that the shockwave exhibits a large degree of self similarity in terms of the scaled distance $Z=R/W^{(1/3)}$. To fairly high accuracy:
  - The incident and reflected pressure and shock velocity only depends on the scaled distance.
  - The reflected impulse scales as $i=I(Z)*W^{(1/3)}$, i.e. larger charges yield slightly larger impulses for the same scaled distance.
  - The shockwave has a characteristic shape well approximated by e.g. the Friedlander expression.
- Note: Self similarity and scaling laws follows also from theoretical analysis, see e.g. G.Taylor, "The Formation of a Blast Wave by a Very Intense Explosion. I. Theoretical Discussion", Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences, Vol. 201, No. 1065. (Mar. 22, 1950), pp. 159-174.

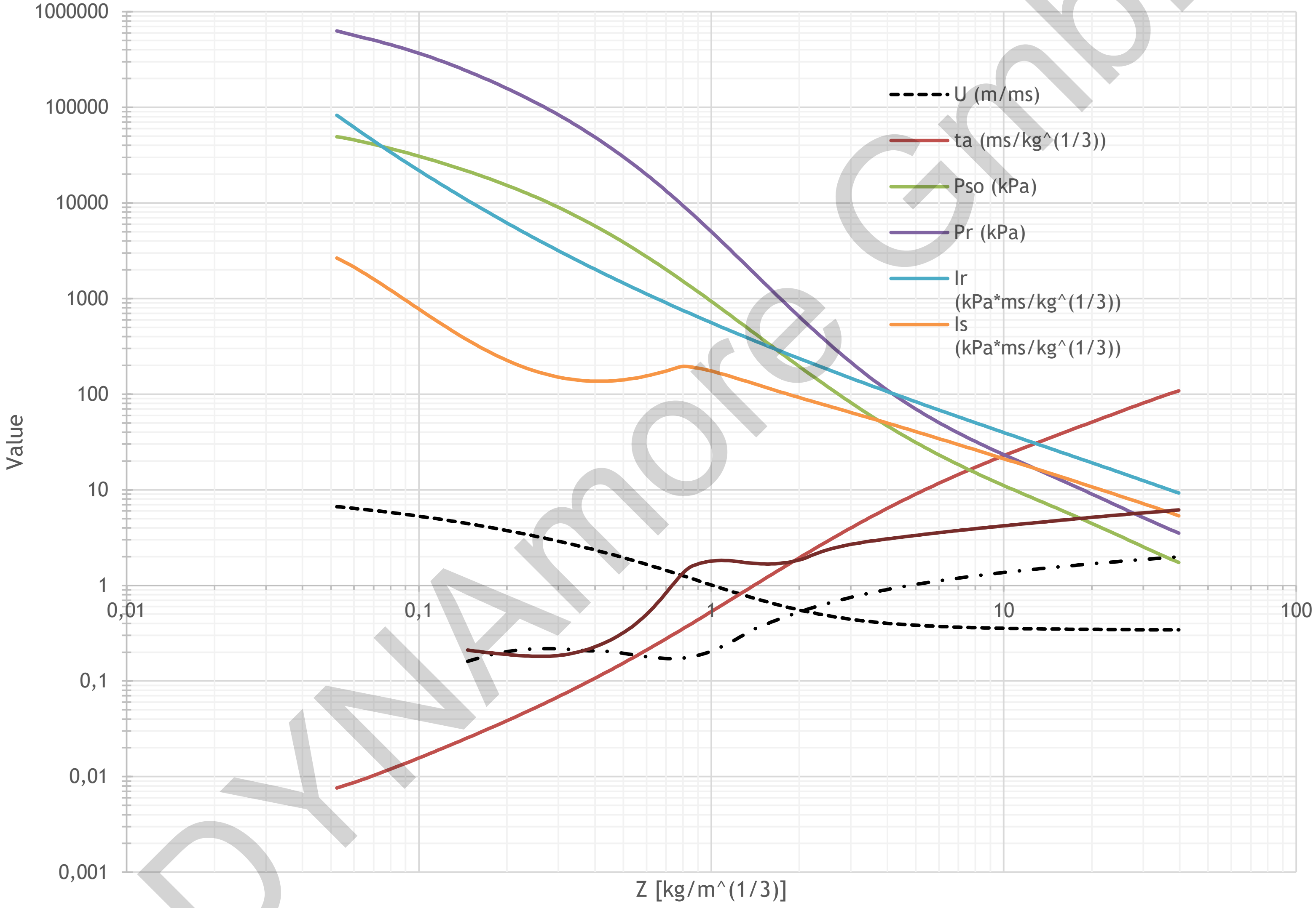




Handbooks

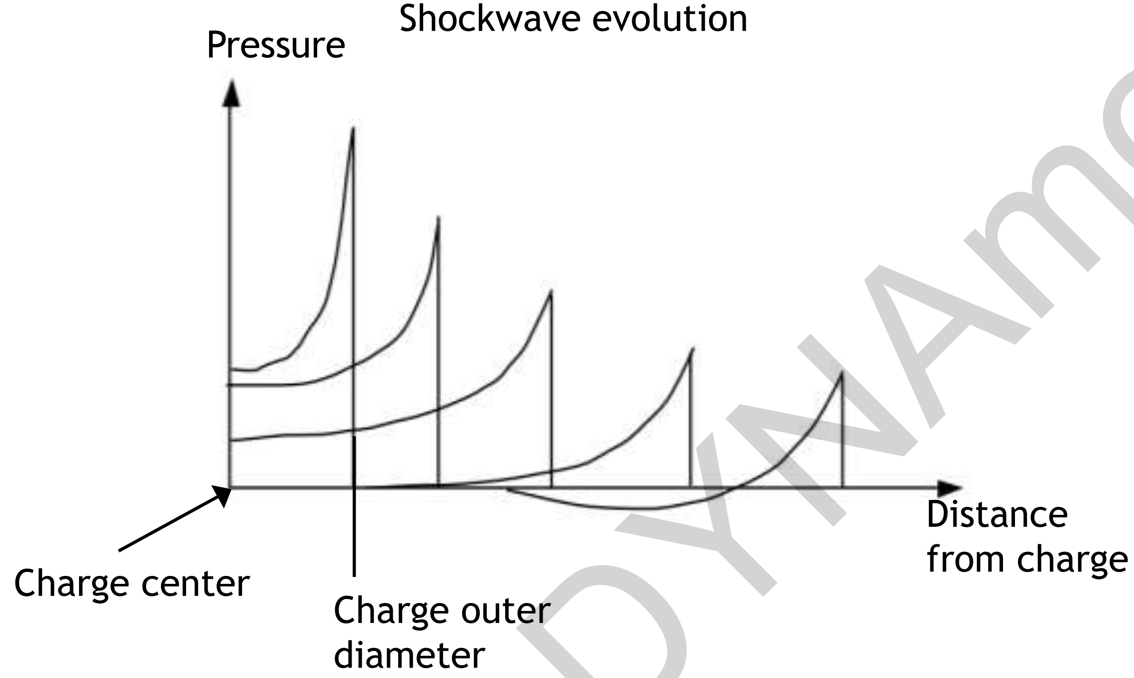
- There are a lot of empirical methods for calculation of explosive/blast loads on structures. One well known and available handbook is TM 5-1300.
  - Army Technical Manual 5-1300 1990/NAVFAC P-397/AFR 88-22, “Structures to Resist the Effects of Accidental Explosions”
    - “First published in 1969 as TM 5-1300 (Department of the Air Force, 1969). It is based primarily on explosive tests of reinforced concrete walls, the manual provides a comprehensive introduction to the blast design process including load calculation, dynamic analysis, structural design, and detailing.
- To be able to do simulations using continuum solvers (ALE, SPH, et c), the material properties of the explosives are needed. One source is the LLNL explosives handbook.
  - Dobratz, B. M., and Crawford, P. C., “LLNL Explosives Handbook”, UCRL-52997 Change 2, January 31, 1985.

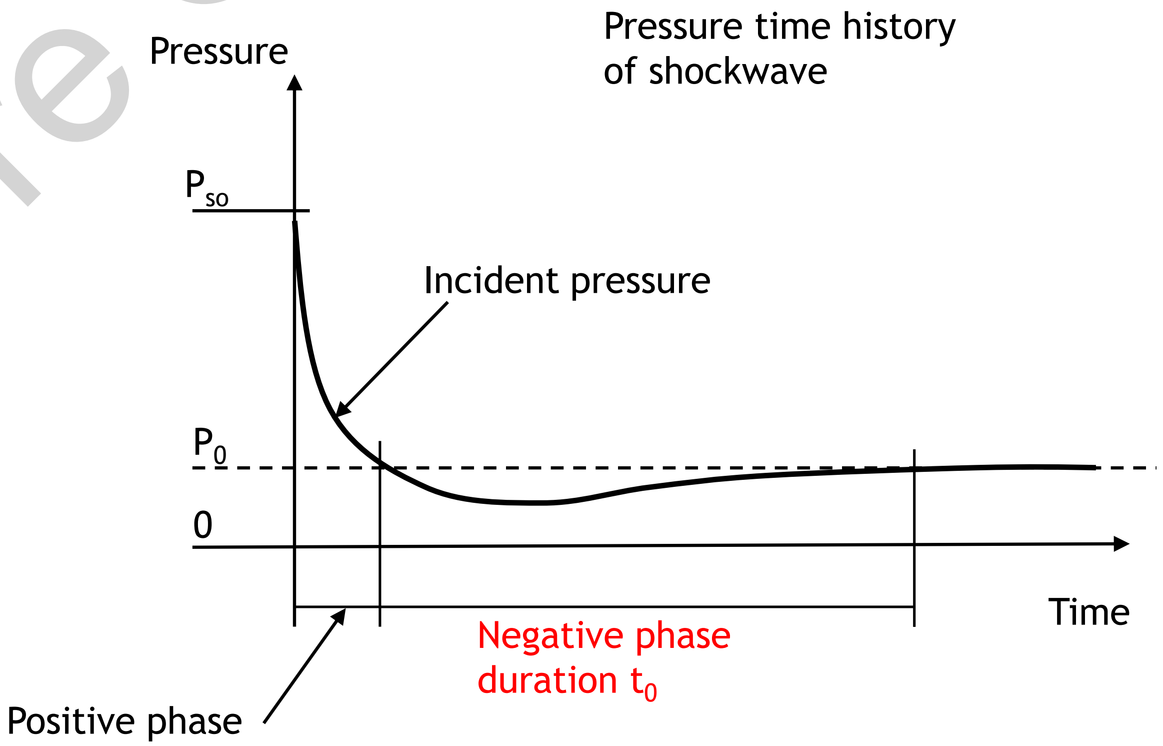
TM 5 1300, Fig 2-7 - Positive phase parameters for a free spherical air blast of TNT



The shockwave from a spherical explosion

- For a 1 kg TNT charge at R=1 m
  - Peak over-pressure in free air ~9 bar (note reflected peak pressure on a structure facing the charge is ~5 times higher)
  - Speed of the shock front: ~800 m/s
  - Length of the positive phase ~0.15 m





Empirical/phenomenological models for explosive loads

- *LOAD_BLAST(_ENHANCED) – Air blast loads from conventional explosives.
- *LOAD_BRODE – Pressure loads from explosions at (higher) altitudes.
- *INITIAL_IMPULSE_MINE – Loads from buried mines on vehicles.
- *LOAD_SSA - Submarine shock analysis (loads from underwater explosions).
- Summary:
  - Short run-times and very easy to use.
  - Documented accuracy for the situations for which the model was calibrated.
  - Correlates will with methods used in standard handbooks, e.g. TM 5-1300.
  - Not a general solution method. Reasonable results only for situations (simple geometry, charge type et c) for which the method was developed.

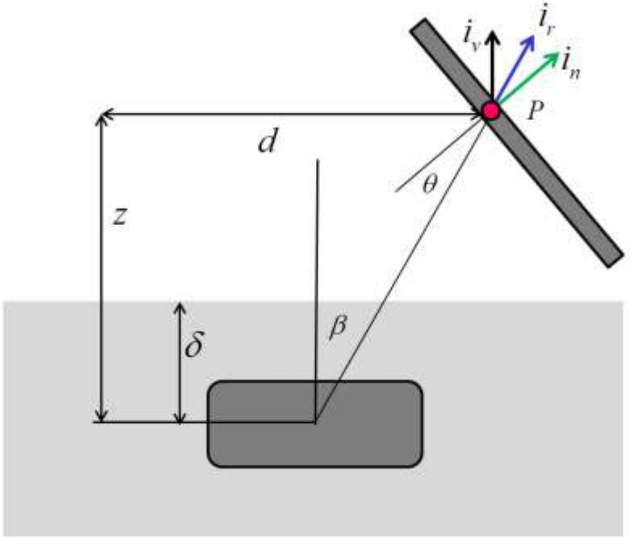


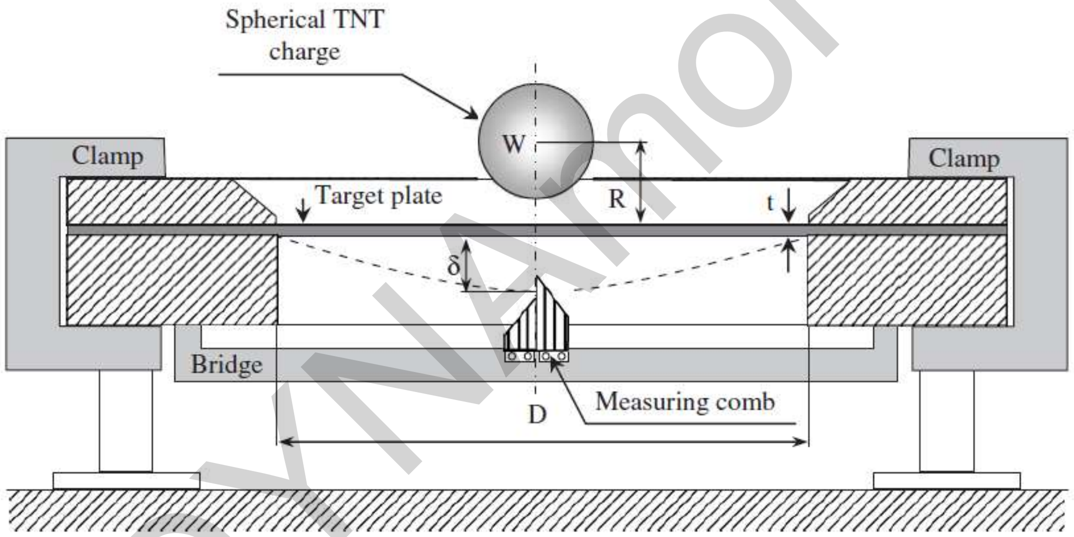
Figure from T. Slavik & L. Schwer, "Buried charge engineering model: verification and validation", 9th European LS-DYNA conf.

“First principle” physics based methods for explosive load calculation

- Solvers
  - Multi-Material ALE (Euler formulation)
  - Particle blast (*PARTICLE_BLAST) – CPM - Corpuscular Particle Method
  - SPH – Smooth Particle Hydrodynamics
  - CE/SE including Chemistry module and support for hybrid solution with *LOAD_BLAST_ENHANCED
  - All of the above except the particle blast solver are continuum solvers.
- Summary:
  - In principle capable of modelling any situation, it is like virtual testing.
  - Can yield a deep insight into physics of the situation being simulated, which often not even physical testing can provide.
  - Requires the user to develop his own modeling guidelines (meshing, numerical parameters) and also verify the accuracy of the results when using these guidelines.
  - Can require large computational resources.

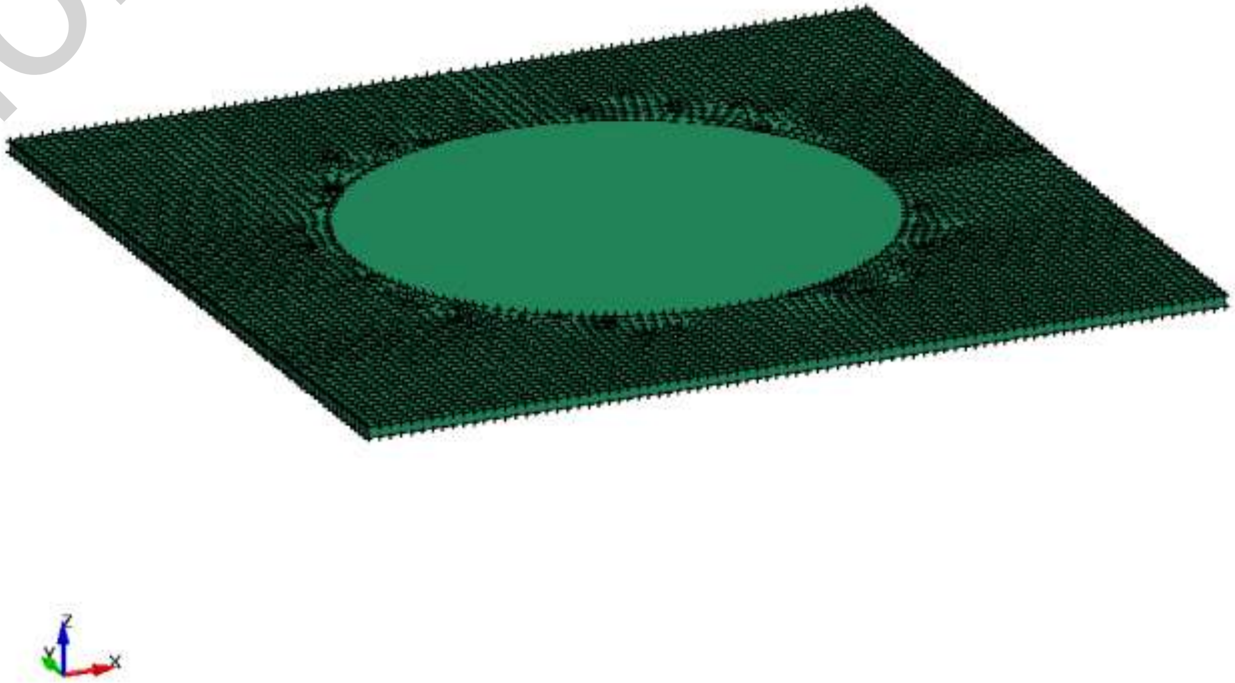
Comparison of methods – the Neuberger et al. experiment

- A. Neuberger, S. Peles, D. Rittel, “Scaling the response of circular plates subjected to large and close-range spherical explosions. Part 1: air blast loading”, Int. J. of Impact Eng. 34, 2007, pp 859-873
- Rolled Homogenous Armor plate, yield strength 950 MPa, t=20 mm



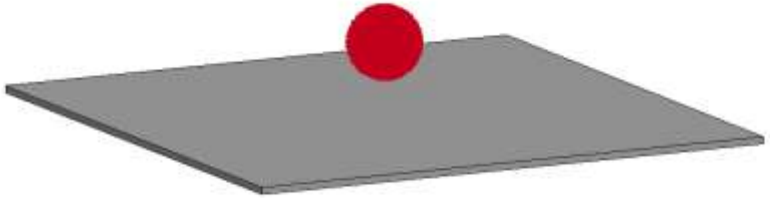
Comparison of methods – the Neuberger et al. experiment

- Dimensions: 20x1600x1600 mm
- Non-clamped area: Diameter 1000 mm
- Explosive property data from the LLNL explosives handbook.

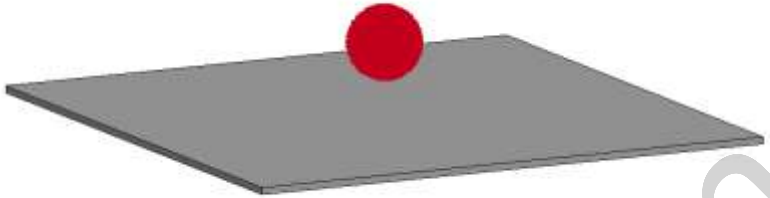


Comparison of methods – the Neuberger et al. experiment – 5 approaches

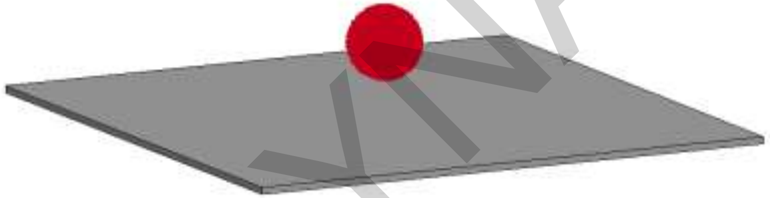
t=20 mm, R=200mm, W=8.75 kg TNT, Z=0.097 kg/m$^{1/3}$



SPH

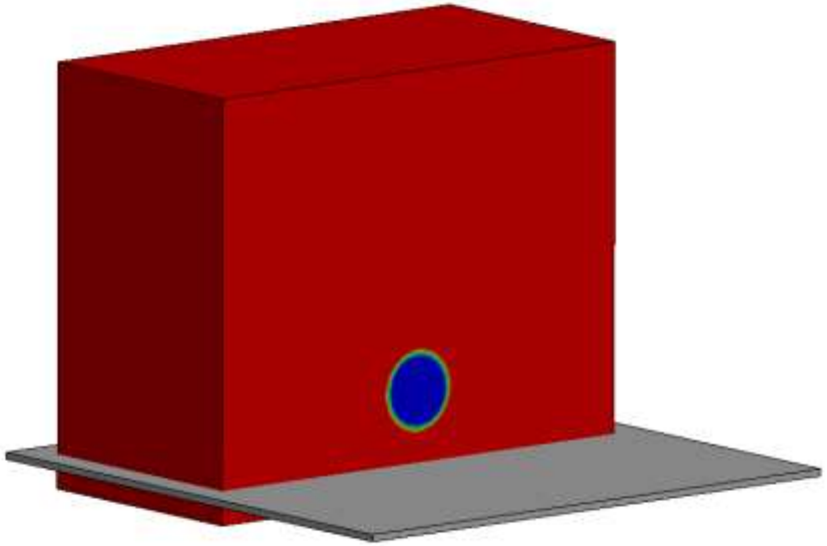


Particle blast, no air



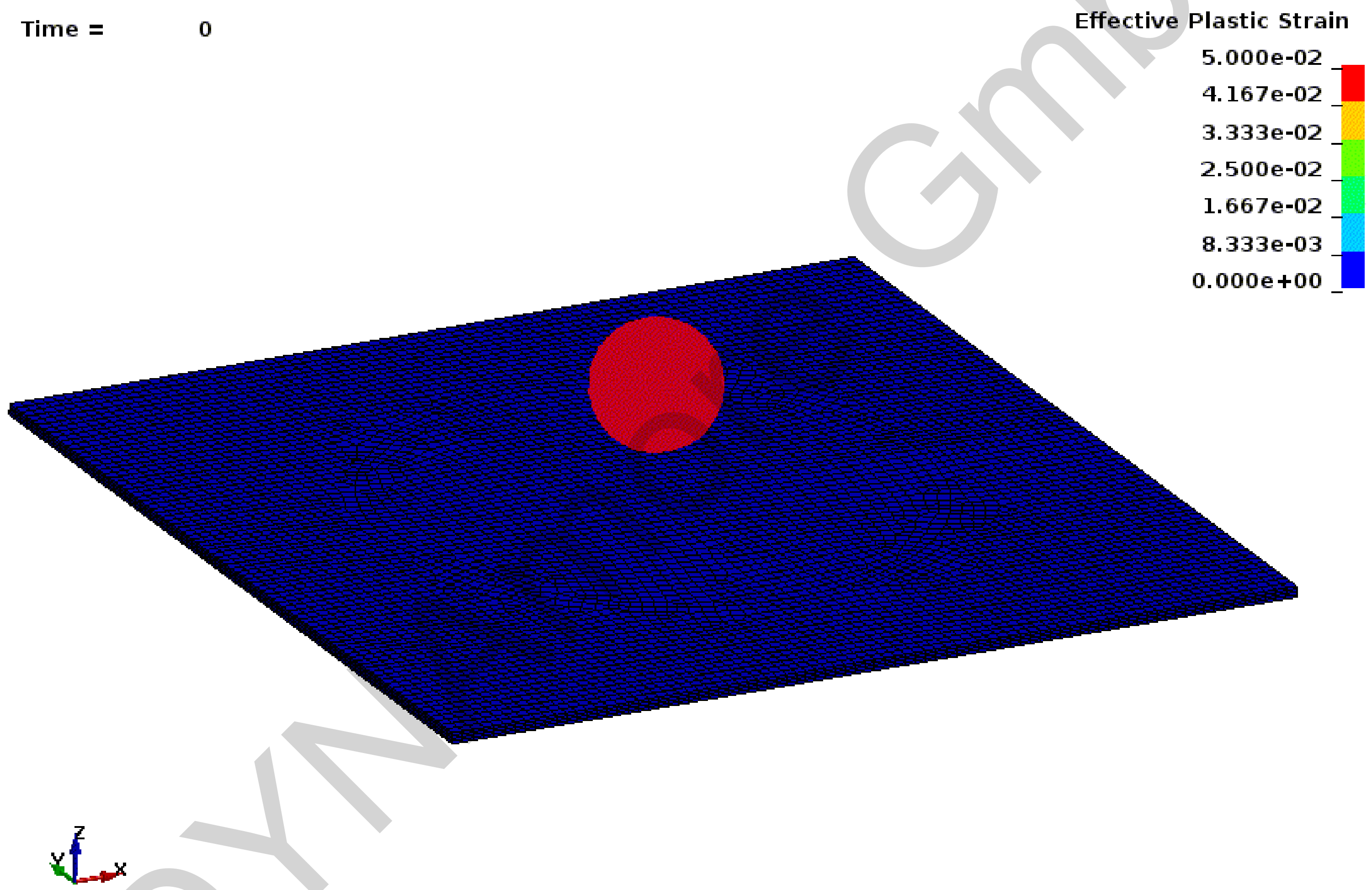
*LOAD_BLAST

Particle blast, with air

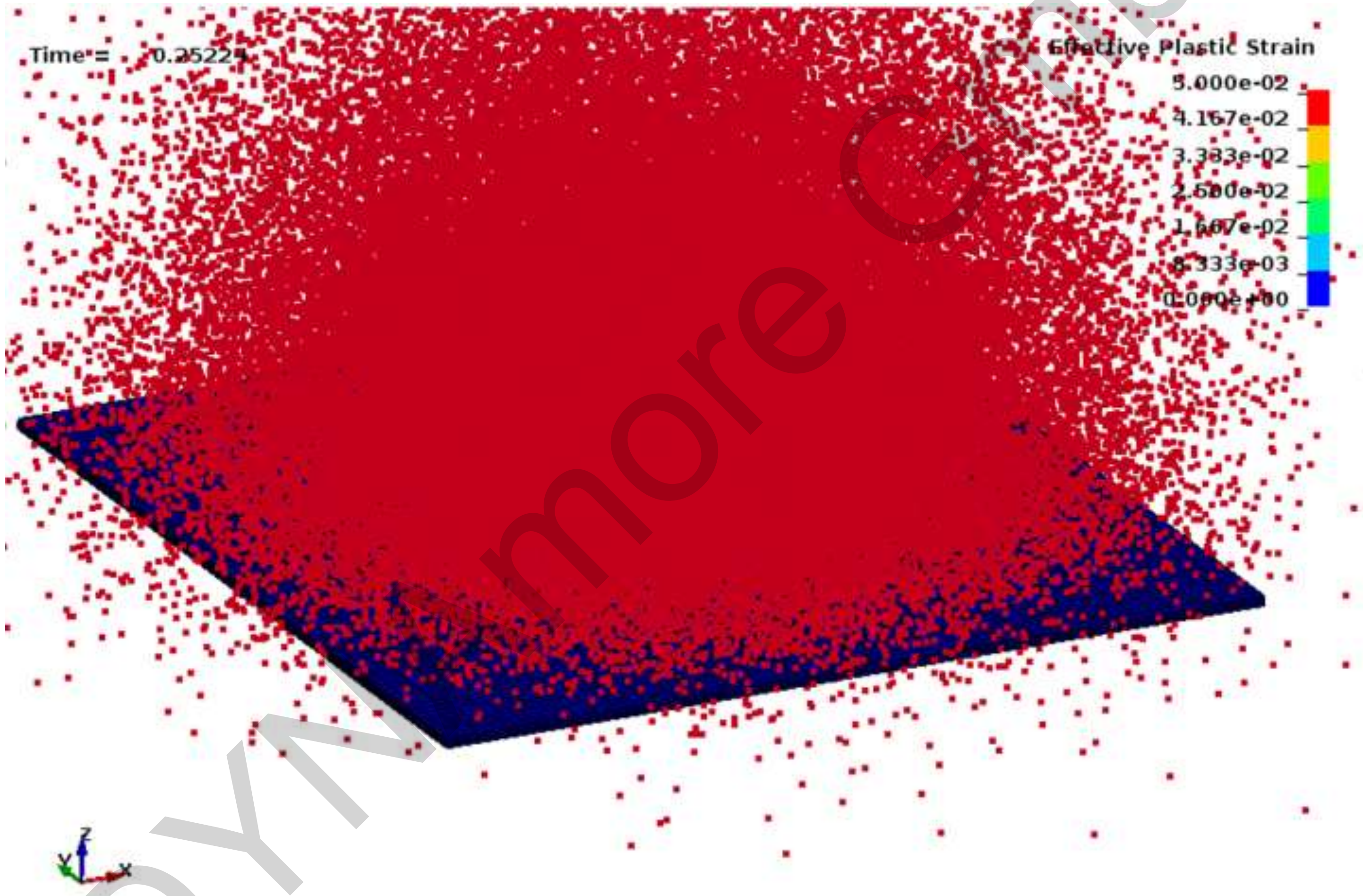


MMALE (S-ALE), with air, cross section.

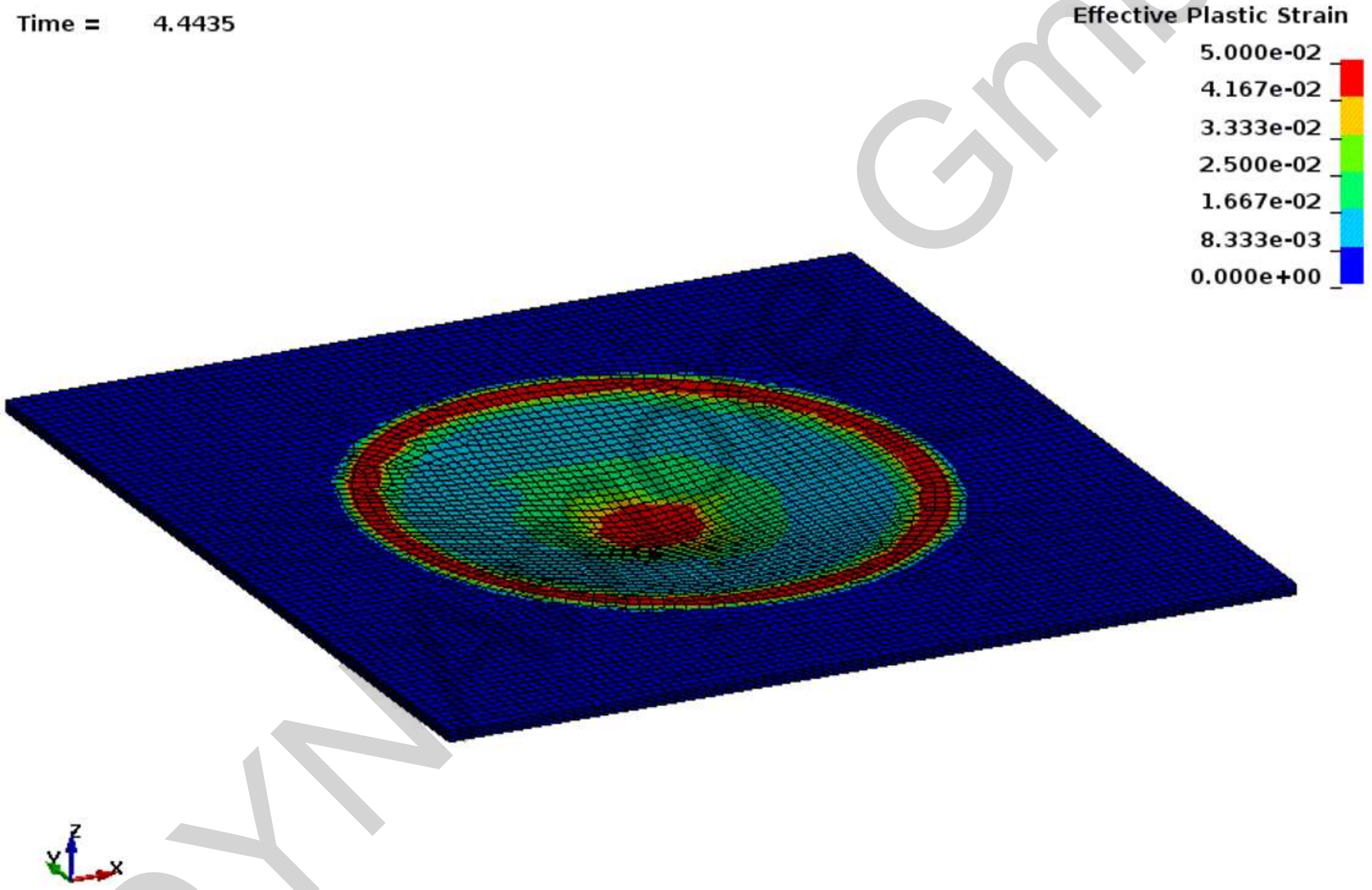
Comparison of methods – the Neuberger et al. experiment (*PARTICLE_BLAST)



Comparison of methods – the Neuberger et al. experiment (*PARTICLE_BLAST)

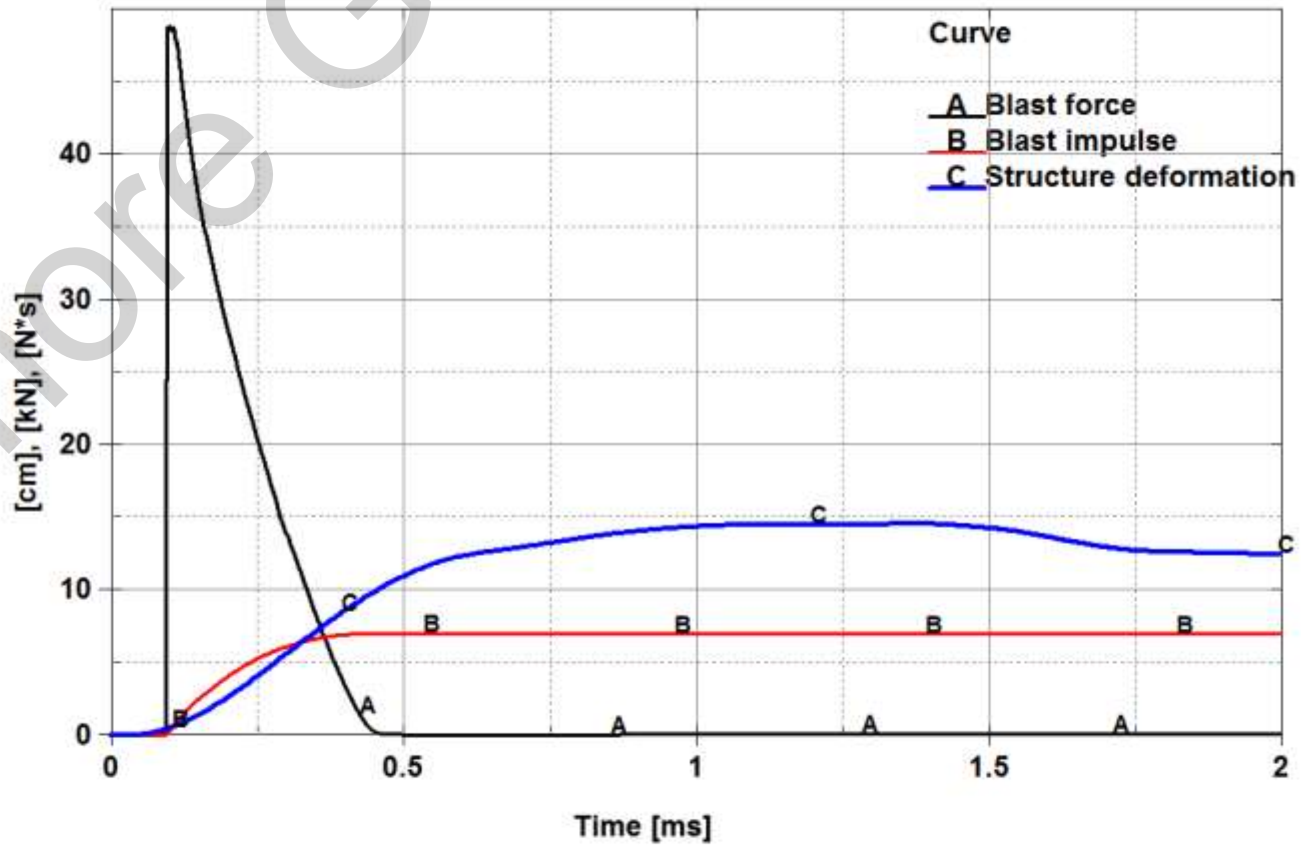


Comparison of methods – the Neuberger et al. experiment (*PARTICLE_BLAST)



Comparison of methods – the Neuberger et al. experiment

- Blast force duration (positive phase) 0.4 ms.
- Continuum solvers
  - To capture the peak pressure accurately force a very fine mesh is required.
  - Less fine mesh is required to capture the impulse with comparative accuracy.
  - Depending on structure, the accuracy of the calculated response may be more or less dependent on capturing the peak pressure accurately.



Comparison of methods – the Neuberger et al. experiment

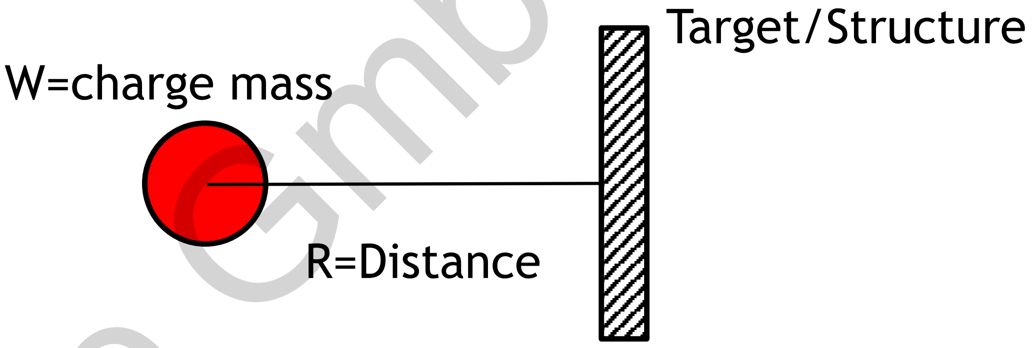
- Experiment case: D=1.0 m, t=20 mm, R=200mm, W=8.75 kg TNT, Z=0.097
- LS-DYNA R8 or R9, single prec.
- 5 ms physical time was simulated, δ is the maximum measured backside deflection.

Method	Solver parameters	Experiment δ [mm]	Simulation δ [mm]	Difference [%]	Solution time [seconds]
Particle blast	No air, 80k part.	107	99.1	-7	85 on 8 cores
SPH	No air, 80k part.	107	84.1	-21	270 on 8 cores
*LOAD_BLAST[1]		107	146	+36	151 on 4 cores
MMALE/S-ALE	Air, 2.4M elements	107	75.8	-29	17334 on 20 cores
Particle blast	Air, 80k HE part., 800k Air part.	107	95.9	-10	407 on 8 cores

[1]*LOAD_BLAST theory is not valid for a blast this close. Results are only included to illustrate the run time.

Explosive blast in air – Regimes for spherical TNT charge in free air at NTP

- Scaled distance $Z=R/W^{(1/3)}$
- Arbitrary classification – reasonable in line with common use in the relevant literature.



Classification	Scaled distance Z m/kg$^{(1/3)}$
Far field	>4 - ~40[1]
Medium field	0.4-4
Near field	~0.053-0.4
Contact	~0.053[2]

For a 1 kg charge	Distance R (m)
Far field	>4 m – ~40m [1]
Medium field	0.4-4 m (0.4 m = ~8 charge diameters)
Near field	~0.053-0.4
Contact	~0.053[1] m

[1] At Z=40 m/kg$^{(1/3)}$ peak shockwave pressure is about 2% of normal air pressure.

[2] Assuming a charge density of about 1600 kg/m^3

Summary: Scenarios and solution methods for air blast and mines.

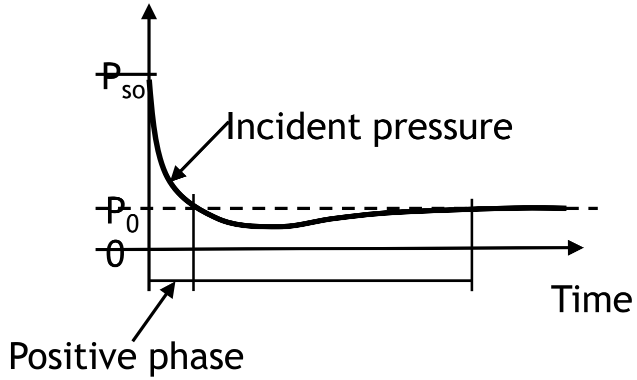
- Pick the right tool for the job. Also consider the know-how required to use it.

Classifi-cation	Scaled distance Z m/kg$^{(1/3)}$	MM-ALE/S-ALE	SPH	Particle Blast (new method)	CE/SE	*LOAD_BLAST(_ENHANCED)	*INITIAL_IMPULSE_MINE
Far field	>4-40	Yes*			Yes*	Yes	
Medium field	0.4-4	Yes or Yes*		Maybe	Yes*	Yes	
Near field	~0.053-0.4	Yes	Yes?	Yes	Yes?**	Yes (border case)	
Contact	~0.053[1]	Yes	Yes	Yes	Yes?**		
Buried mine & vehicle	~0.053 - ~1	Yes	Yes	Yes			Yes

Yes* = If using hybrid with *LOAD_BLAST_ENHANCED (or mapping method is also available for ALE).
Yes?** = Possibly if using the built in chemistry solver (author has not used it himself).

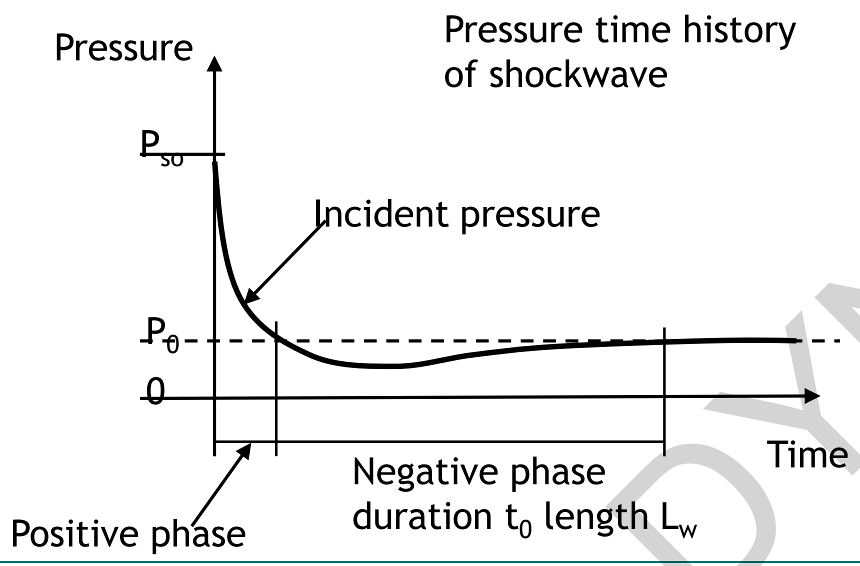
Needed resolution for continuum solvers of the MMALE/S-ALE type

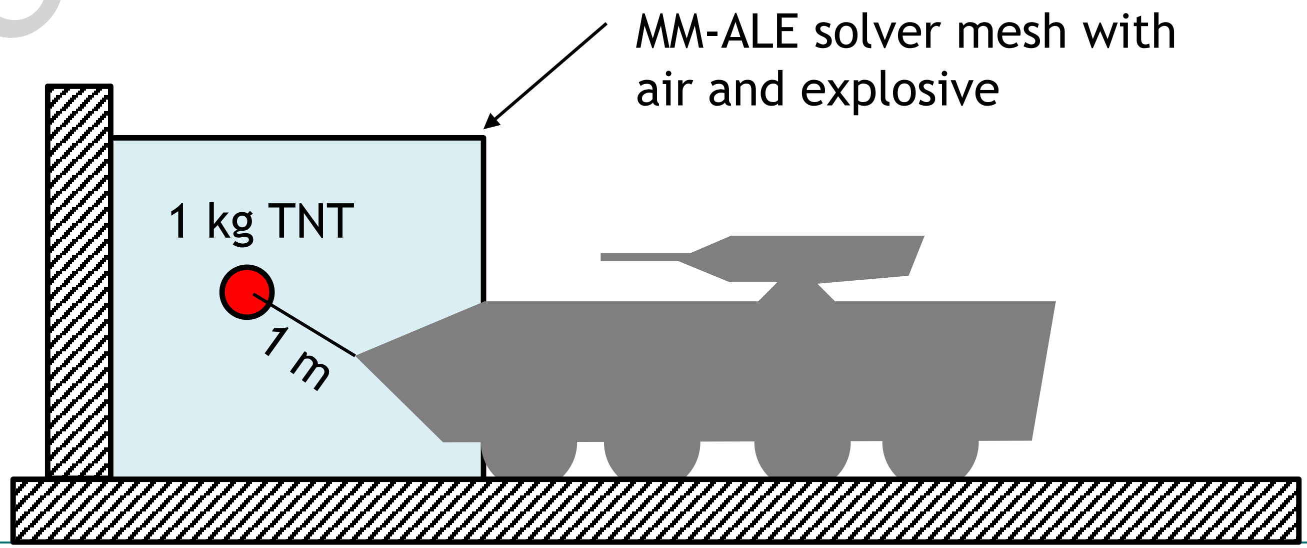
- For air blast analysis with the MM-ALE/S-ALE solver, both explosive and air need to be meshed.
- For continuum solvers to obtain a reasonably accurate solution a sufficiently fine discretization is needed.
- There are no available detailed recommendations on element size, please use convergence studies.
  - For a close range situation one may assume *ad hoc* that element/grid size should be less than about “charge diameter”/10. The mesh might may be coarsened gradually away from the charge as the pressure decreases and the length increases of the shockwave.



Needed resolution for continuum solvers – Example MM-ALE-solver

- Consider the example below. The solver mesh must be large enough to avoid boundary effects, e.g. 2x2x2 m.
- For a 1 kg TNT charge at 1 m, the charge diameter is about=0.1m and also the length of the positive phase of the blast wave is about 0.15m. Thus one may guess an element size of 1 cm to reasonably simulate the blast.
- <u>The above leads to an ALE-mesh with 2^3/0.01^3= 8e6 elements.</u>





Needed resolution for continuum solvers

- Due to the rapid increase in number of elements required for continuum solvers like MM-ALE, SPH, and CE/SE as the scaled distance increases, direct use of this type of solver is often restricted to contact and near field explosive analyses.
- To drastically decrease the computational effort when using the MM-ALE solver, several strategies can be used in LS-DYNA:
  - ALE & CE/SE: Coupling to *LOAD_BLAST_ENHANCED
  - ALE: Mapping or coupling of simulation results from a 2D or 1D analysis to a 3D analysis.
- More about these methods further on.

1 General information on empirical air blast models in LS-DYNA

- *LOAD_BLAST_ENHANCED (LBE) is a an extended and easier to use version of the original *LOAD_BLAST (LB). For the subset of options in LBE that cover the functionality in LB, the results should be identical.
- LBE (and LB) are based on tables of experimental data for conventional explosions converted into approximating polynomials using classical scaling laws (see e.g. the LLNL Explosives Handbook).
- LBE (and LB) have roots (equations, used experimental data) that are similar to the ConWep software but the ConWep-software is not built into LS-DYNA.
- LB and LBE when used as intended provide a proven, reliable, easy to use, and quick method to apply blast loads on structures.

1 *LOAD_BLAST

- Empirical blast model for conventional explosives (TNT) implemented with two options:
  - spherical charge free air burst
  - surface burst
- Based on the blast load equations in [1] derived from test results fitted to analytical blast load models and scaling laws. The implementation in DYNA is described in detail in [2]. A study on limitations and accuracy is made in [3].
- References

  - 1 Kingery, Charles N., and Gerald Bulmash, "Airblast Parameters from TNT Spherical Air Burst and Hemispherical Surface Burst," U.S. Army Ballistic Research Laboratory Technical Report ARBRL-TR-02555, Aberdeen Proving Ground, MD, April 1984.
  - 2 Randers-Pehrson, Glenn, and Kenneth A. Bannister, "Airblast Loading Model for DYNA2D and DYNA3D," U.S. Army Research Laboratory Technical Report ARL-TR-1310, Aberdeen Proving Ground, MD, March 1997.
  - 3 Swisdak, Michael M Jr, ”Simplified Kingery Airblast Calculations”, Naval Surface Warfare Center, 1994

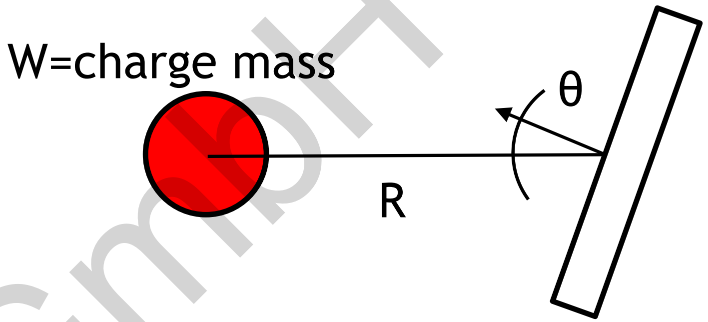
1 *LOAD_BLAST

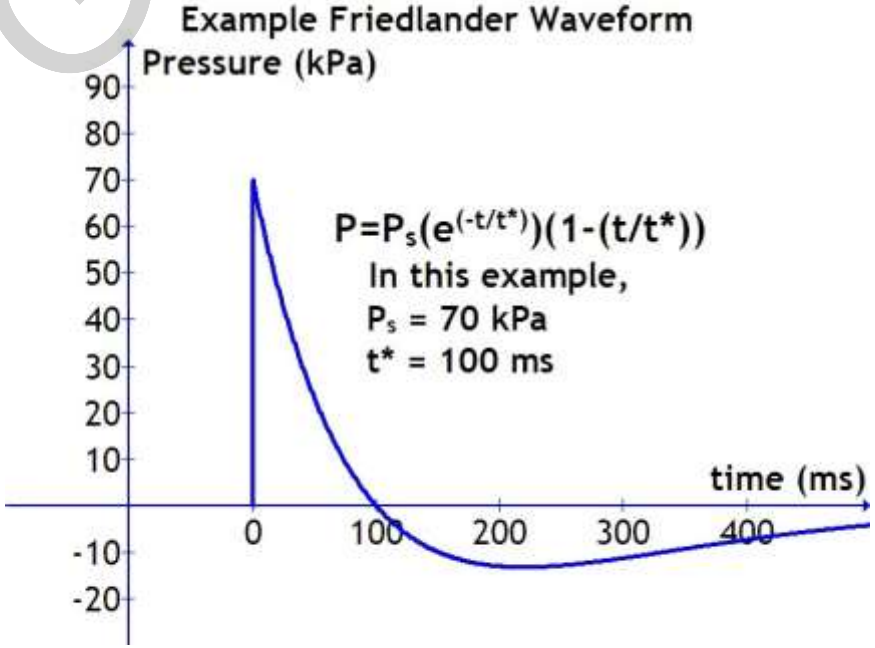
LOAD_BLAST

- Valid for a scaled standoff distance $Z=R/W^{(1/3)}$ between $0.147<Z<40\ m/kg^{(1/3)}$ for the free airburst case.
- Considers only the positive pressure phase and angle of incidence:

$$\text{PressureLoad} = \text{ReflectedPressure}\cdot\cos^2\theta + \text{IncidentPressure}\cdot(1 + \cos^2\theta - 2\cos\theta)$$

- Very easy to use.
- TNT data assumed: DCJ=6930 m/s, density 1.57 g/cm^3





A Friedlander waveform is the simplest form of a blast wave in a free-field environment.

Source: Wikipedia (Creative Commons Attribution-Share Alike)

1 *LOAD_BLAST

- The accuracy of the *LOAD_BLAST (and ConWep) model has been evaluated in [4]:
  - ”the experimentally measured blast parameters are generally predicted to a high degree of accuracy by the ConWep code […] a maximum difference of 7% between the experimental data and ConWep predictions.”
  - “remarkably accurate and can be used with confidence as a first-order approach for quantifying the blast load a structure will be subjected to”

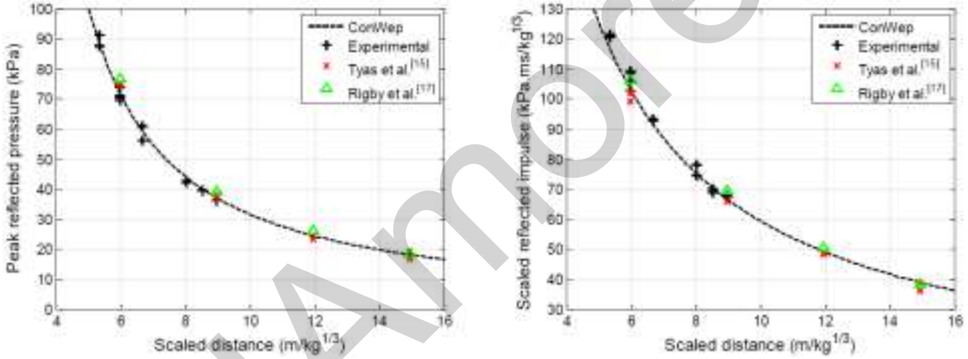


Figure from [4] Rigby et al.

- [4] Rigby SE, Tyas A, Fay SD, Clarke SD & Warren JA (2014), “Validation of Semi-Empirical Blast Pressure Predictions for Far Field Explosions - Is There Inherent Variability in Blast Wave Parameters?”, 6th International Conference on Protection of Structures against Hazards. Tianjin, China, 16 October 2014 - 17 October 2014.

1 *LOAD_BLAST – Notes

- If other explosives than TNT are to be considered one needs to input the mass of the corresponding charge of TNT (M_{TNT}). One approximate method is:

$$M_{TNT} = \mathrm{M}\frac{DCJ^2}{{DCJ_{TNT}}^2}$$

$$DCJ_{TNT} = 0.693\ cm/\mu s$$

Where the non-TNT explosive has mass M and the Chapman-Jouget detonation velocity DJC.

1 *LOAD_BLAST_ENHANCED

- *LOAD_BLAST_ENHANCED is a newer version of *LOAD_BLAST, the improvements are:
  - Loads are applied to segments defined using *LOAD_BLAST_SEGMENT.
  - Allows multiple blast sources in the same simulation (*LOAD_BLAST allows only 1).
  - Additional options:
    - Effect from ground reflected waves from surface air bursts (*LOAD_BLAST only considers surface burst and free air burst).
    - The negative phase pressure can be included (Friedlander equation) otherwise ignored like in *LOAD_BLAST.
    - Output of blast pressure (*DATABASE_BINARY_BLSTFOR).
    - Option to simulate the effect of blast from explosives moving at high speed (e.g. missiles).
  - Support of 2D-axisymmetric analysis.
  - <u>Can be used as a boundary condition for a more detailed 3D MMALE shockwave propagation analysis.</u>

1 *LOAD_BRODE

- *LOAD_BRODE implement the blast model by Brode [1970]. It seems to have been developed for large charges, i.e. nuclear weapons at high altitudes for which *LOAD_BLAST(_ENHANCED) is not suitable. For more information see the reference (which may be hard to obtain).
- Ref.: Brode, H.L.: Height of Burst Effects at High Overpressures, DASA 2506, Defense Atomic Support Agency, 1970

1 *INITIAL_IMPULSE_MINE

- The LS-DYNA keyword *INITIAL_IMPULSE_MINE for buried mine blast analysis on vehicles is based on Trembley [1], which is turn is based on the model [2] developed by the US Army Tank Command.
- For details on how to use this card in LS-DYNA see the LS-DYNA Keyword Users Manual and reference [3], which also contains verification data with respect to [2] and notes on accuracy.
- References

  - 1 Trembley, J. E., "Impulse on blast deflectors from a landmine explosion", Defence Research Establishment Valcartier, TR DREV-TM-9814, 1998.
  - 2 P.S. Westine, B.L. Morris, B.L. Cox, and E.Z. Polch, "Development of computer program for floor plate response from land mine explosions," Technical report No. 13045, US Army Tank-Automotive Command, Warren, MI, 1985.
  - 3 Schwer L., Slavik T., "Burried charge engineering model: Verification and validation", 9th European LS-DYNA conference, 2013.

1 *INITIAL_IMPULSE_MINE

- Applies an initial impulse on the selected surface segments on the structure, this is reasonable given the application (land-mines under vehicles) using the formulas for impulse per area at a point (z,d):

$$i_v(x,y) = 0.1352\left(1+\frac{7}{9}\frac{\delta}{z}\right)\left(\frac{\tanh(0.9589\zeta d)}{\zeta d}\right)^{3.25}\sqrt{\frac{\rho E}{z}}$$

$$\zeta = \frac{\delta}{z^{5/4}A^{3/8}\tanh\left(\left[2.2\frac{\delta}{z}\right]^{3/2}\right)}$$

$$i_n = i_v\frac{\cos^2\theta}{\cos^2\beta}$$

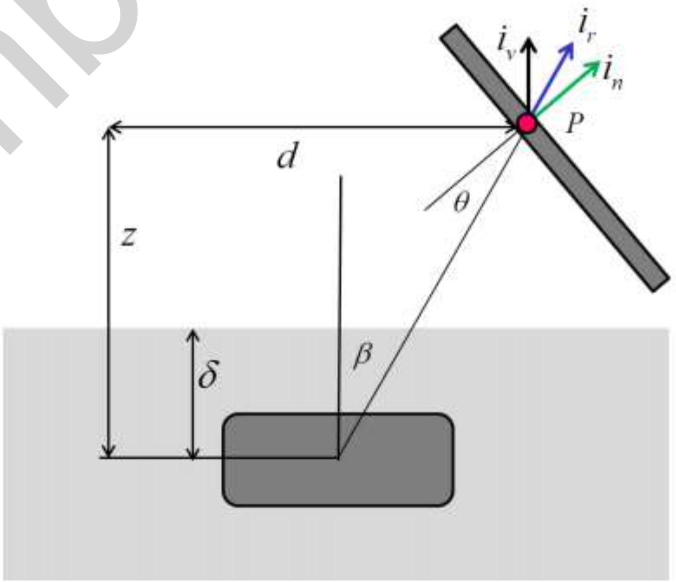


Figure from T. Slavik & L. Schwer, "Buried charge engineering model: verification and validation", 9th European LS-DYNA conf.

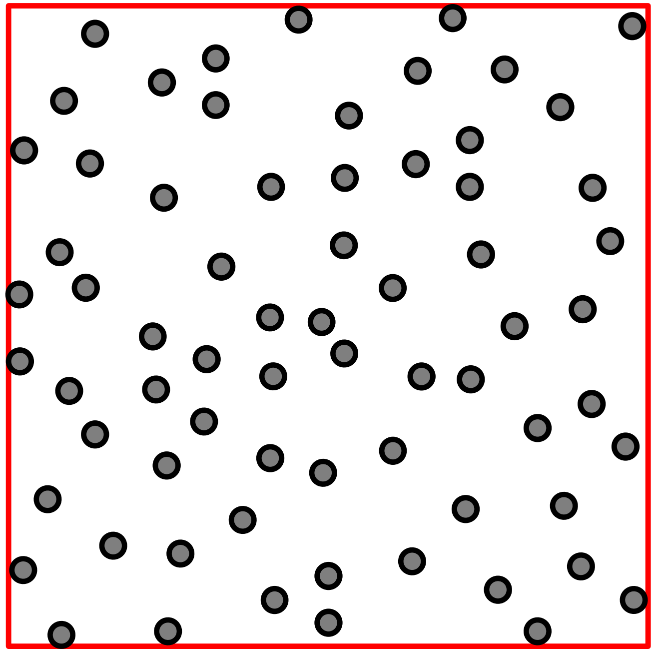
E [J] = Explosive released energy
A [m²] = Charge cross section area
rho [kg/m³] = Soil density
delta [m] = depth of burial
z & d = distance

First principle physics based methods for explosive load calculation

- Particle blast – Corpuscular Particle Method
- Multi-Material ALE
- SPH – Smooth Particle Hydrodynamics
- CE/SE including Chemistry module

2 Particle blast - Corpuscular Particle Method

- The CPM is a particle based method for ideal gas simulation based on kinetic gas theory.
- Gas law: pV=nRT, ideal gas.
- Developed for airbag unfolding simulations.
- Presented in 2007 at the 6th international LS-DYNA conference, see [1].
- Reference regarding theory
  - 1 Lars Olovsson, "Corpuscular method for airbag deployment simulations", 6th international LS-DYNA conference, 2007.



2 Particle blast - Corpuscular Particle Method Theory

- Particles are spherical and rigid to speed up contact calculations.
- For a monoatomic gas, particle-particle collisions are perfectly elastic.
- For non-monoatomic gases, for each particle there is a balance between kinetic energy and spin & vibrational energy. The balance between the latter defines the gamma value (compressibility) of the gas assuming local thermal equilibrium.
- Each particle represents many molecules (i.e. 1e15 or more).
- To arrive at the ideal gas law, particle sizes must be small compared to the mean free length. For computational efficiency they cannot be too small. LS-DYNA sets the particle size automatically.

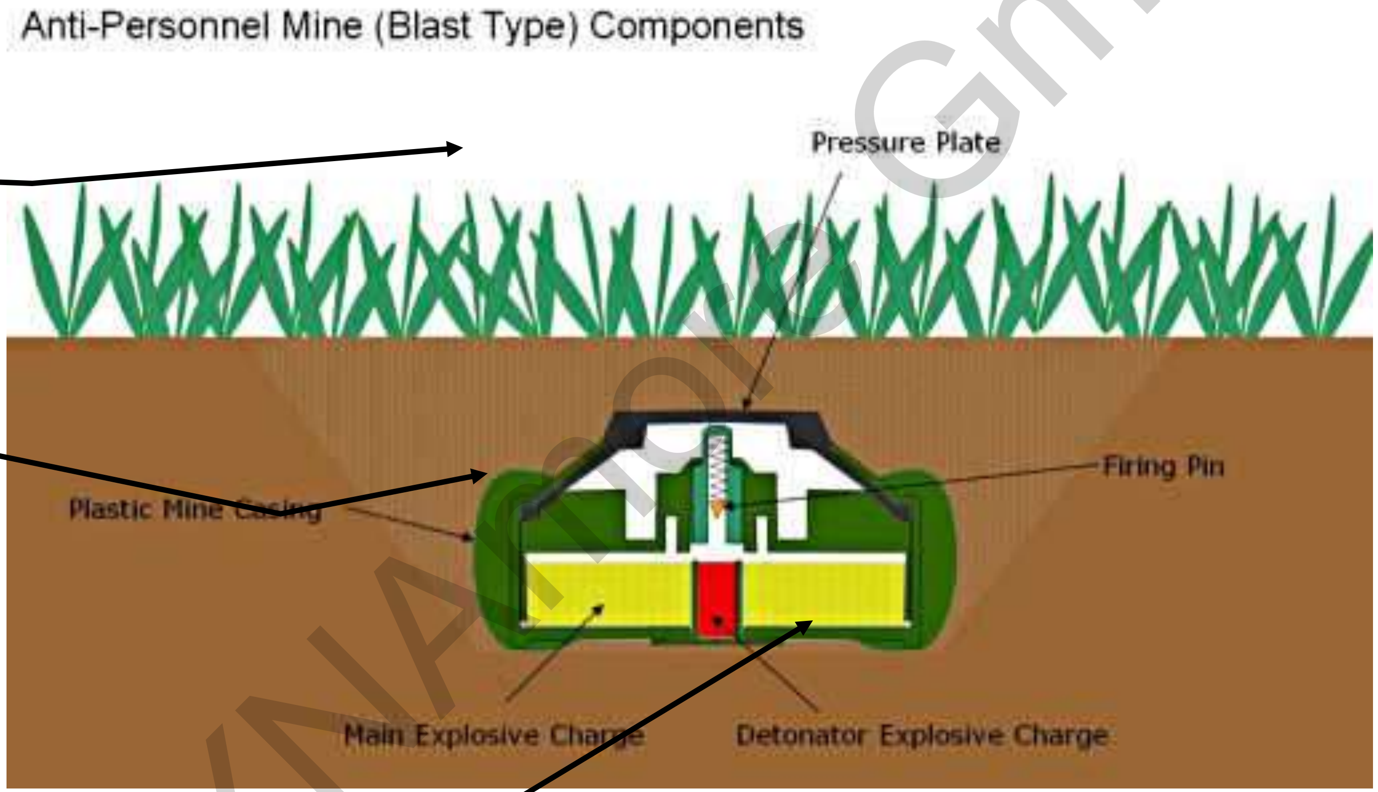
2 Particle Blast – Extension of the CPM

- Air
  - Ideal gas law (CPM): pV=nRT, no thermal exchange with the structure.
  - Particles are at time 0 are initialized with random speeds, positions et c. according to the required statistical distribution (e.g. Maxwell distribution for speeds) to obtain a gas at initial thermal equilibrium.
- High Explosive (HE) – modified CPM
  - In the HE the molecules are initially so tightly packed that they cannot accurately be modelled using the ideal gas las. Thus a modification of the CPM method was made to handle this.
  - Detonation: The HE is a frozen highly compressed gas representing the detonation products. The ignition time is calculated by the distance to the ignition point and the input Chapman-Jouget detonation velocity. At ignition of a particle it is released with the proper speed, spin/vibrational energy.

2 Particle Blast – Land mine simulations

Air particle (Ideal Gas Law)

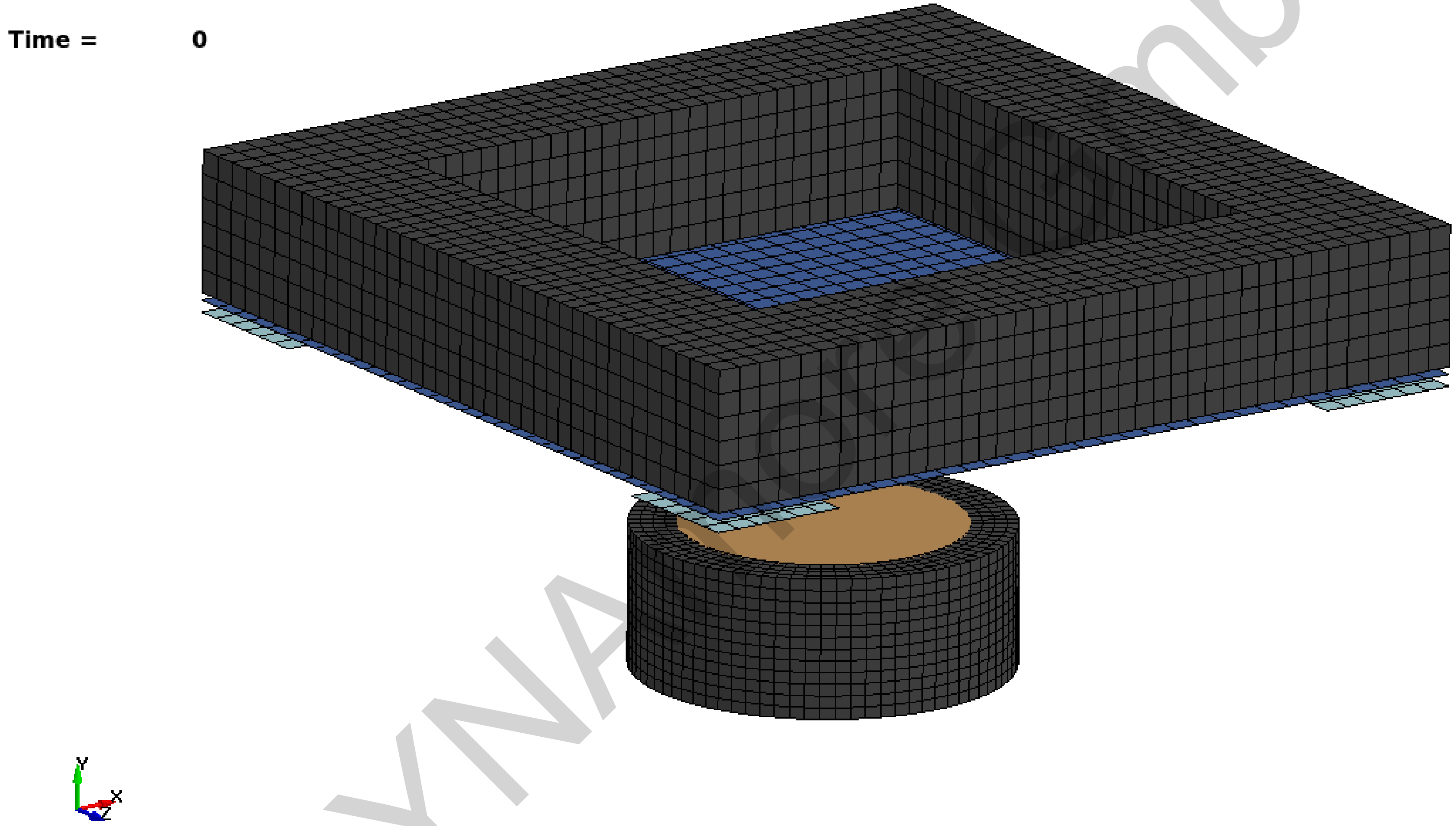
Discrete Element Method (DEM)



HE Particle Real Gas Law)

Source: LSTC presentation

2 Particle Blast – Land mine simulations



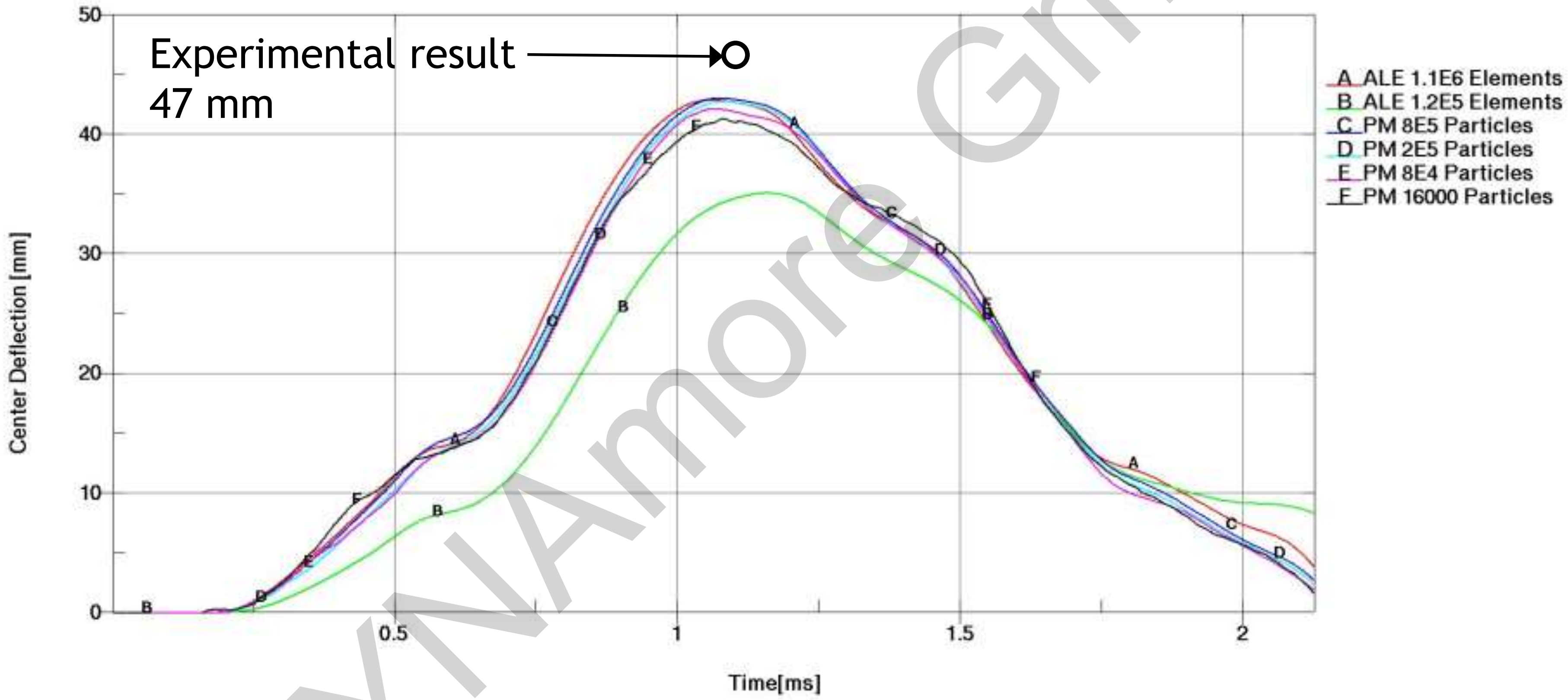
2 Particle Blast – Land mine simulations

2 Possible advantages and disadvantages of the particle blast method

- Possible advantages of the particle blast method compared to Eulerian solvers based on authors experience with LS-DYNA particle blast and MMALE solver
  - Works well with particle soil solver (discrete element method).
  - Seems, based on current findings, to be superior both in accuracy and solution time for close range blasts, such as land mine blasts.
  - Easy to setup and use.
- Disadvantages of the particle blast method
  - A fairly recent development, thus theory and implementation are not as mature.
    - E.g. only limited options, e.g. air is always at NTP.
  - Limited selection of explosive material models.
  - Limited post processing, i.e. no pressure contour plots can be made.
  - Pressure wave propagation at longer distances is subject to (significant?) dispersion.

2 Simulation results - Convergence rate

- Results from a study by Hailong Teng, LSTC, is shown below



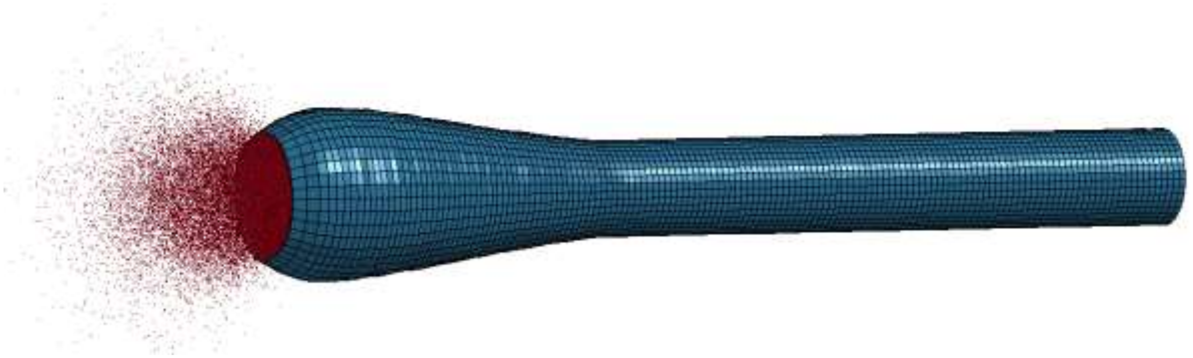
The peak deflection in the experiments has been estimated as 47mm (Neuberger et al. 2009)

2 Simulation results – Cylinder test

- Ref.: "Cylinder Test on C-4", UCRL-TR-230845, LLNL, P. C. Souers, 2007
  - Cylinder test set up

Explosive Name	Cylinder Shot No.	Expl. Density (g/cc)	Cylinder Material	Approx Diam inches	Detvel Diameter (mm/µs)	Inner Thickness (mm)	Wall Shot (mm)	Date
COMP C-4	289	1,601	Cu	1	8,193	25,43	2,593	740314

- Example model: CylinderTest
- Simulation
  - 1e6 particles, default C-4 parameters.
  - LS-DYNA: SMP version R9, double prec. (double prec. probably not needed)
  - Tube length 300 mm
  - 1 layer of ELFORM=1 solid elements
  - OHFC material model – Grüneisen EOS & Zirelli-Armstrong yield model



2 Cylinder test

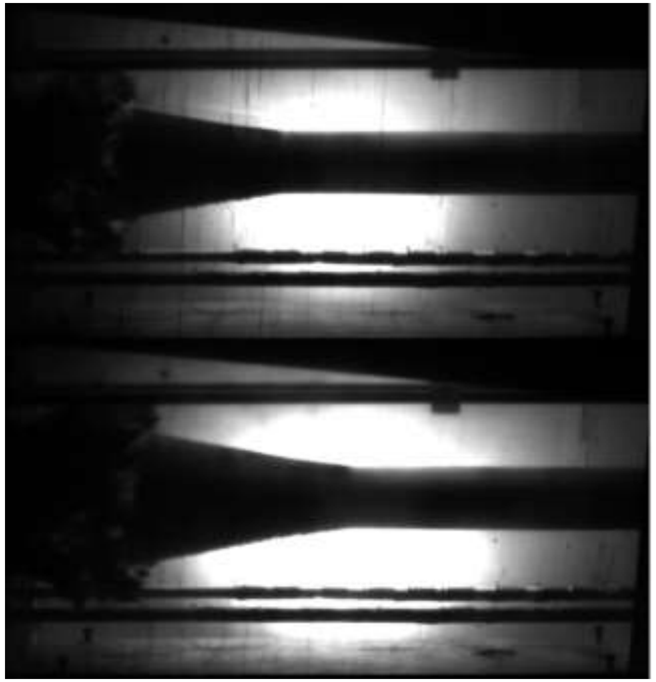
- Cylinder test – Often used to determine explosive material EOS
  - Images below from Jacksson, S. I., ” Scaled Cylinder Test Experiments with Insensitive PBX 9502 Explosive“, Los Alamos National Laboratory, LA-UR-14-24823, 2014.
  - Velocity & expansion often measured about 1/3 from tube ignition end.
  - Classical fitting function for wall radial expansion

$$R(t) - R_0 = \frac{V_\infty (t - t_0) f(t)}{\frac{2V_\infty}{a_0} f(0) + f(t)}$$

with

$$f(t) = (1 + t - t_0)^\omega - 1$$

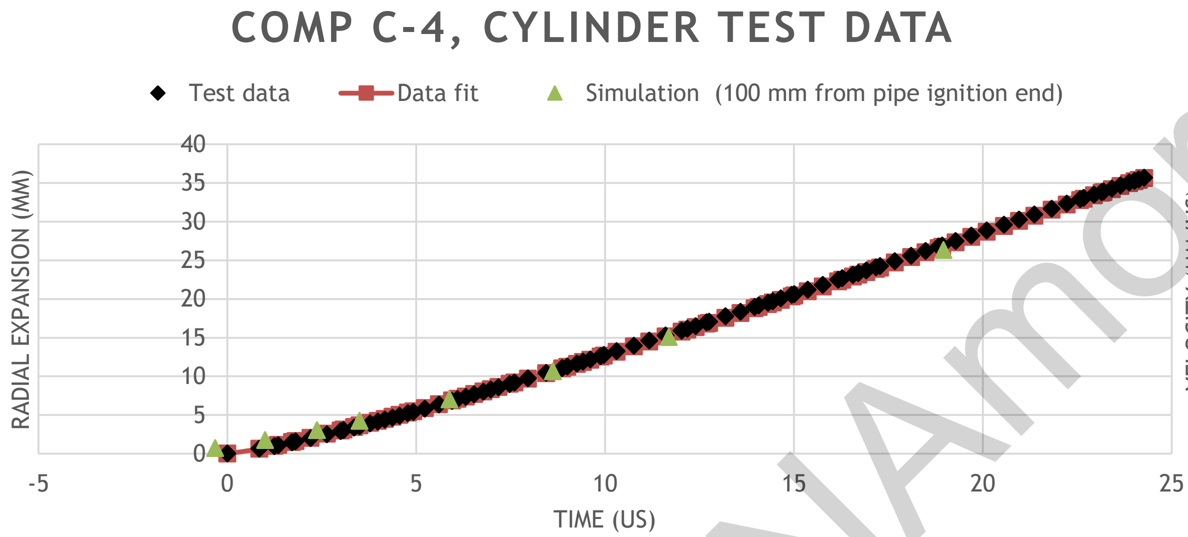
Test rig, 1 in. tube, 2x2 Photon Doppler Velocimetry sensors.

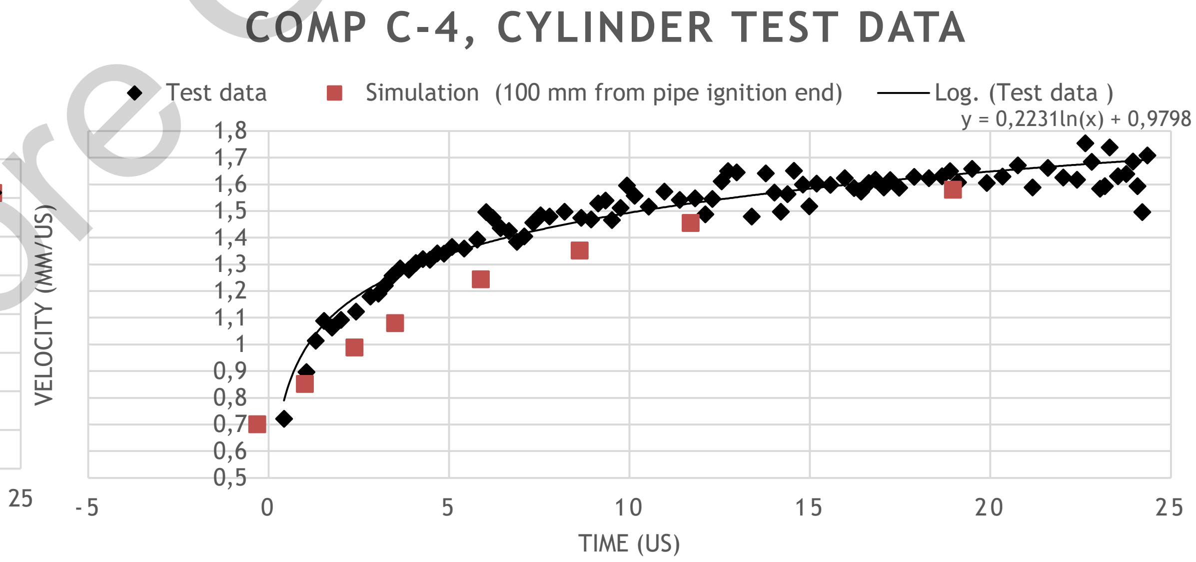


High speed photos of the event.

2 Simulation results – Cylinder test

- Comparison between test and simulation
  - Simulation data from cross section 100 mm (=1/3) from beginning of tube.





2 Particle blast for air-blast – Final comments

- The particle blast method is promising. As it is a fairly recent development one can expect further significant improvements over time in e.g. features, accuracy and scalability.
- Further benchmarking is needed to determine the accuracy and limitations/advantages.

3 3D ALE for air-blast

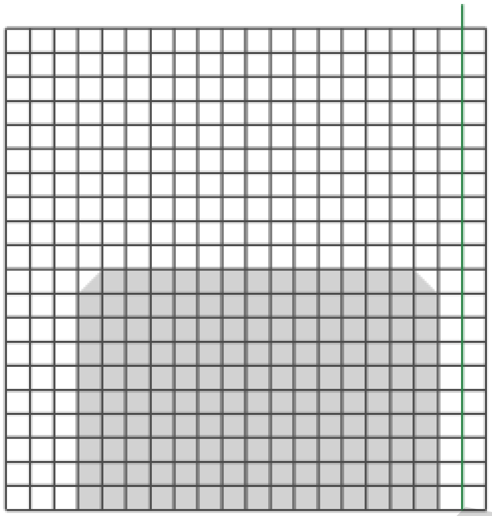
- The Multi-Material Arbitrary Lagrangian-Eulerian solver in LS-DYNA has long history, very many features and is used both for solid and fluids and fluid-structure interaction.

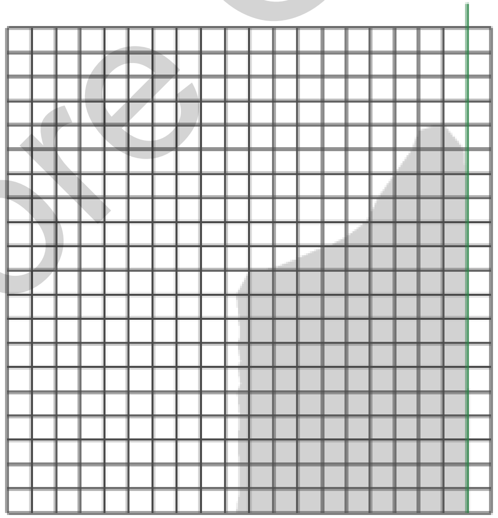
3 3D ALE for air-blast

- It is a fairly challenging task to set up a model the first time:
  - Complex keyword input format with many options.
  - Need to have at least a basic understanding of explosive EOS (Equation of State) and material properties, and the physics of detonation & shockwaves.
  - Need to have a least a basic understanding of the theory of the MM-ALE solver and the key numeric parameters.
  - Successful FSI (Fluid Structure Interaction) simulation requires a good understanding of the *CONSTRAINED_LAGRANGE_IN_SOLID, the theory behind it and its use.
  - Need to develop modeling guidelines including carrying out mesh convergence studies.
  - For most problems of interest, it can require significant computer resources.
  - Often advanced analysis strategies are needed to reach an acceptable ratio of accuracy/computational cost: 2D-3D mapping, coupling to *LOAD_BLAST, restarts, and/or deactivation of the MMALE solver when the shockwave has passed.

3 Multi-Material ALE analysis run in the Eulerian mode

- The mesh is fixed (the so called Euler mesh) and the material flows through the mesh. The degrees of freedom are the nodal velocities and the densities of each species(=material, i.e. air and explosive) in the simulation.





3 Multi-Material Eulerian formulation

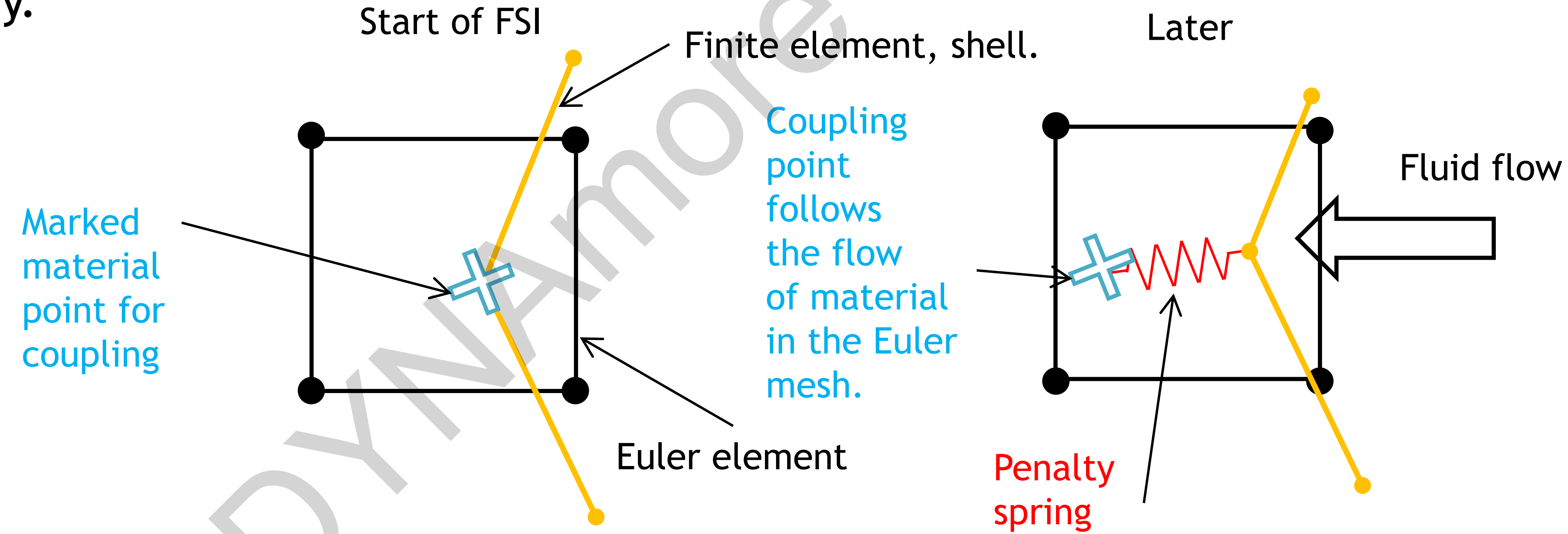
- The steps performed each time step are
  - Finite element timestep (using the explicit central difference method). This deforms the mesh.
  - Advection step: The solution on the deformed mesh is mapped back to the original un-deformed mesh.
- Note: To run the MM-ALE solver in Euler mode set AFAC=-1 on *CONTROL_ALE and use (for 3D) element formulation ELFORM=11 on *SECTION_SOLID.

3 Multi-Material Eulerian formulation - Advection

- There are several different advection methods in LS-DYNA (set using METH on *CONTROL_ALE).
- The advection schemes are designed to conserve the total momentum (on the expense of kinetic energy). Thus one can often observe a certain loss of energy in the simulation.

3 Fluid-Structure Interaction

- Usually the penalty option is used. The penalty based algorithm tracks the relative displacement between fluid and the structure. Node forces, proportional to the magnitude of the relative displacements, are applied forcing the fluid and structure to follow each other. The method conserves energy.



3 Fluid-Structure Interaction

- Ideally an FSI coupling would have no artificial energy/momentum losses <u>and</u> no leakage <u>and</u> be perfectly immersive for solids and shells.
- Coupling between structure and solid is done using the keyword *CONTRAINED_LAGRANGE_IN_SOLID. It is an immersive-type FSI.
  - Complex keyword to set up, many options and features.
  - Recommended to use the penalty based FSI for explosive applications.
  - Only truly immersive for structural solid models. For shells it works best if there is a clear in-and out-side of the structure.
  - MM-ALE (Euler) element size should preferably be similar to structural element size.
  - Expect leakage to be a problem for blast/explosive FSI, especially in areas of the structures with corners. Careful tuning of numerical parameters can often reduce/resolve the problem. A finer mesh and shorter timestep will also very much reduce such problems.

R9.0.0 – Automatic mesh generation

- In R9.0.0 a structured MM-ALE mesh can be automatically generated using *ALE_STRUCTURED_MESH.
  - A structured mesh is sufficient in many practical situations.
  - Easy to use and carry out convergence studies.
  - Much smaller input files.
  - Due to the structured mesh, LS-DYNA runs faster and uses less memory.

3 Mapping 2D to 3D as method to increase the accuracy/”computational effort” ratio

- LS-DYNA also has a 2D and 2D-axisymmetric MM-ALE solver. 2D-axisymmetric analysis is much quicker for a given mesh resolution than a 3D MM-ALE simulation.
- It is possible, using the mapping commands in LS-DYNA to simulate the initial detonation of the charge and formation of the air shock wave using the 2D MM-ALE solver and then map the 2D solution to a coarser 3D MM-ALE model as an initial condition. This can save significant CPU-resources.

3 Example: Mapping 2D to 3D

- Steps
  - A 2D axisymmetric model is run with the following command:
    - ls971 i=explo2d.k map=2dto3d
  - After the last time step 2D data (density field, velocity field,…) are written in the file 2dto3d to be mapped to the 3D model. Copy this file to the 3D folder.
  - For the 3D model:
    - Remove *INITIAL_DETONATION, replace *MAT_HIGH_EXPLOSIVE_BURN with *MAT_NULL.
    - Add *INITIAL_ALE_MAPPING card
  - Run the 3D model with the same command:
    - ls971 i=explo3d.k map=2dto3d
  - The file 2dto3d is read to initialize the 3D run.

3 Mapping 2D to 3D as method to increase the accuracy/"computational effort" ratio

- More information on the usage is given in [3] by LSTC and [4] and [5].
- References

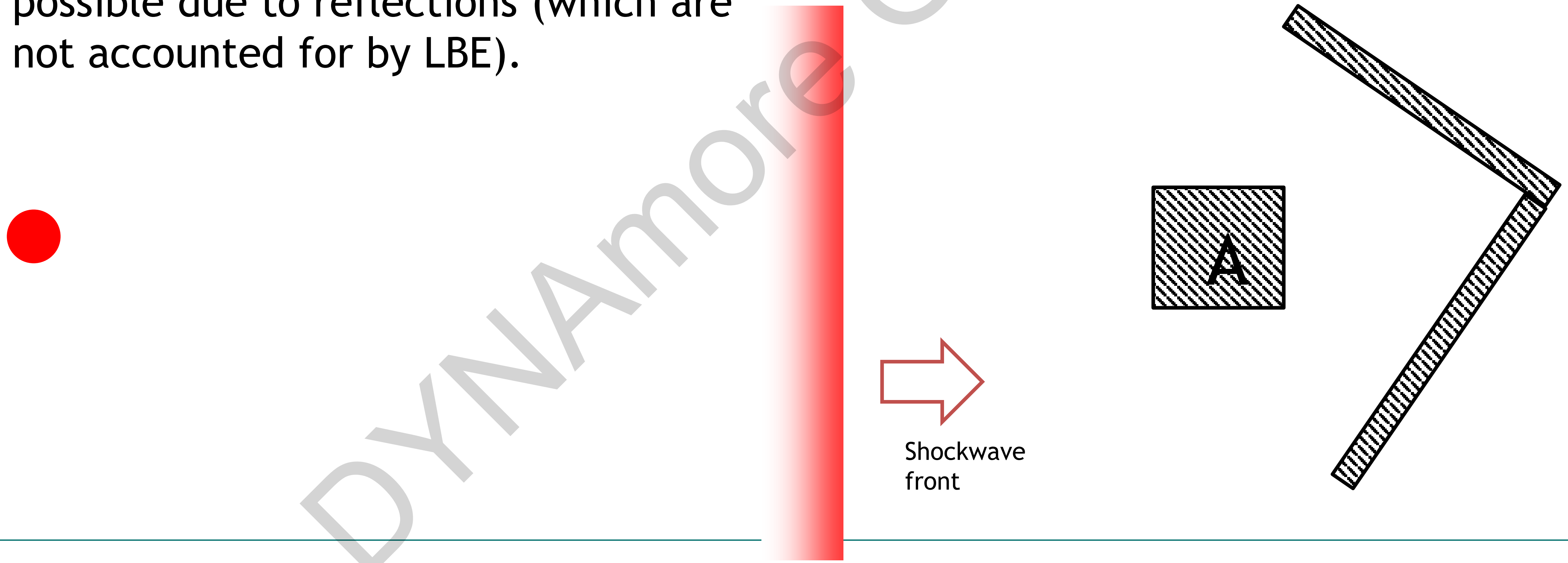
  - 3 N Aquelet, M Souli,"2D to 3D ALE Mapping", 10th International LS-DYNA Users conference, Detroit.
  - 4 A Karla, et al, "Key parameters in blast modelling using 2D to 3D ALE mapping technique", 13th International LS-DYNA Users conference, Detroit.
  - 5 V Lapoujade, et al, "A study of mapping technique for air blast modelling", 11th International LS-DYNA Users conference, Detroit.

3 Multi-Material ALE in LS-DYNA - Summary

- Functionality for explosions
  - Solvers: 3D, 2D, 2D-axisymmetric, and 1D.
  - Mapping: Mapping of solutions from 1D->2D, 1D-3D, 2D-3D
  - 3D hybrid simulation with *LOAD_BLAST_ENHANCED – See next slides.
  - Reuse recorded explosive loads on a structure (using *ALE_FSI_TO_LOAD_NODE) from a previous MM ALE-analysis to structures with a near identical external shape and blast load case.
- Explosive EOS models (i.e. material data for simulation)
  - JWL & JWLB, data for many explosives readily available (see e.g. LLNL Explosives handbook).
- Note on buried mine simulation: MM-ALE simulation models can readily include soil and sand.

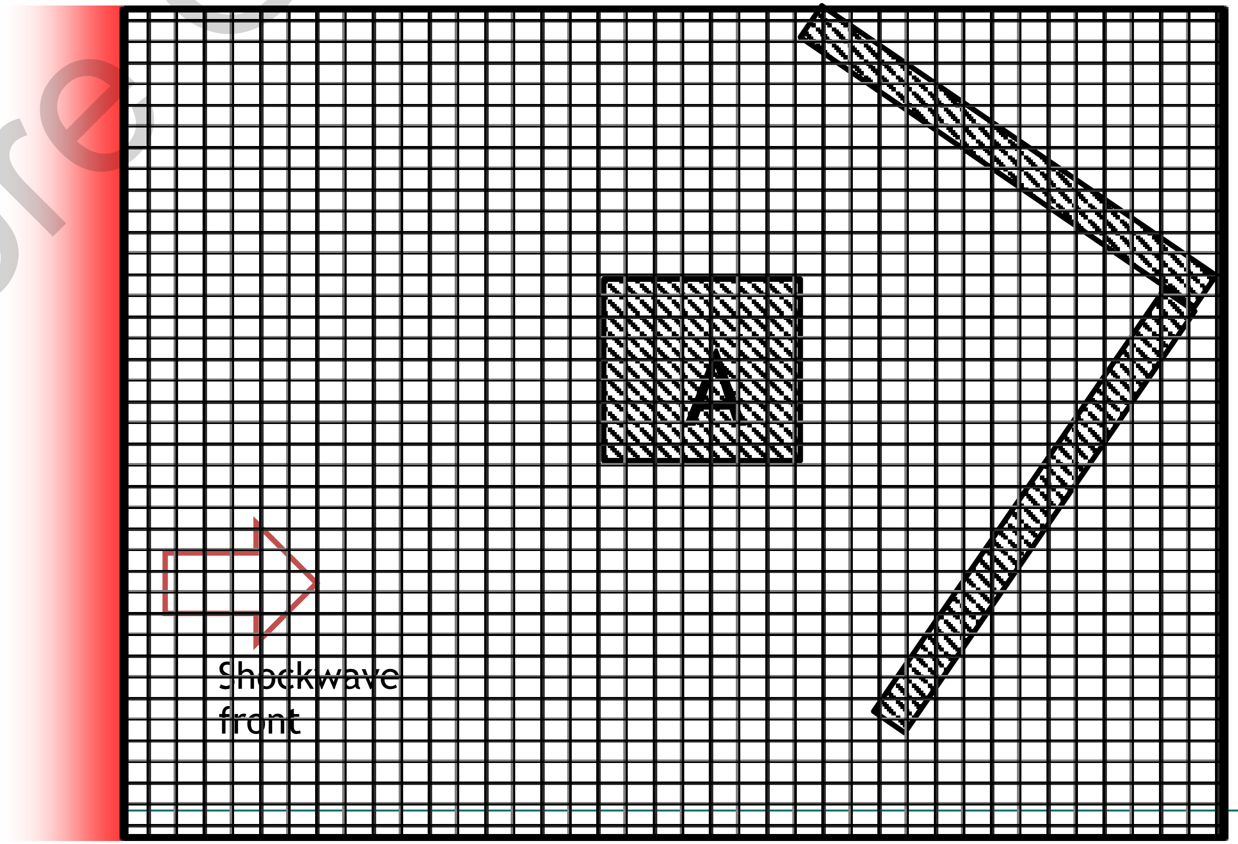
3 *LOAD_BLAST_ENHANCED and MM Euler hybrid

- *LOAD_BLAST_ENHANCED (LBE) applies a phenomenological blast pressure. It is easy to use, proven, and fast but limited to situations of simple geometry. For instance, determining the loading on object A below will be not be possible due to reflections (which are not accounted for by LBE).



3 *LOAD_BLAST_ENHANCED and MM-ALE coupling

- With LBE to MM-ALE coupling a MM-ALE mesh can be put around the region of interest (to account for the reflections) and the outside of the MM-ALE mesh is loaded by LBE.
- The MM-ALE mesh needs to be large enough to avoid boundary effects.
- This method allows use of MM-ALE analysis also to larger scaled distances.



3 *LOAD_BLAST_ENHANCED and MM-ALE coupling

- For information and comparison on the use of the LBE to MM Euler coupling please read ref [6]. Reference [7] provides a comparison for a fairly close range loading.
- References

  - 6 L Schwer,"A Brief Introduction to coupling Load Blast Enhanced with Multi-Material ALE: The best of both worlds for air blast simulation", 9th LS-DYNA Forum, Bamberg, 2010.
  - 7 L. Gilson, J. Van Roey, C. Gueders, J. Gallant, L. Rabet, "A simple coupling of ALE domain with empirical blast load function in LS-DYNA", DYMAT 2012 conference, Freiburg, 2012.

Final notes on new technology

- CE/SE – The Conservation Element/Solution Element Compressible CFD-solver. Results for shock type problems are very good - a significant improvement over current MM-ALE-technology.
  - Automatic shock capturing without Riemann solver.
  - Can be coupled to *LOAD_BLAST_ENHANCED (cf. MMALE).
  - Direct simulation of explosives like with MM-ALE is not practically possible* today: The CE/SE solver is missing multi-species surface tracking and a phenomenological explosive models/EOS such as the Jones-Wilkins-Lee EOS (*EOS_JWL). (*In the opinion of the author.)
  - For more information visit: http://www.lstc.com/applications/cese_cfd

Questions and Answers

Thank you!

Your LS-DYNA distributor and more