

Blast Loading in LS-DYNA®

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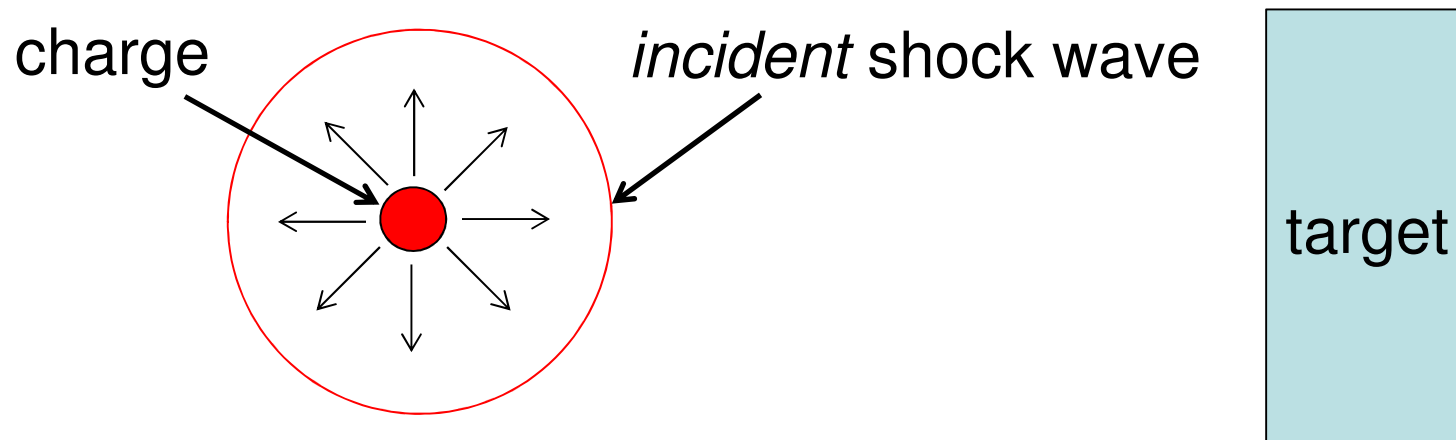
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University of California – San Diego



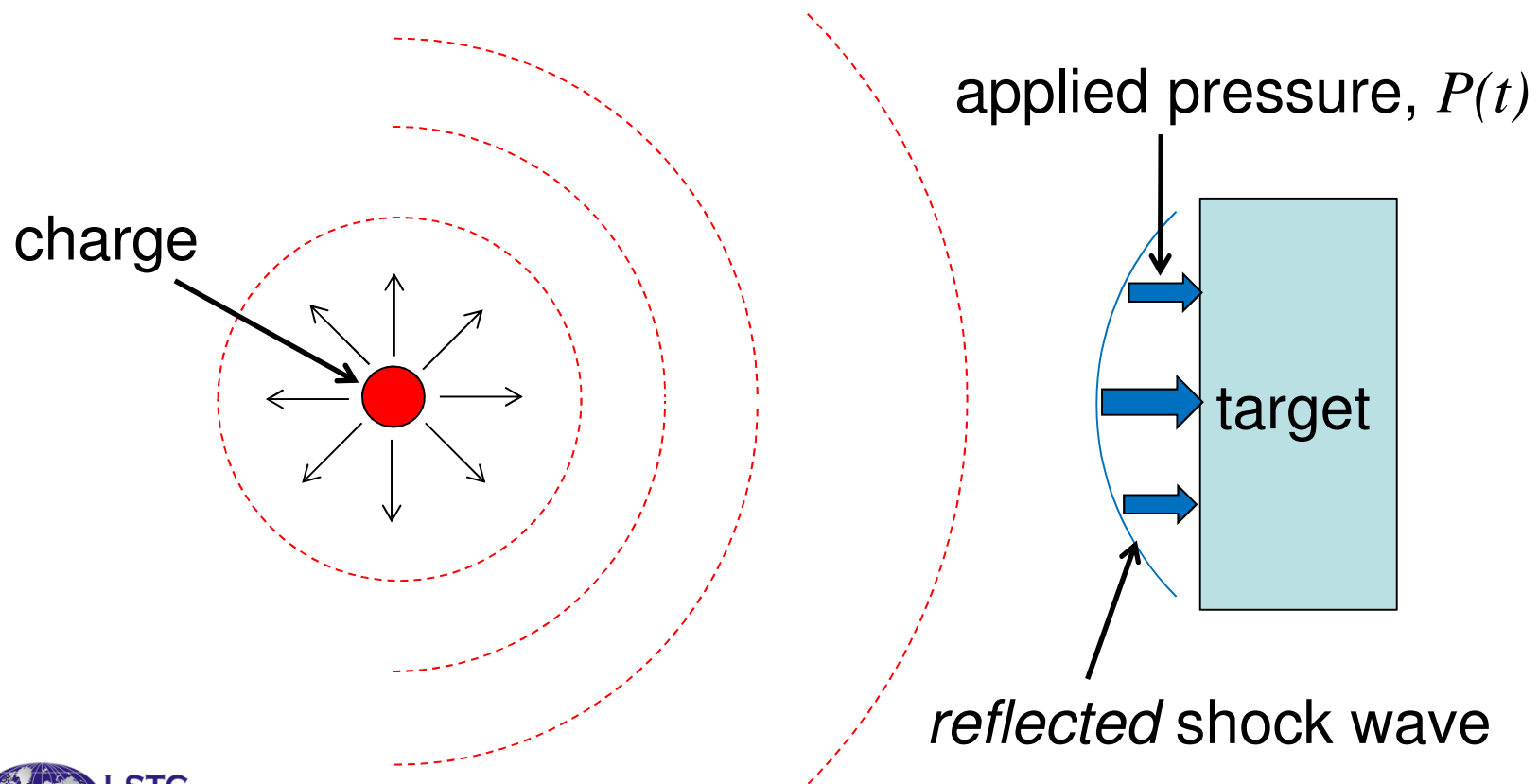
Explosion in Air - Incident Shock Wave

- The detonation of an explosive charge liberates energy causing pressure disturbances in the surrounding air which develop into a blast wave system led by an incident shock wave.



Reflected Shock Wave - Blast Load

- The incident wave strikes the target and rebounds with greater amplitude as a reflected wave. This reflected pressure becomes the applied blast load.



Blast Simulation in LS-DYNA

1. *LOAD_BLAST_ENHANCED

- Empirical pressure loads applied directly to the nodes of a Lagrangian structure

2. Arbitrary Lagrangian-Eulerian

- Explicit modeling of explosive and air using equations-of-state
- Lagrangian structure is loaded through Fluid Structure Interaction

3. A hybrid combination of the methods above

4. Particle Methods



*LOAD_BLAST_ENHANCED

- This feature grew from *LOAD_BLAST in response to a sharp rise in interest from the counter-terrorism community circa 2002
- The flexible framework allows: multiple charges, database support, ALE coupling, etc.
- Related keywords
 - *LOAD_BLAST_SEGMENT
 - *DATABASE_BINARY_BLSTFOR
 - *DATABASE_BLSTOUT (on the horizon)

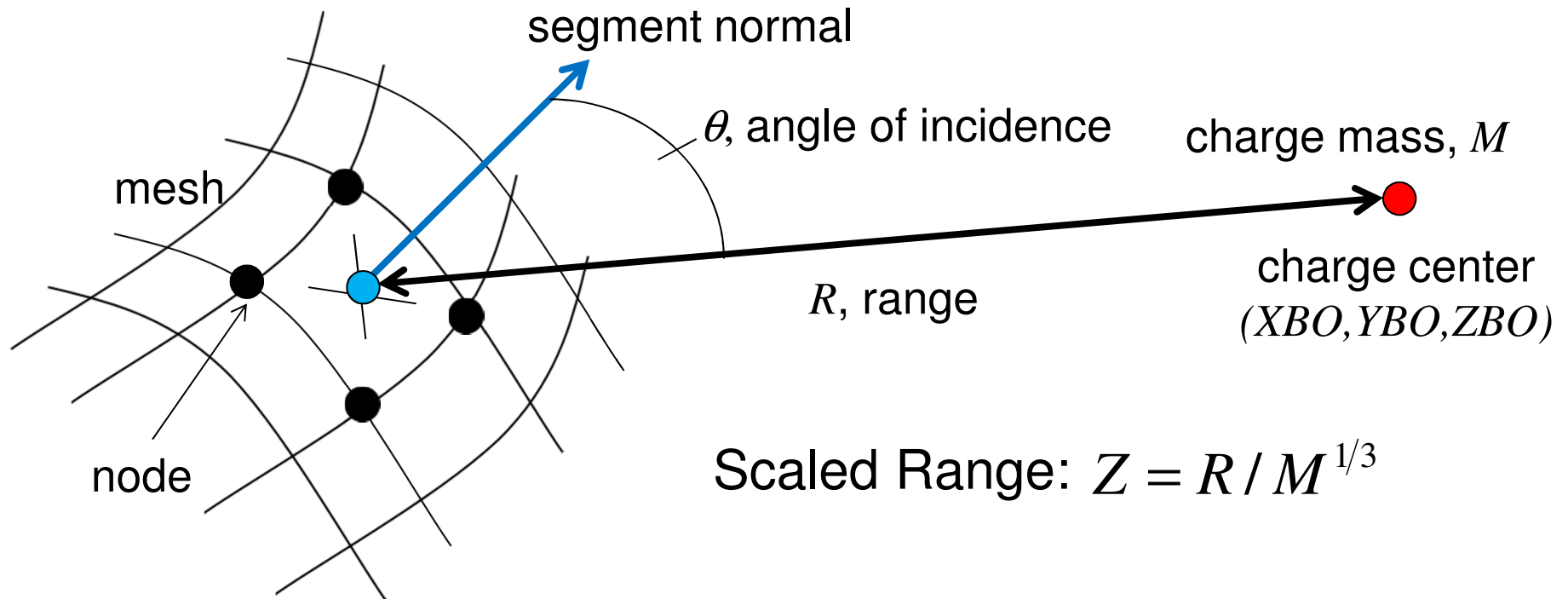


Background

- *LOAD_BLAST_ENHANCED draws upon a database of experimental data which provides empirical pressure histories due to conventional chemical explosions
- It has roots similar to that of the CONWEP software package but strictly speaking CONWEP is *not* embedded in LS-DYNA
- Provides a simplified and proven analysis approach over the computationally expensive ALE method



Basics of the Blast Load Model



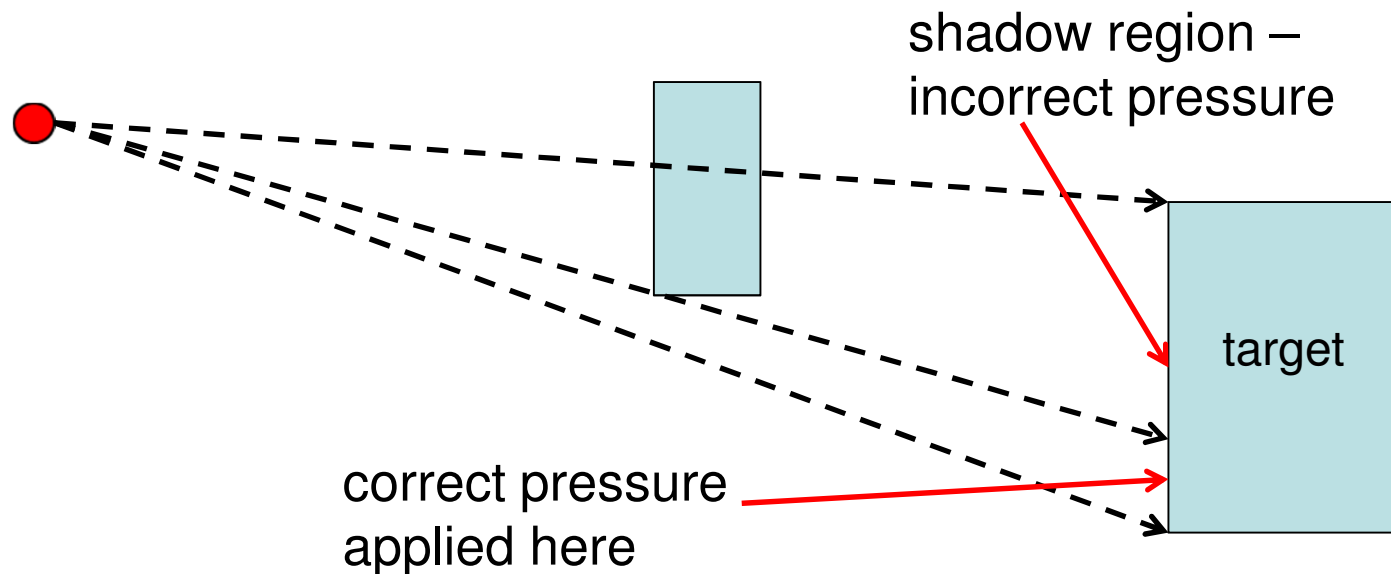
- The blast pressure $P_{eff}(t)$ at the segment centroid is computed using Z and θ
- This pressure is converted to forces applied to the nodes of the finite element mesh

Range / Angle of Incidence

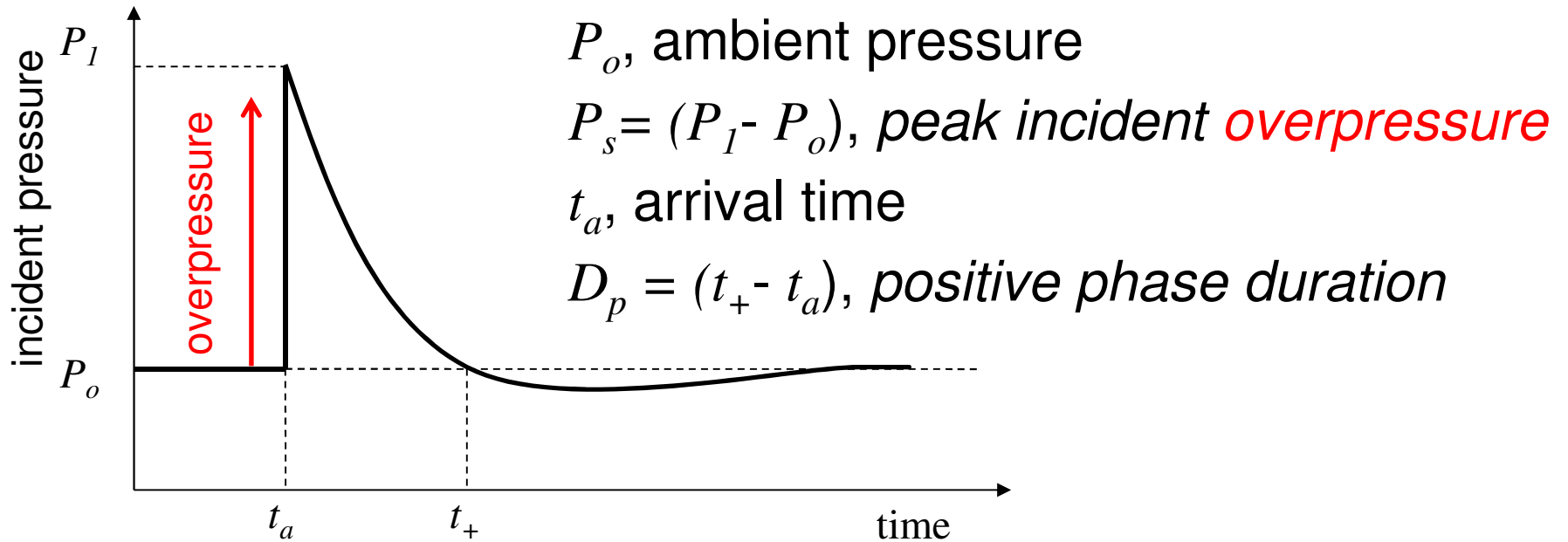
- Quadrilateral or triangular segments subjected to the blast load are formed by of nodes of the finite element mesh.
- As the mesh distorts/translates the nodal coordinates and the segment normal change accordingly.
- The *range* and *angle of incidence* is computed by LS-DYNA on every integration cycle and in turn the corresponding blast pressure is computed.

Line of Sight

- A clear *line of sight* from charge to target is assumed with *LOAD_BLAST_ENHANCED.
- The full blast load is applied to the target even if shadowed by an intervening object.



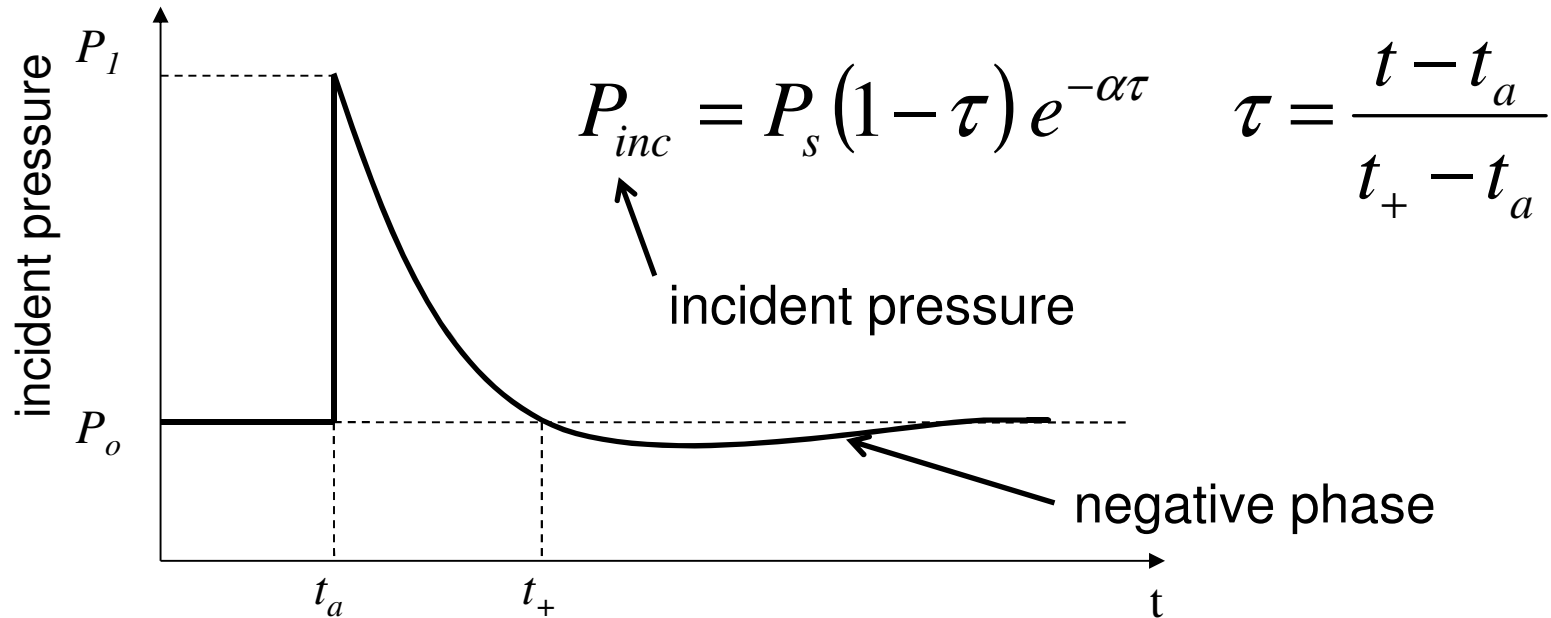
Air Blast Wave Characteristics



- The shock front arrives at point in space at time t_a
- Pressure jumps above the ambient pressure P_o then decays, sometimes below P_o , and returns to ambient conditions.
- Blast pressure in free-air is called the *incident pressure* (same as static pressure).

Empirical Air Blast Model

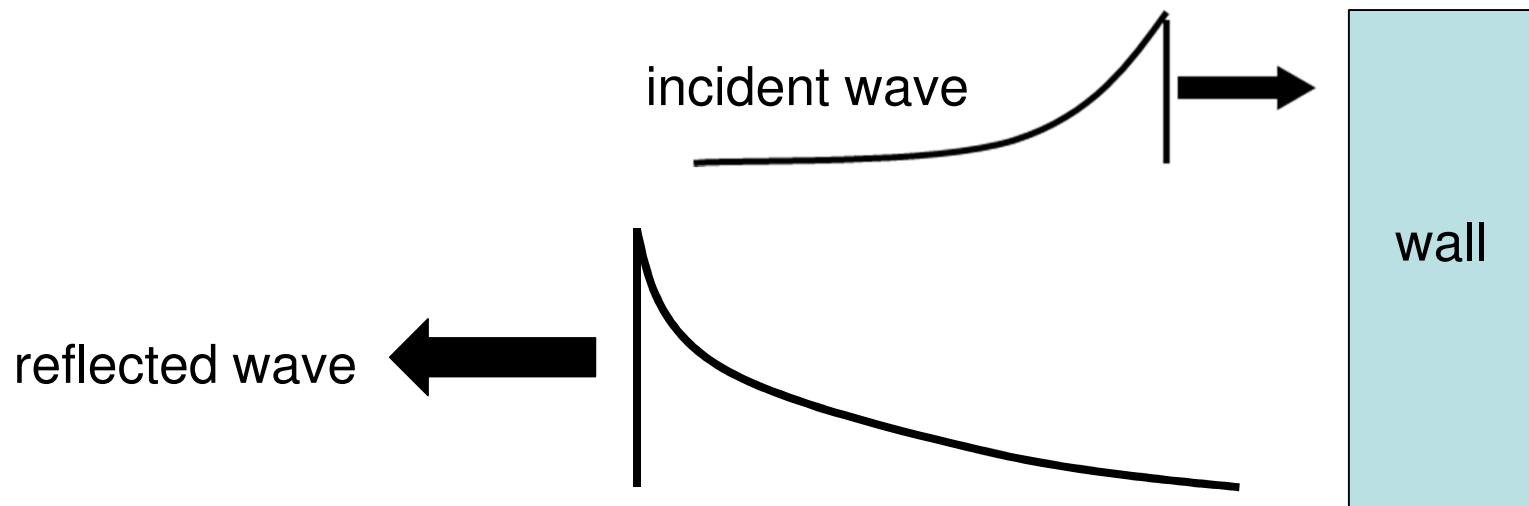
The Friedlander Equation



- Empirical parameters were derived from experimental data.
- The Friedlander equation accommodates the *negative phase* where in an elastic rebound effect the displaced air must eventually “pull back”.

Reflected Wave

- When a shock wave strikes an unyielding surface the motion of the air particles is terminated and a new *reflected wave* moving in the opposite direction results.



Normal Reflection

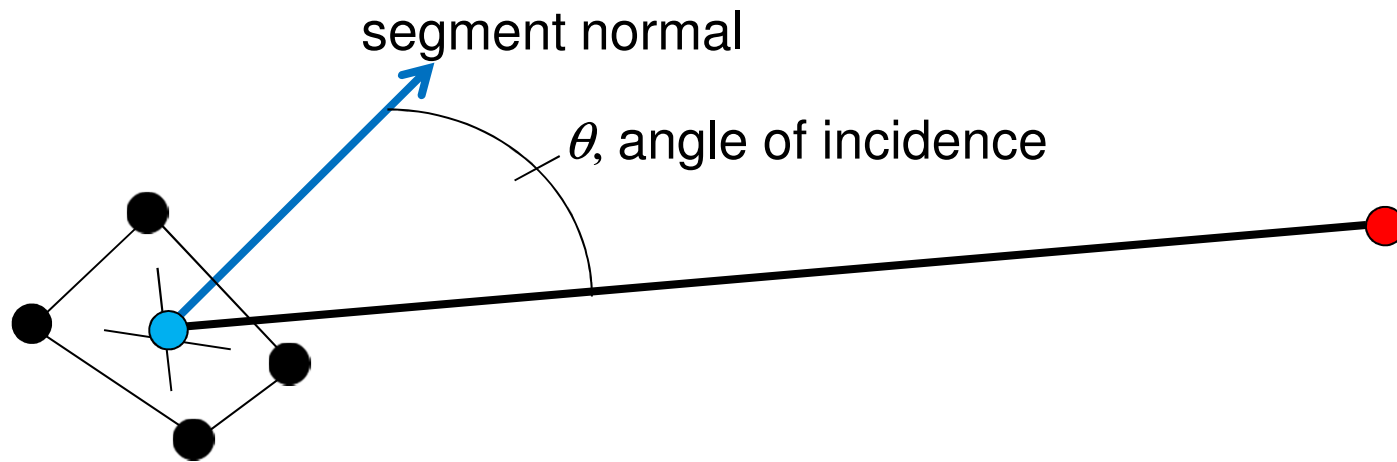
- At normal incidence the *peak reflected pressure* P_r lies in the range:

$$2P_s \leq P_r < 13P_s$$

- This is due to the great compressibility of air and depends on the strength of the incident shock.
- This is the stagnation pressure.
- The upper bound is often reported as $P_r = 8P_s$ but applies only to air with specific heat ratio $\gamma = 1.4$
- The Friedlander equation is also used to describe the decay behavior of the reflected pressure.

$$P_{ref} = P_r (1 - \tau) e^{-\beta\tau}$$

Oblique (Regular) Reflection



- When a shock wave encounters a target surface at an oblique angle of incidence the *effective pressure* is given by

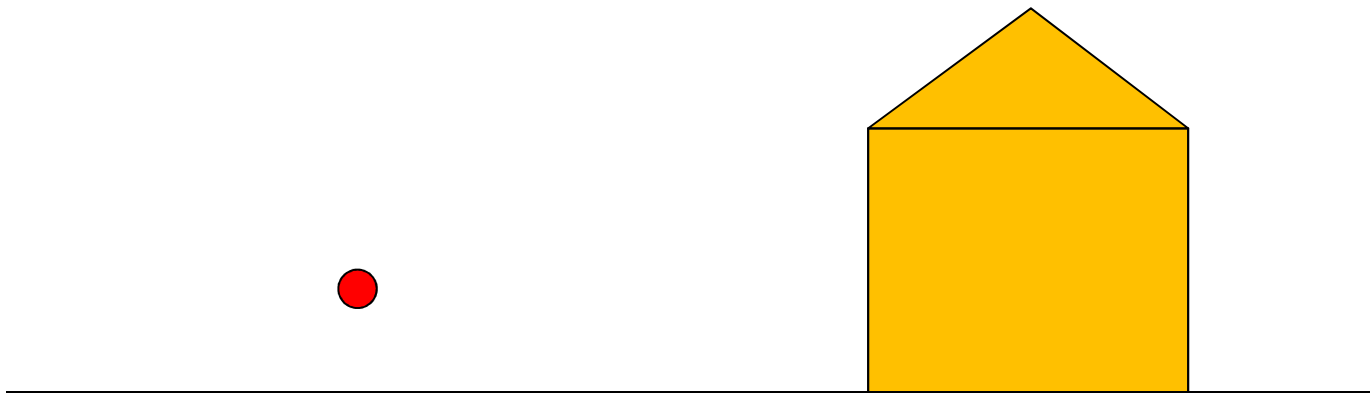
$$P_{eff} = P_{ref} \cos^2 \theta + P_{inc} (1 + \cos \theta - 2 \cos^2 \theta)$$

Effective Pressure

- The effective pressure is applied to the target segment – this is the blast load
- at normal incidence, $\theta = 0^\circ$: $P_{eff} = P_{ref}$
- for $90^\circ \leq \theta \leq 180^\circ$: $P_{eff} = P_{inc}$
 - Target segments which face away from the charge receive only the incident pressure (sometimes referred to as *side-on pressure*).
 - LS-DYNA does not account for shadowing. Those segments would *at most* see the incident pressure (conservative assumption).

Example

- A 10 kg TNT charge, 1.5 m above ground, is detonated 10 m from the face a building (*see related keyword input on next slide*)



Essential Input for Blast Load

*LOAD_BLAST_ENHANCED

\$	bid	m	xbo	ybo	zbo	tbo	unit	blast
	1	10.0	0.0	1.5	1.5	0.0	2	2
\$	cfm	cfl	cft	cfp	nidbo	death	negphs	
	0.0	0.0	0.0	0.0				

discussed later

charge mass and location

*LOAD_BLAST_SEGMENT_SET

\$	bid	ssid	alepid	sfnr	scalep
	1	1			

*SET_SEGMENT

\$	sid			
	1			
\$	n1	n2	n3	n4
	5	1	2	6
	6	2	3	7

node IDs defining a quadrilateral segment (set n3=n4 for a triangle)

- etc. -



Structural Damage Levels

- “rules of thumb” with no consideration of pulse duration or target orientation (i.e., angle of incidence)

Incident Overpressure	Residential Homes	Multi-story Commercial/Industrial
1 psi (7000 Pa)	<i>Moderate</i> broken windows, partial collapse, extensive repairs	
3 psi (20,000 Pa)	<i>Severe</i> collapse, damage beyond repair	
10 psi (70,000 Pa)	<i>Destroyed</i>	<i>Moderate</i> partial collapse, extensive repairs

Databases

- The D3PLOT binary database involves all model topography and contains nodal quantities (displacements, velocities, etc.) and elemental quantities (stress, strain, etc.)
- The BLSTFOR binary database involves only blast segment topography and contains nodal quantities plus blast segment quantities (P_{eff} , P_{inc} , etc.)
 - This database is opened in LS-PREPOST in the same manner as D3PLOT: File→Open→LS-DYNA Binary Plot

***DATABASE_BINARY_BLSTFOR**

\$	dt	lcdt
	0.001	0



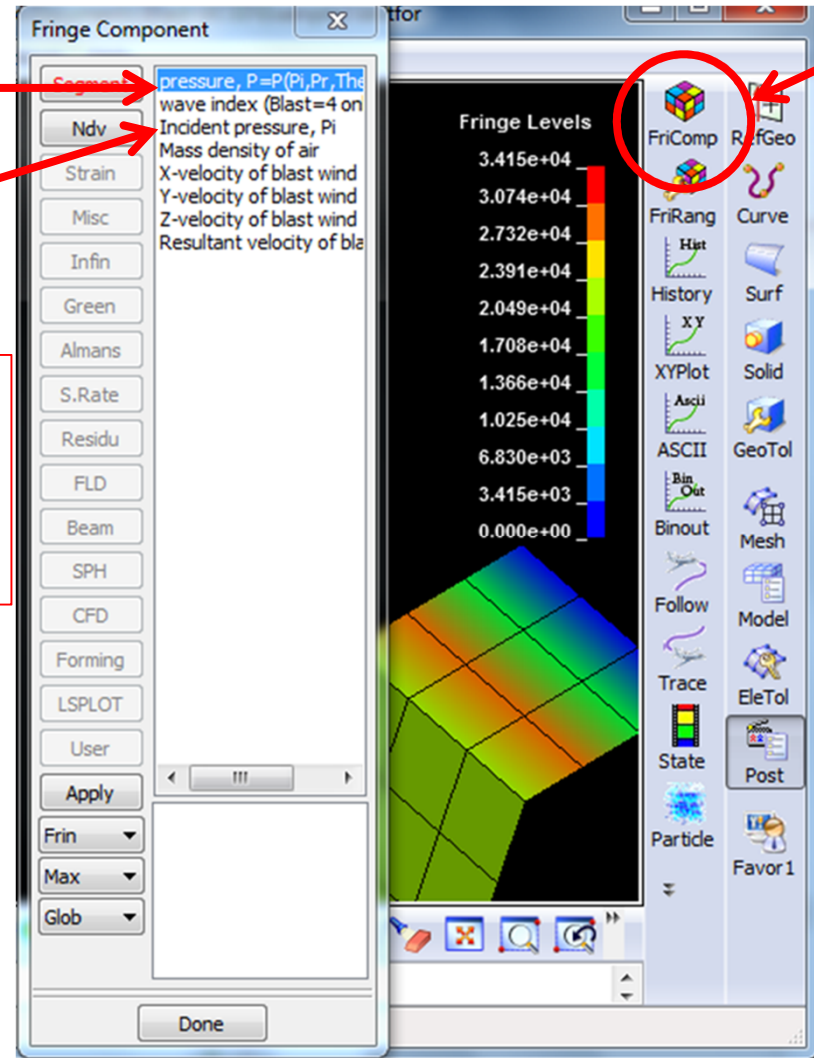
Post-Processing BLSTFOR Fringe Plots

effective pressure, P_{eff}

incident pressure, P_{inc}

Use the **FriComp** button to display pressure fringes on the blast segment mesh

The pressure reported here is always **overpressure** – pressure in excess of ambient pressure



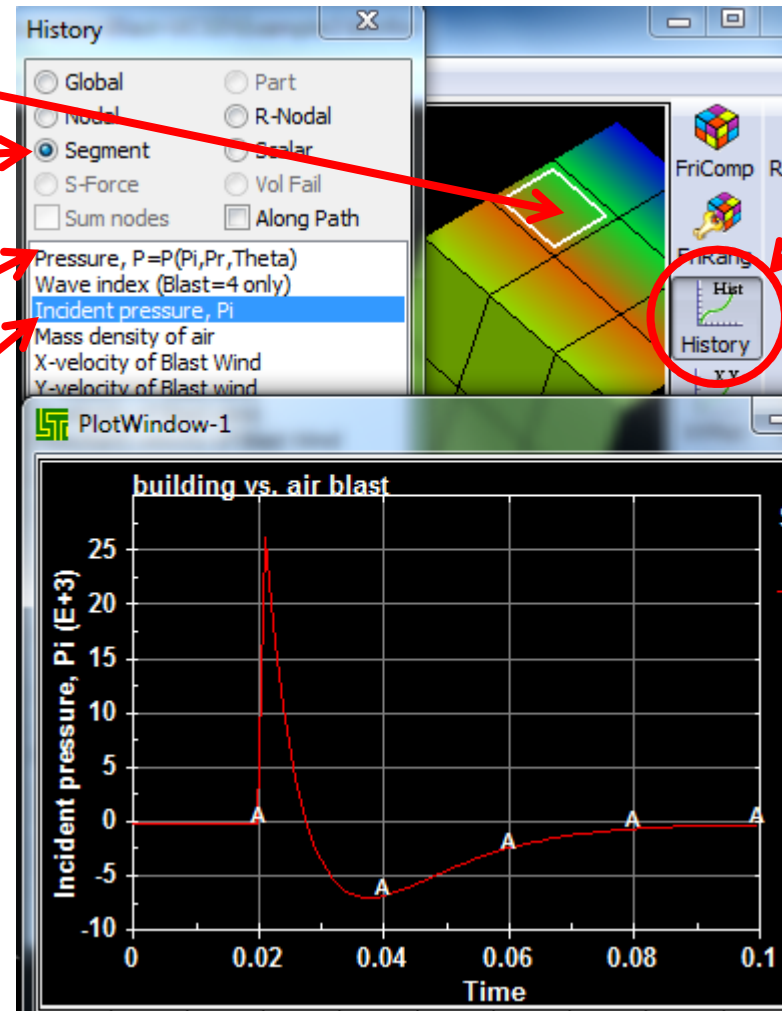
Post-Processing BLSTFOR History Plots

highlight segment(s)

segment

effective pressure, P_{eff}

incident pressure, P_{inc}



Use the **History** button to
make time history plots for
blast segments

The **overpressure** is always
reported here

2D Axisymmetric Analysis

- *LOAD_BLAST_ENHANCED is available for 2D axisymmetric analysis
 - See *SECTION_SHELL, ELFORM = 14 & 15
- Input remains the same except for segment definition

```
*SET_SEGMENT
```

```
$      sid
```

```
      1
```

```
$      n1      n2      n3      n4
```

```
      1
```

```
      5
```

```
      5
```

```
      5
```

```
← repeat n2=n3=n4
```

- A segment normal points away from the structure when node ordering is counter-clockwise around the structure.
- BLSTFOR database is not available for 2D → BLSTOUT



Warning and Error Messages

- Always check for warning/error messages on the screen scroll and messag & d3hsp files
 - Error messages are bad – fix it
 - warning messages are sometimes acceptable

*** Warning 30302 (INI+302)

number of blast segment normals pointing away from blast origin = 66

- This warning is acceptable since we know the ramifications of the normals on the back of the building pointing away from the charge, i.e., they will only see the incident pressure.



Type of Burst

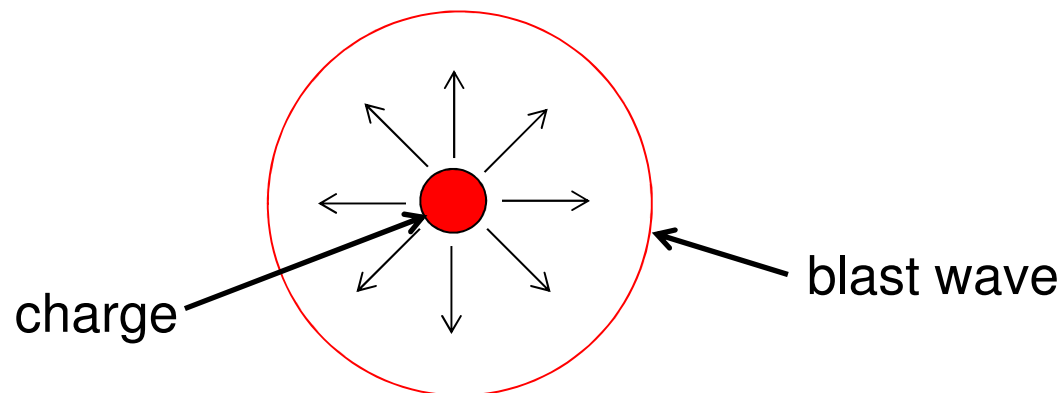
*LOAD_BLAST_ENHANCED

\$	bid	m	xbo	ybo	zbo	tbo	unit	blast
	1	10.0	0.0	1.5	1.5	0.0	2	2
\$	cfm	cfl	cft	cfp	nidbo	death	negphs	
	0.0	0.0	0.0	0.0				

- The parameter BLAST specifies the type of explosive burst.

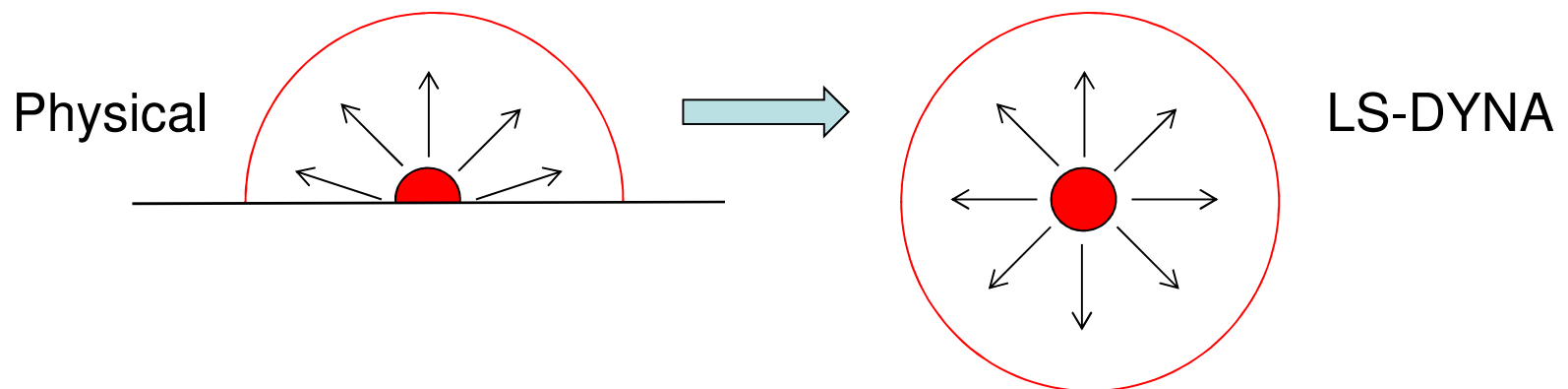
Spherical Free-Air Burst

- BLAST=2: Spherical Free-Air Burst
 - Charge is suspended in the air.
 - Interaction between blast wave and ground is not considered.
 - Target points equidistant from the charge are loaded identically.



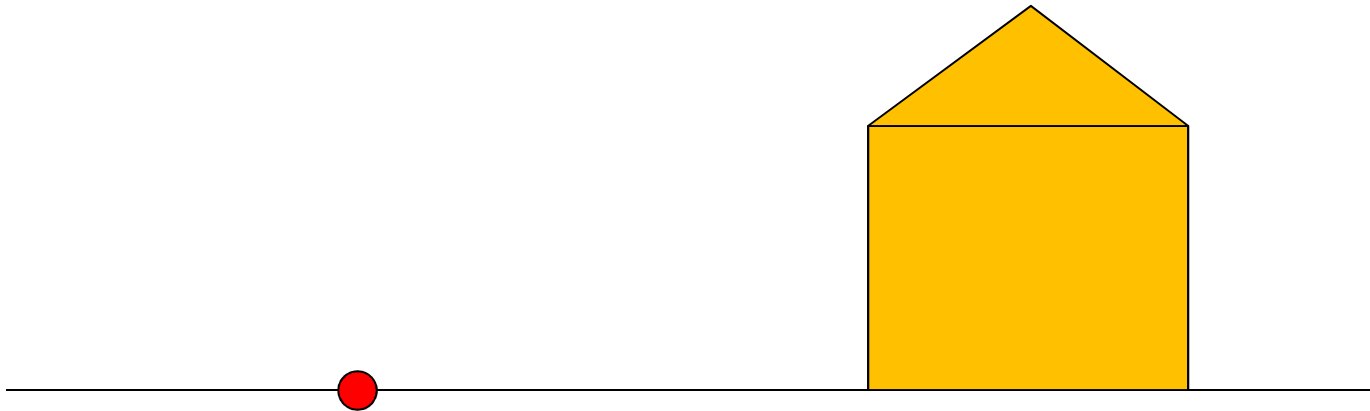
BLAST=1: Hemi-Spherical Surface Burst

- Simulates a charge placed on or near the ground.
 - In effect the charge size is nearly doubled by the ground reflection (2X for perfect reflector).
- An imaginary ground plane passes through the charge center but there is no sense of orientation.
 - Equidistant target points are loaded identically.



Example

- A 10 kg TNT charge lying on the ground is detonated 10 m from the face a building



Range of Applicability

- The empirical curve fits apply to experimental data for following scaled ranges.
 - Results obtained outside these bounds should be treated with suspicion.

Spherical Free-Air Burst

$$0.147 [\text{m/kg}^{1/3}] < Z < 40 [\text{m/kg}^{1/3}]$$

Hemi-spherical Surface Burst

$$0.178 [\text{m/kg}^{1/3}] < Z < 40 [\text{m/kg}^{1/3}]$$

- The lower bounds listed above are dictated by the positive phase duration. Some of the empirical parameters are valid down to the surface of the charge ($Z=0.0531$ and $Z=0.0647$, respectively).



Warning Messages - Scaled Range

- The following warning messages appear when the scaled range $Z=R/M^{1/3}$ falls outside the range of applicability.

*** Warning 40935 (SOL+935)

Segment too close to charge.

*LOAD_BLAST equations may not be valid.

*** Warning 40936 (SOL+936)

*LOAD_BLAST resetting positive phase duration

– Check for input errors.

– In some situations the message is acceptable.

(a forthcoming example illustrates such a case)



System of Units

*LOAD_BLAST_ENHANCED

\$	bid	m	xbo	ybo	zbo	tbo	unit	blast
	1	10.0	0.0	1.5	1.5	0.0	2	2
\$	cfm	cfl	cft	cfp	nidbo	death	negphs	
	0.0	0.0	0.0	0.0				

- The FE model and blast model work with their own system of units.
 - It is essential that these units systems match.



Consistent Units Systems

- A *consistent set of units* for mass, length, time, forces, gravity, pressure, etc. must be used throughout the model and interpretation of results
 - Test #1: 1 force unit = 1 mass unit * 1 acceleration unit
 - Test #2: 1 acceleration unit = 1 length unit / (1 time unit)²
- SI Units Example (kilogram, meters, seconds)
 - density: kg/m³
 - elastic modulus: Pascals
 - geometry is built in meters
 - force: Newtons
 - stress: Pascals
 - velocity: meter/sec

} most units mistakes occur
in material properties



Units Systems for the Blast Load

- The units system used to define the blast load must match the units system used by the FE model.
- Pre-defined and user-defined systems are specified with UNIT in *LOAD_BLAST_ENHANCED
 - UNIT=1: inconsistent system used in the original empirical development. Do not use for analysis! Left in for legacy...
 - UNIT=2: kilogram, meter, second, Pascal
 - UNIT=3: dozen slugs??, inch, second, psi
 - UNIT=4: gram, centimeter, microsecond, megabars
 - UNIT=5: User-defined
 - others



A dozen slugs?

- UNIT=3 is used to define the English unit system (inch, lbf, second, psi) and the corresponding mass unit is referred to as a *dozen slugs*.
- Example: 100 lbm (pound-mass) weighs 100 lbf (pound-force) at sea level

weight = mass x gravitational acceleration

100 lbf = mass x 386.4 inch/sec²

mass = 0.2588 lbf x sec² / inch

mass = 0.2588 dozen slugs

(FYI: density of steel in English units is 7.33×10^{-4} lbf x sec² / inch⁴)



Equivalent TNT Mass

- The empirical laws used to determine blast pressure are computed for a given mass of TNT.
- An *estimated* TNT mass equivalent of a particular explosive can be computed from ratios of: maximum pressure, impulse, detonation velocity, ratio of specific energy, etc.
 - Each explosive is unique – *there is no correct method*
- The properties of the explosive under investigation must be assessed to appropriately estimate an equivalent mass of TNT.

Blast Arrival Message

- A message concerning the first encounter of the blast wave is reported in the screen scroll as well as the messag and d3hsp files

enhanced blast # 1: pmax = 0.69346E+05 at time = 0.19000E-01

 ↑

 effective pressure, P_{eff}

 ↑

 blast ID (BID)

Blast Arrival Message - Initialization

- During initialization the following message is reported to the messag and d3hsp files

Blast wave reaches structure at 1.7340E+01 milliseconds

- This should match the other blast arrival message issued during integration but may be off due integration time step considerations.
- To obtain this message quickly the simulation can be terminated immediately with sense switch SW1 or NCYCLE=1 in *CONTROL_TERMINATION.
- Note: the time units are fixed (milliseconds) and may differ with the units used to define the model.



Offsetting the Detonation Time

- If no other loads or actions are applied to the FE model before the blast wave arrives then computational time is wasted “waiting” for the wave to hit the structure.
- A great cost savings can be realized by offsetting the time which the charge is detonated.



Detonation Time Offset

```
*LOAD_BLAST_ENHANCED
$      bid      m      xbo      ybo      zbo      tbo      unit      blast
      1      10.0      0.0      1.5      1.5      -0.016      2      2
$      cfm      cfl      cft      cfp      nidbo      death      negphs
      0.0      0.0      0.0      0.0
```

- For the wave to arrive just after the start of the calculation TBO should be a negative number slightly smaller in magnitude than the reported first encounter arrival time.
(the following illustrates proper and improper use)



Warning – Arrival Time < 0

- If the blast wave is found to hit the structure before the integration commences the following message is issued.

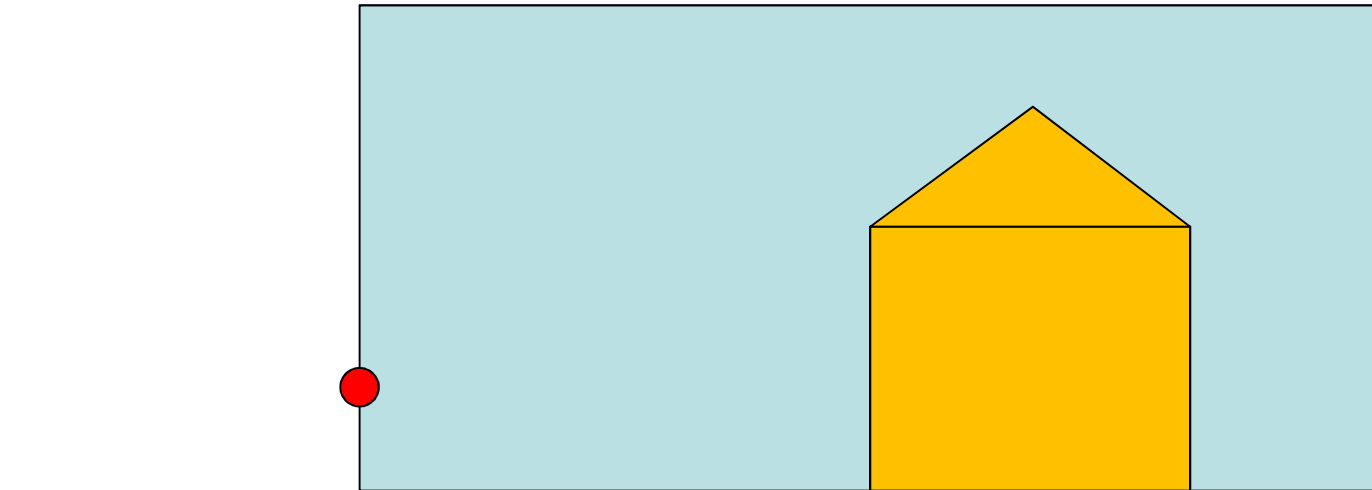
```
*** Warning 40927 (SOL+927)  
    arrival time < 0 in conwep_blast  
    ta = 1.7601E+01 milliseconds
```

- Note the fixed time units.
- Once again this message may be acceptable.
(the following example will illustrate this)



Example

- Visualizing the incident wave in air using a slice of shell elements



- This simulation ilicits “*arrival time < 0*” and “*too close to charge*” warning messages - acceptable.

Effective Impulse

- The *effective impulse* is the time-integrated area under the effective pressure curve.
 - It represents perhaps the most important damage-causing aspect of the blast.

$$I_{eff} = \int_{t_a}^{t_+} P_{eff} dt$$

where: $P_{eff} = P(P_{inc}, P_{ref}, \theta)$, effective pressure

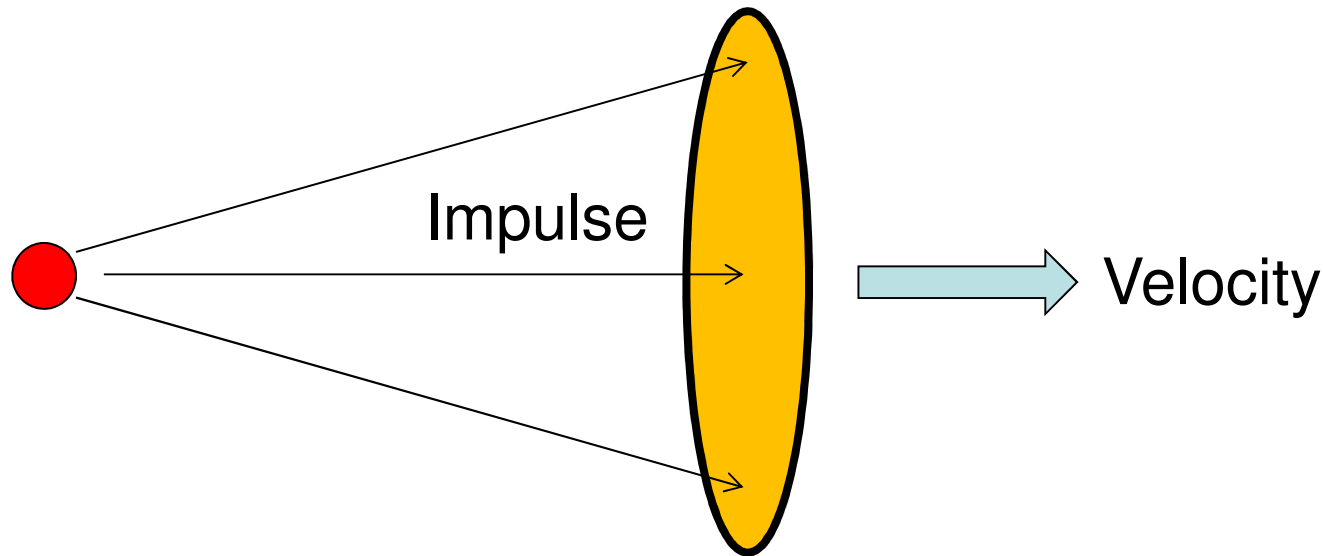
t_a , arrival time

t_+ , end of positive phase duration



Example

- A steel plate (radius=10 cm, thickness=1 cm) is subjected to the blast from a 1 kg charge situated 1 m from its face
 - Check the motion and verify the applied impulse



Impulse – Momentum

- Average pressure impulse, $I_{eff} = 547 \text{ Pascal-sec}$
 - LS-PREPOST: History → Segment → Pressure
 - Oper → Integrate
- Force impulse, $I_{eff} \cdot area = \underline{17.2 \text{ Newton-sec}}$
- Velocity, $V = 7.13 \text{ m/s}$
 - LS-PREPOST: History → Part → Y-Rigid Body Velocity
- Mass, $M = 2.44 \text{ kg} (?)$
 - Search d3hsp file for “mass summary”
- Momentum, $M \cdot V = \underline{17.4 \text{ kg-m/sec}}$

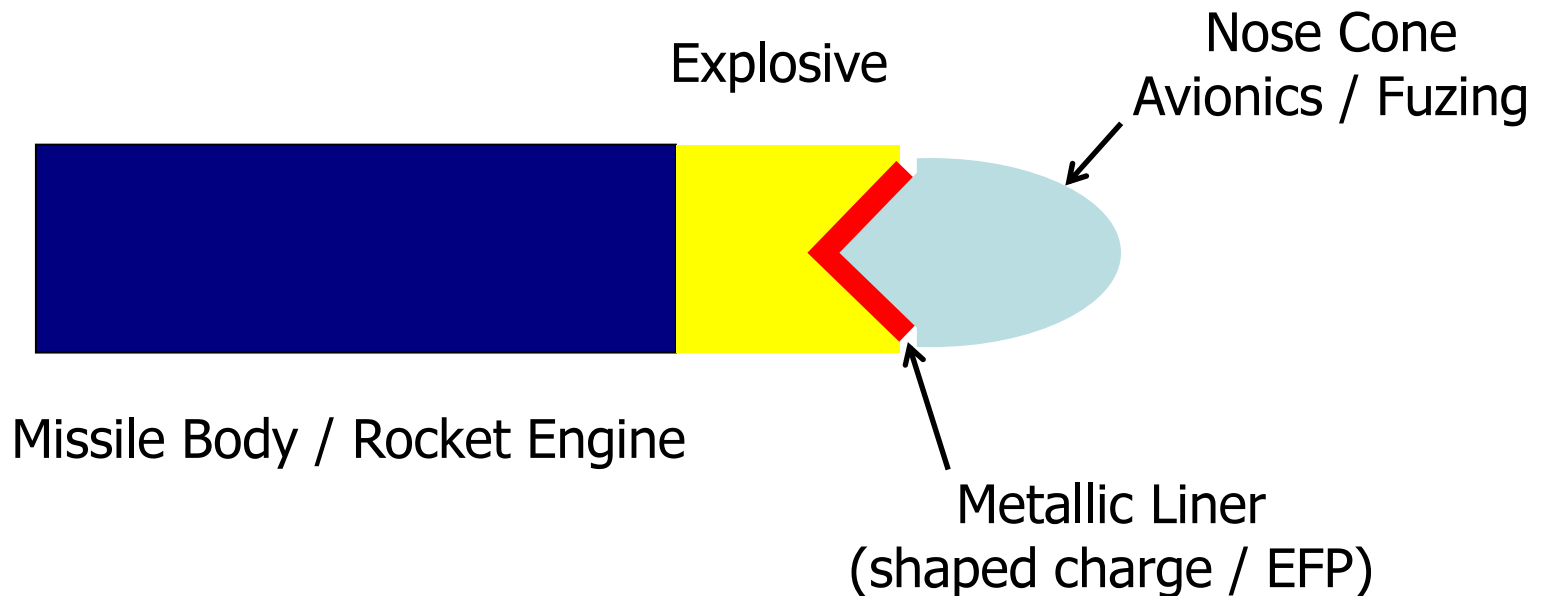
Other Burst Options

- BLAST = 1 & 2 (surface and air burst)
 - Bare charge on ground or in air
- BLAST = 3 (non-spherical, moving air burst)
 - Weaponized configurations create a non-spherical blast front
 - Blast front is modified if weapon is moving
- BLAST = 4 (air burst with ground reflection)
 - Air burst reflects off ground
 - Blast wave system forms a Mach stem



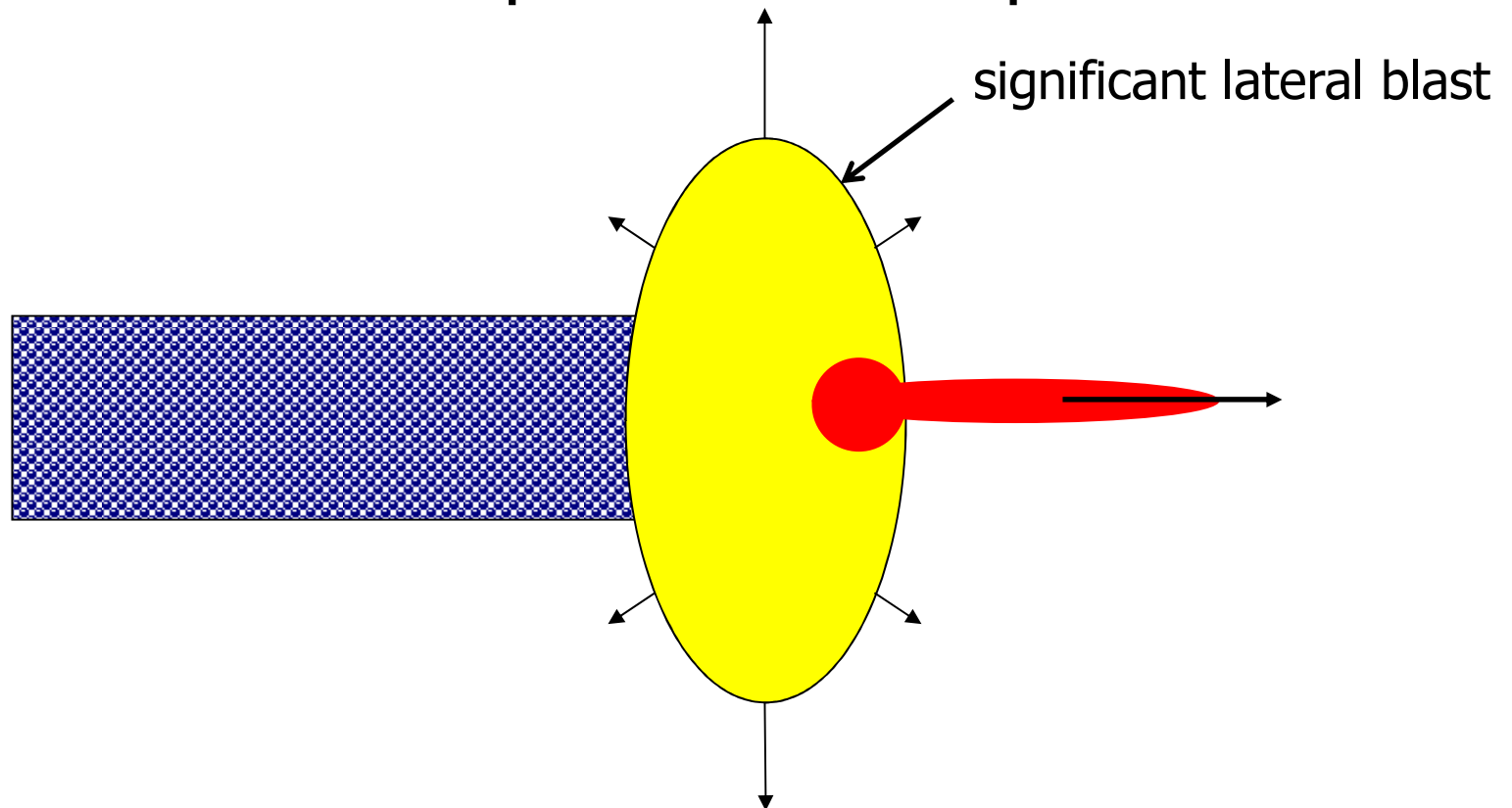
Air Burst From Missile

- When confined in the warhead section of a missile or RPG the explosion results in significant lateral blast



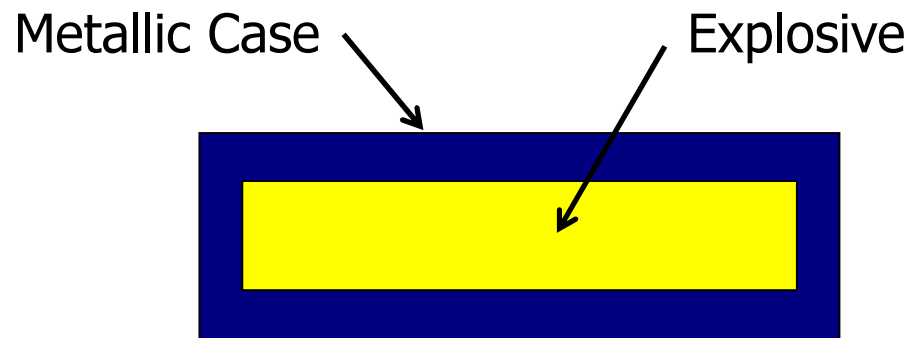
Oblate Spheroidal Blast Front

- BLAST=3, RATIO<1 renders a blast front with an oblate spheroidal shape



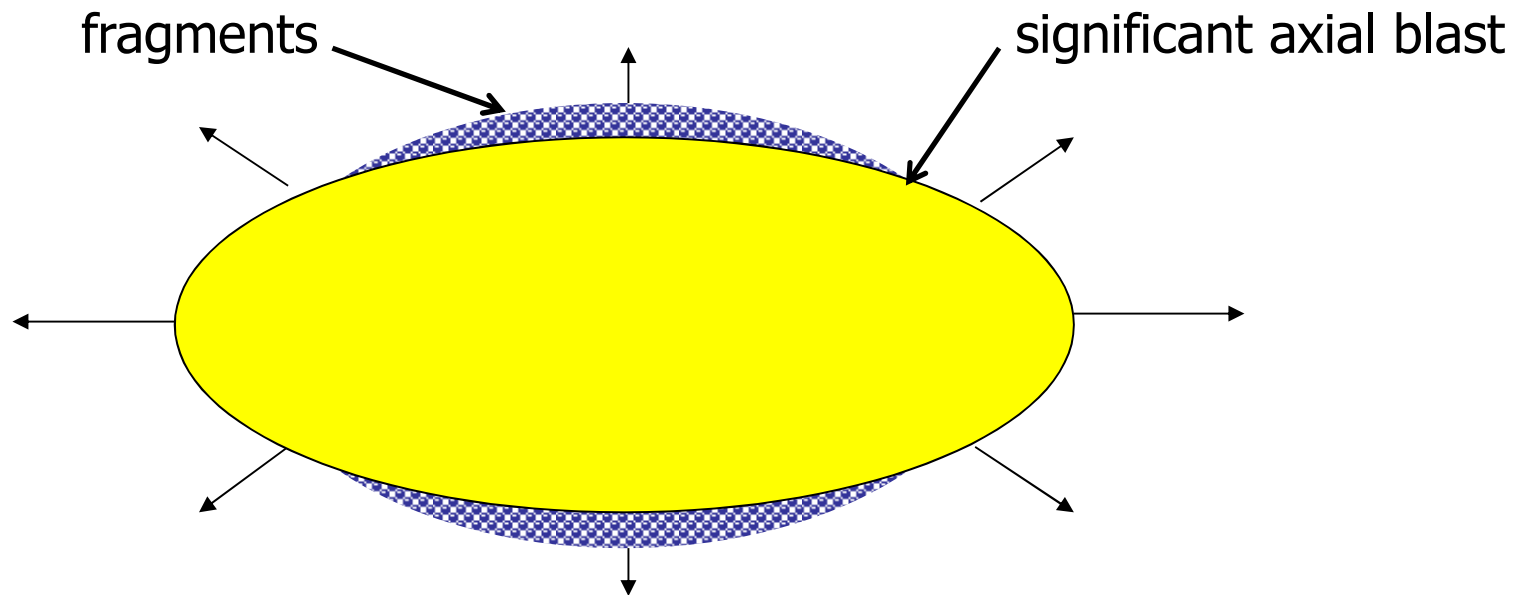
Cylindrically Cased Explosives

- Explosives contained within a heavy metallic cylindrical case (pipe bombs, artillery shells) confine the explosion to produce significant blast in the axial direction



Prolate Spheroidal Blast Front

- BLAST=3, RATIO>1 renders a blast front with a prolate spheroidal shape



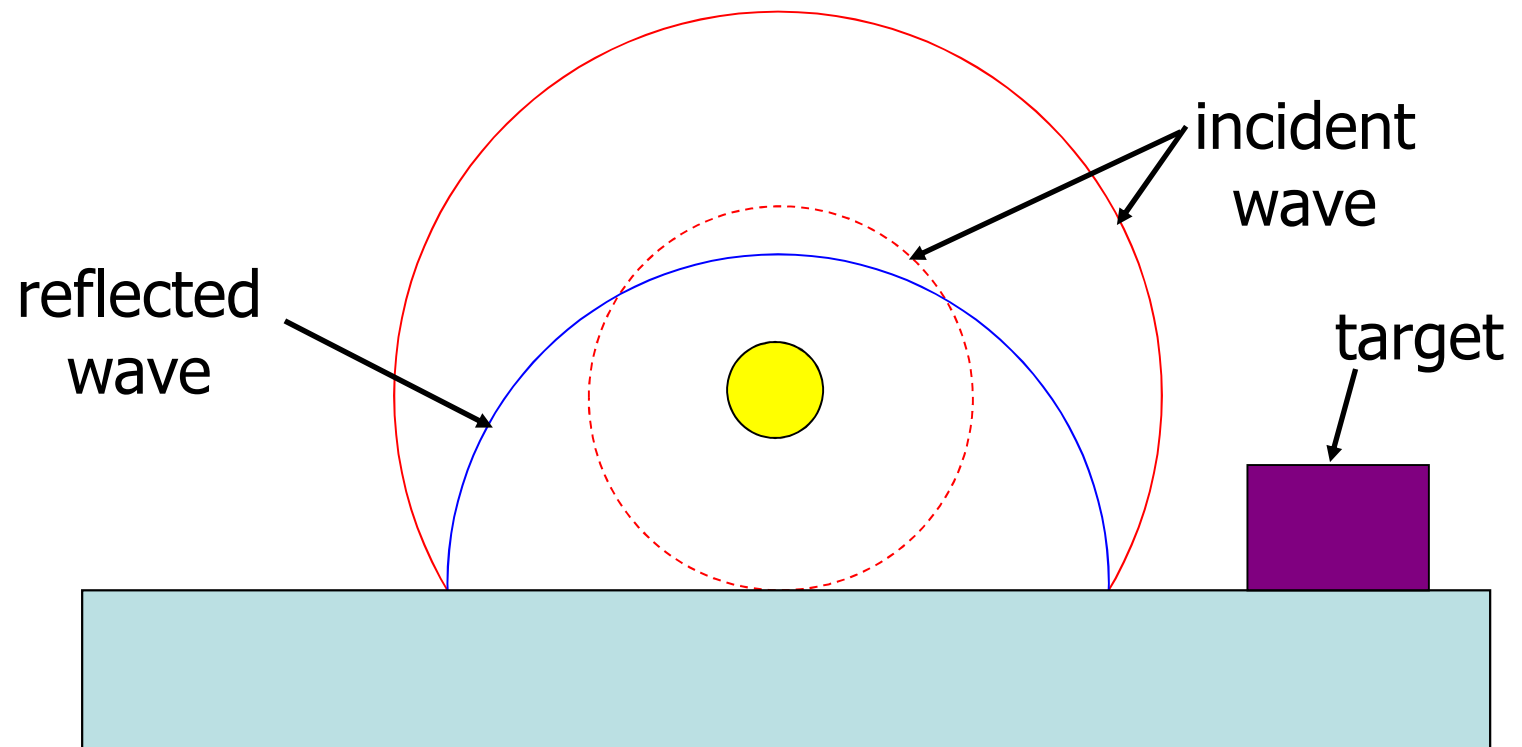
Moving Explosion

- The blast front of a moving explosive can be modified to account for the Doppler effect
 - Time contraction/dilatation affects upstream and downstream pressures
 - Shape of blast front is unaffected; pressure iso-bars are heavily biased to the front
 - Applies only to subsonic regime
- $BLAST=3$, $VEL>0$
 - Can be used in conjunction with $RATIO$

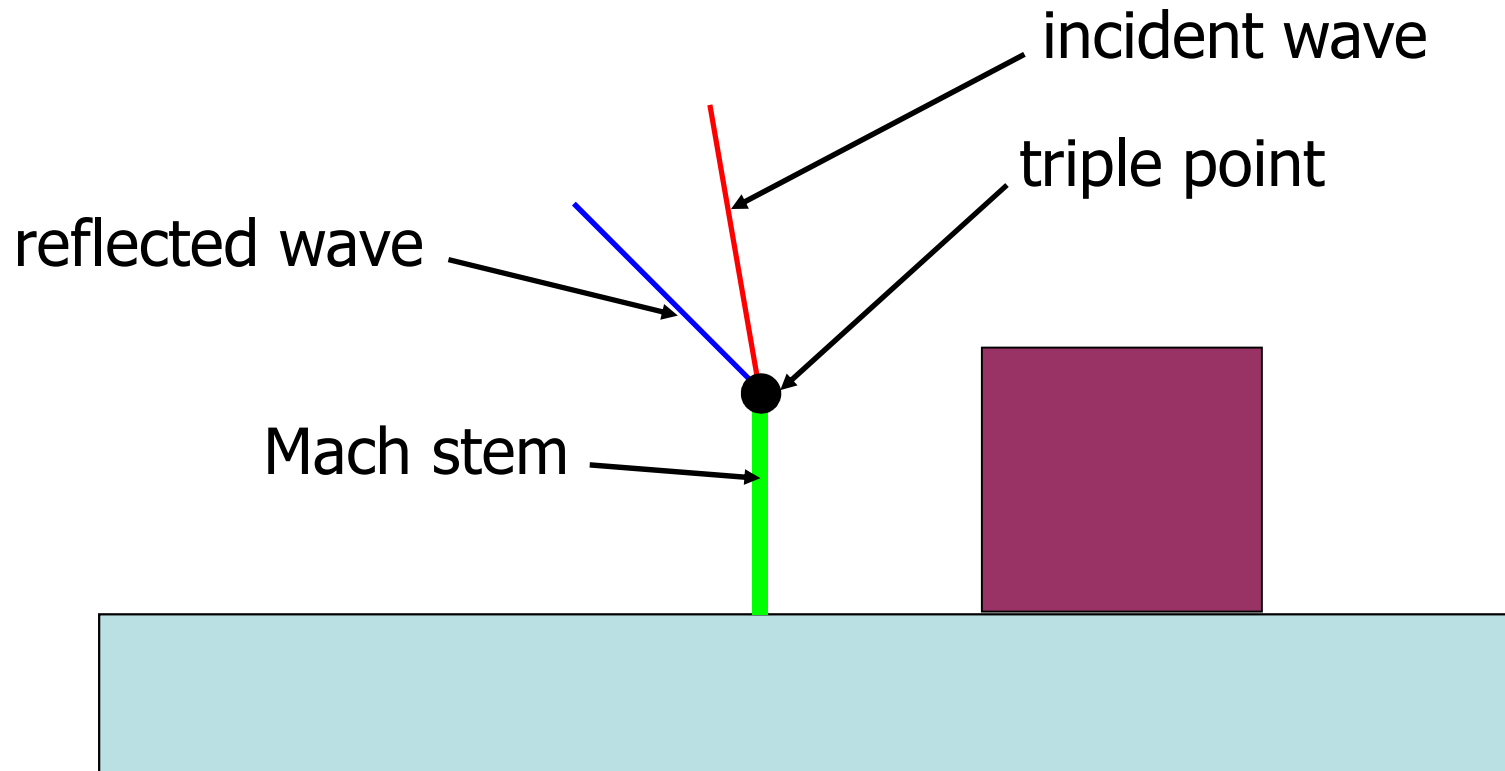
Mach Wave Reinforcement

- For certain heights of air burst the primary blast wave can be strengthened by the ground-reflected wave
- This merging of incident and reflected waves is called the *Mach Effect*
- Overpressure of this Mach wave is considerably more than that of the unreinforced primary blast wave
- Invoked with $BLAST=4$
 - Scaled height of burst has its own range of applicability – look for warnings.

Evolution of the Mach Wave



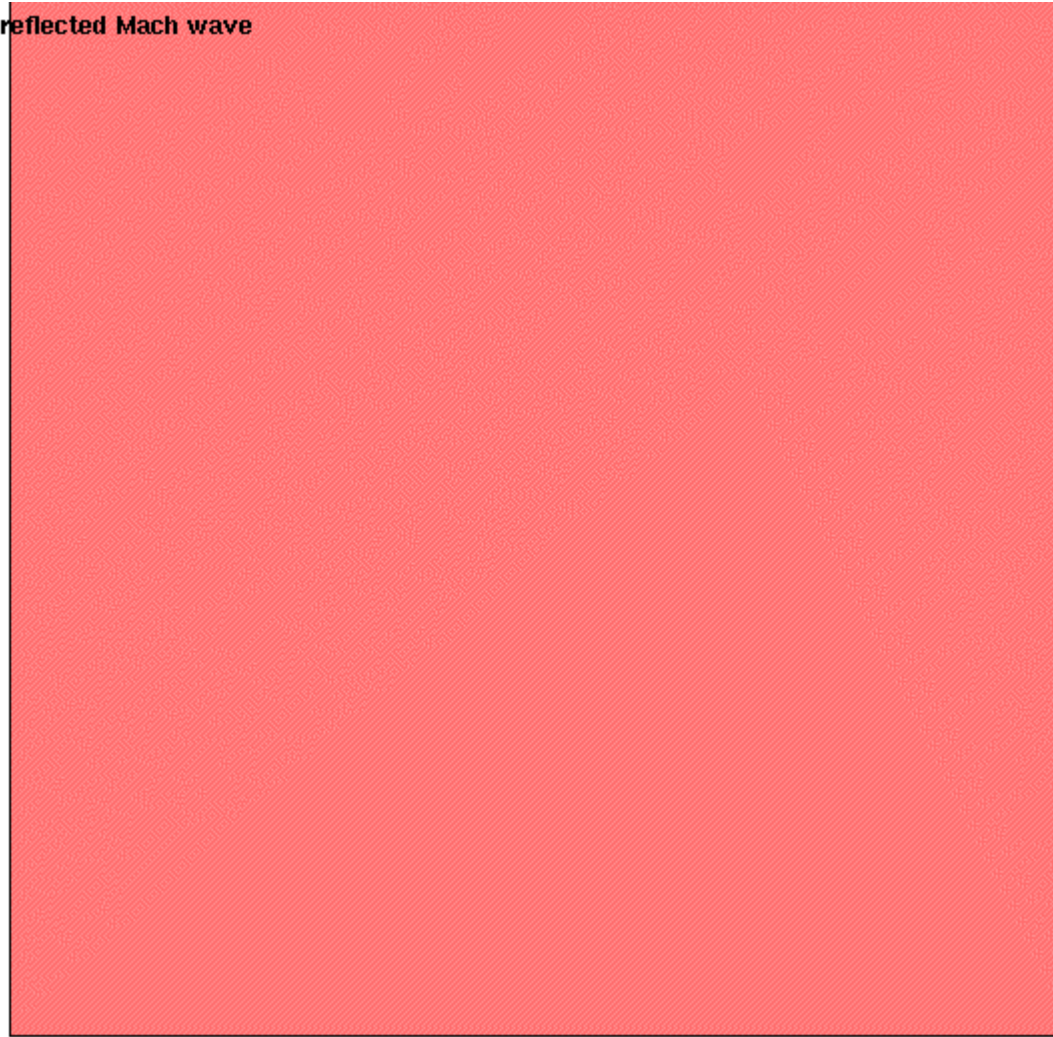
Formation of Mach Stem Due to Wave Confluence



- The Mach stem puts ground targets at greater risk.

Ground Reflected Mach Wave

ground reflected Mach wave

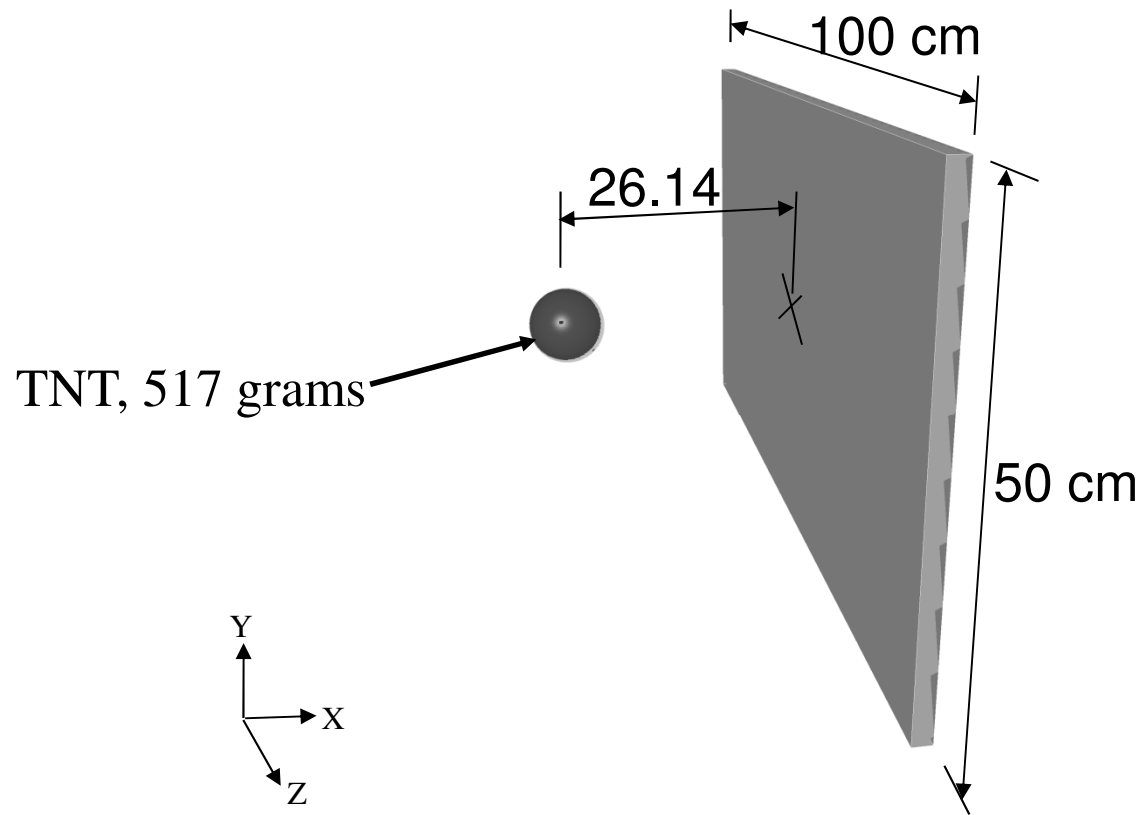


Coupling Empirical Blast Loads to ALE Air Domains

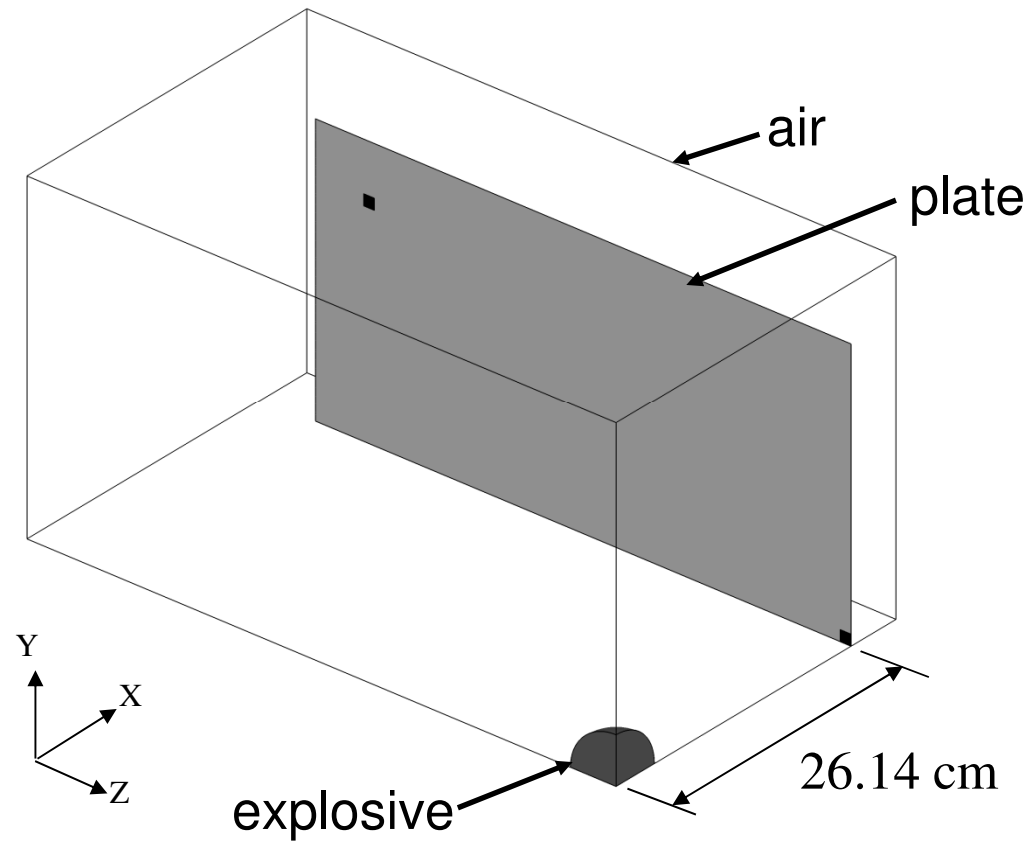
- At long standoff distances the ALE approach becomes impractical since large volumes of air must be modeled with small elements
- Empirical blast models are attractive but are unable to address shadowing effects of intervening structures
- A hybrid combination of these two methods is available with *LOAD_BLAST_ENHANCED
 - Slavik, T., “A Coupling of Empirical Explosive Blast Loads to ALE Air Domains in LS-DYNA,” 7th European LS-DYNA Conference, Salzburg, Austria, 2009.



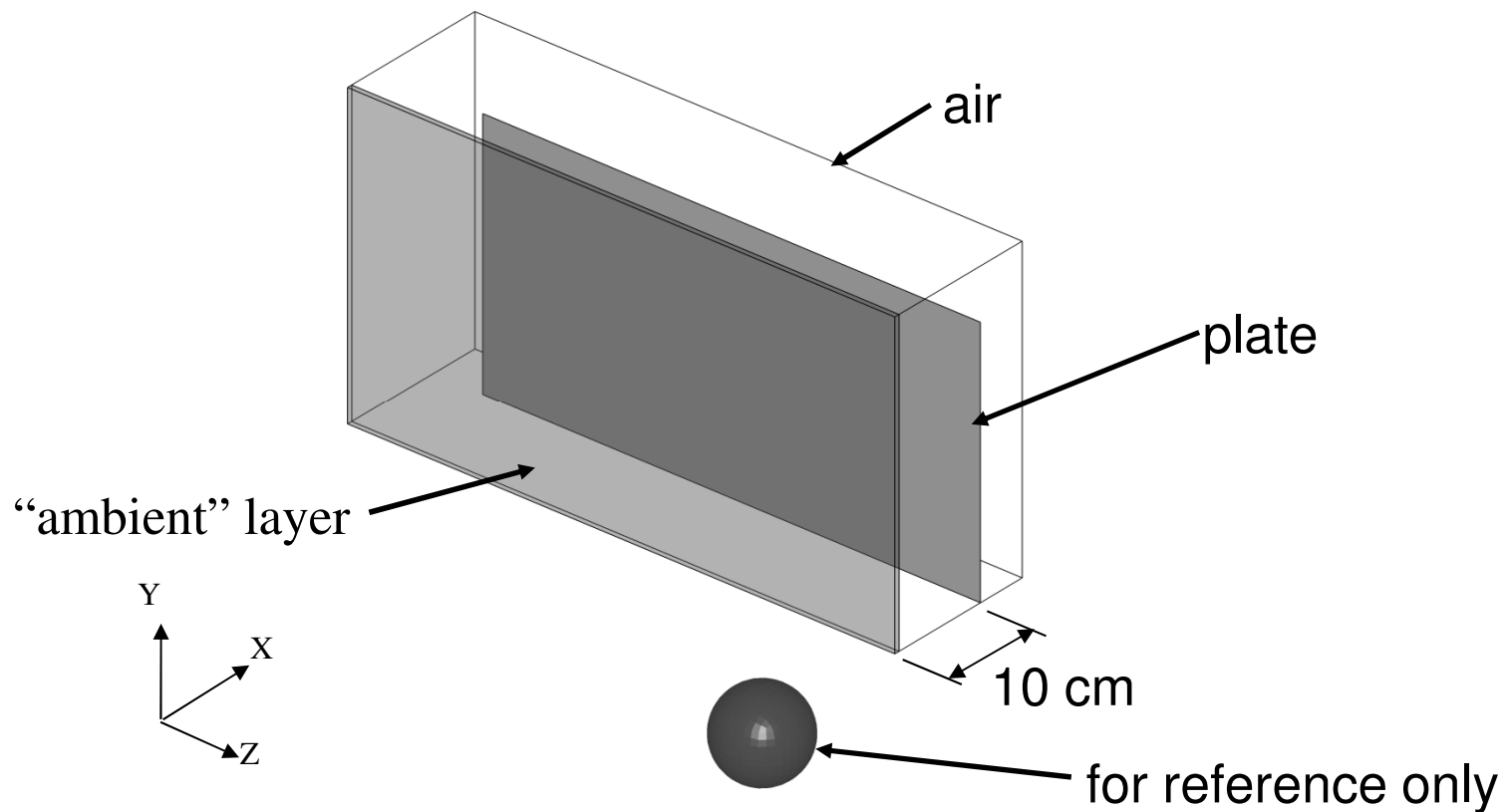
Empirical Blast Loading of Lagrangian Structure



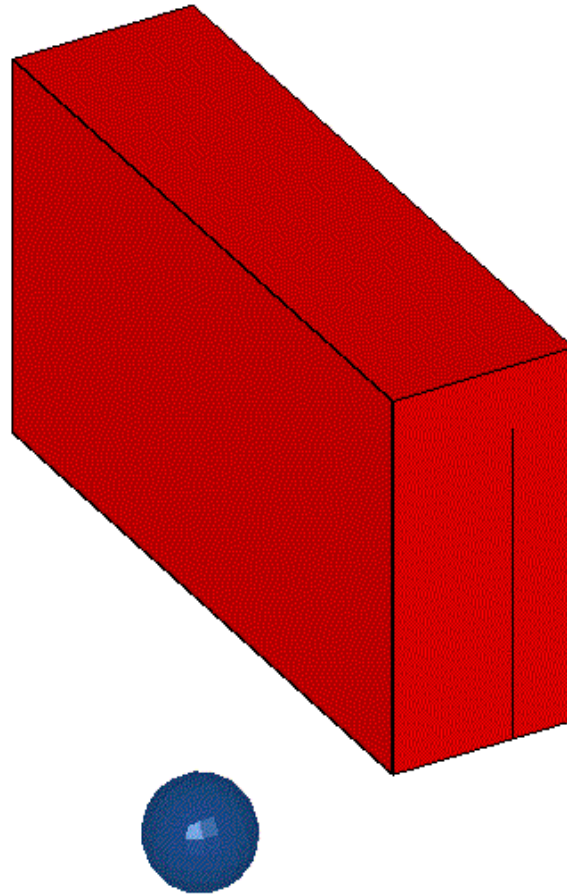
Explosive Blast with ALE and FSI



Empirical Blast Load Applied to ALE Air Domain



*LOAD_BLAST_ENHANCED
Coupled with ALE



Contact Information and Files

- Feel free to contact me at slavik@lstc.com
- Files from this presentation can be downloaded from <http://ftp.lstc.com/anonymous/outgoing/slavik/UCSD/>
 - ucsd.pdf: presentation
 - building.k: building example
 - plate3dc.k: model used in impulse-momentum example
 - plate3ds.k: 3D shell version of the model above
 - plate2dc.k: 2D continuum version of the model above
 - plate2ds.k: 2D shell version of the model above

