

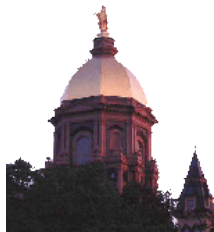
Optimization of One-Dimensional Aluminum Foam Armor Model for Pressure Loading

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Report Documentation Page

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Break down

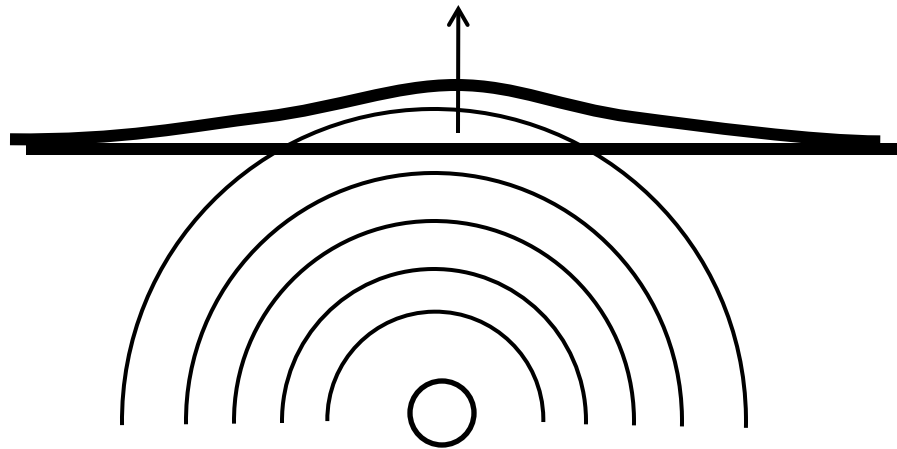
Optimization of One-Dimensional Aluminum Foam Armor Model for Pressure Loading

- Pressure loading
 - i.e. blast
- Aluminum Foam
 - i.e. cellular materials
- Optimization
 - Minimizing acceleration

The Blast Problem

- Rapid expansion of a shockwave with high T and P emanating from a blast source
- Impact from a shock *deforms* and accelerates the receiving structure

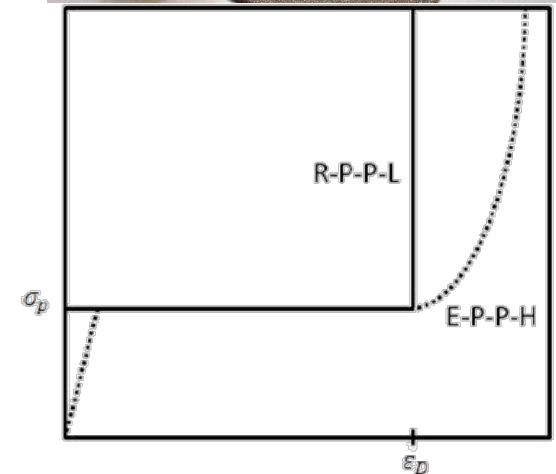
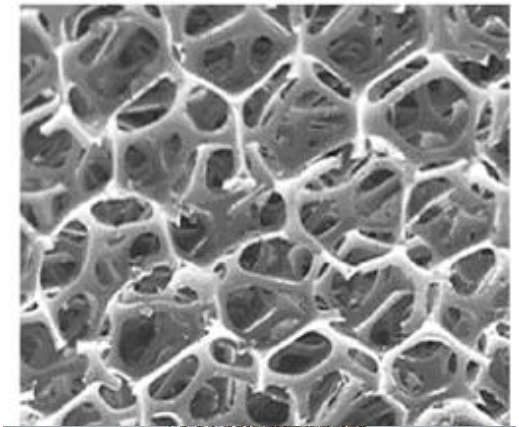
How to mitigate the effects of the blast?



3

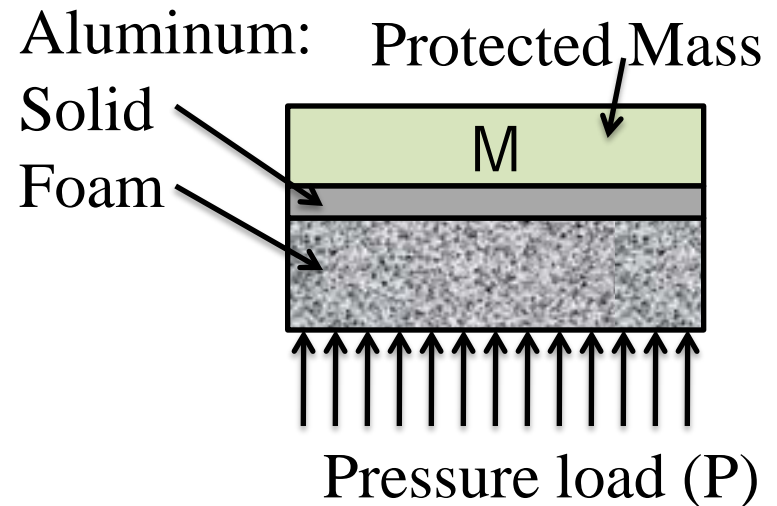
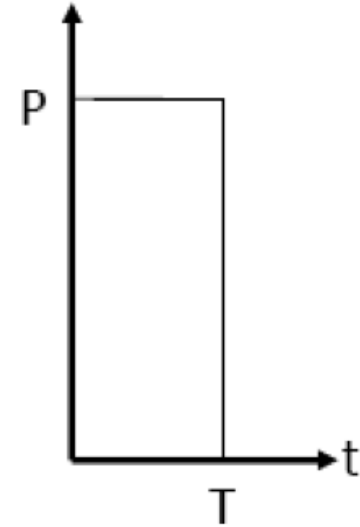
Cellular materials

- Material that contains a repeated base cell structure
 - Foams
 - Honeycombs
- Characterized by
 - Low density
 - Cannot support tensile loadings
- Near ideal compressive deformation behavior:
 - Transmit minimal load
 - Absorb significant energy



Problem Setup

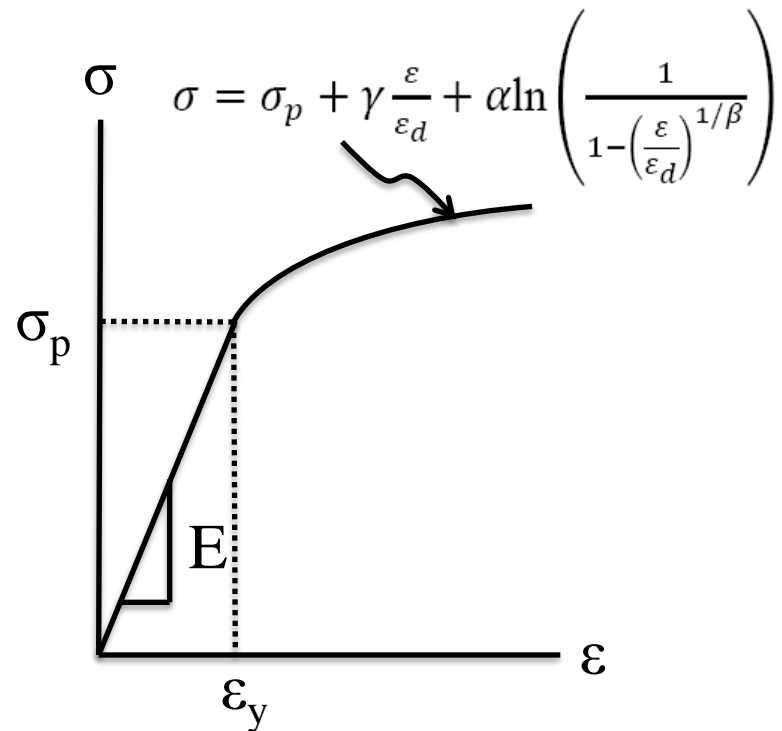
- Objective:
 - To protect a mass from the acceleration effects of a pressure loading
- Modeling:
 - Pressure represented as a square pulse
 - Foam material properties are modeled as a function of relative density
 - System is modeled as series of springs and masses
 - System is unconstrained (inertial BCs)



Material Properties

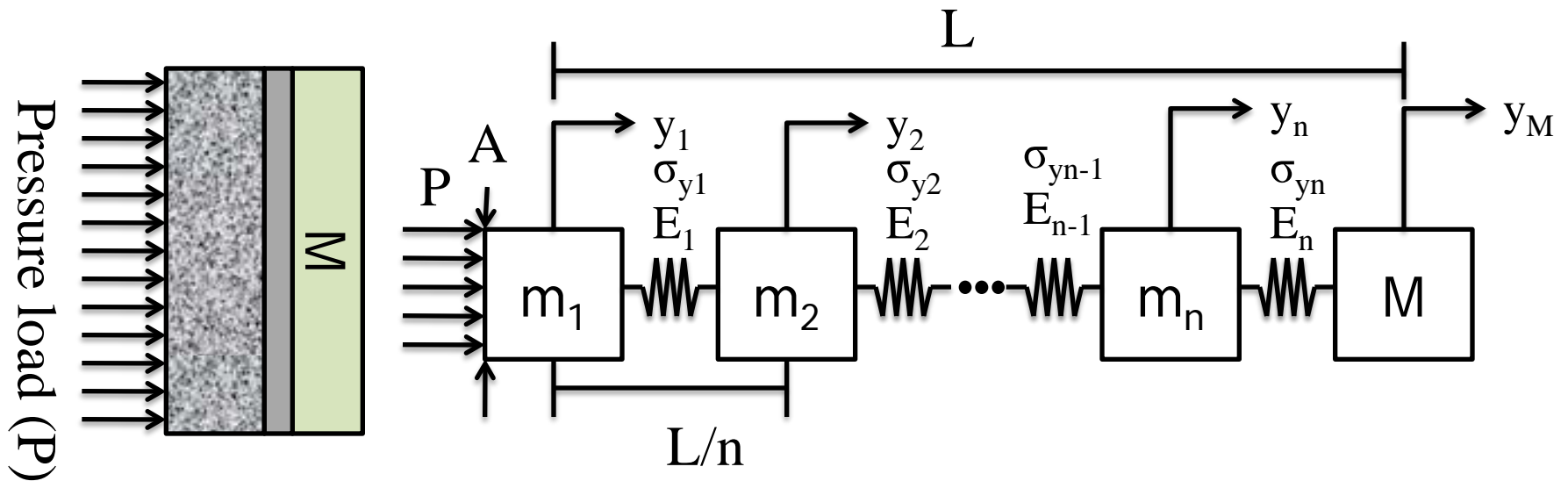
- According to Hanssen (2002), material parameters can be described with calibration functions
- Stress as a function of strain is then a function of the parameters

$$\left\{ \sigma_p, \alpha, \frac{1}{\beta}, \gamma \right\} = C_0 + C_1 \left(\frac{\rho_f}{\rho_0} \right)^n$$



System Model

- System model has an elastic-plastic spring based on the material properties of the given element joining each mass
- There are $n+1$ masses
 - n for the armor
 - 1 for the protected mass



Equations of Motion

$$m_i \ddot{y}_i = F_L - F_R = A(\sigma_L - \sigma_R)$$

$$m_i = \frac{\rho_i L}{\rho_0 n} A \rho_0 = x_i \frac{L}{n} A \rho_0 \quad \omega^2 = \frac{T^2 \sigma_{y0}}{\rho_0 L^2} \quad \dot{y}_i = \frac{\ddot{u}_i L}{T^2}$$

$$\ddot{u}_i = \frac{AT^2 \sigma_{y0} n}{x_i A \rho_0 L^2} \left(\frac{\sigma_{i-1}}{\sigma_{y0}} - \frac{\sigma_i}{\sigma_{y0}} \right) = \omega^2 \frac{n}{x_i} \left(\frac{\sigma_{i-1}}{\sigma_{y0}} - \frac{\sigma_i}{\sigma_{y0}} \right)$$

$$KE_{ND} = \frac{x_i}{2n\omega^2} \dot{u}^2 \quad IE_{ND} = \frac{1}{n} \int_{\varepsilon_0}^{\varepsilon_f} \frac{\sigma_i}{\sigma_{y0}} d\varepsilon \quad W_{ND}^{ext} = u_1 \frac{P}{\sigma_{y0}}$$

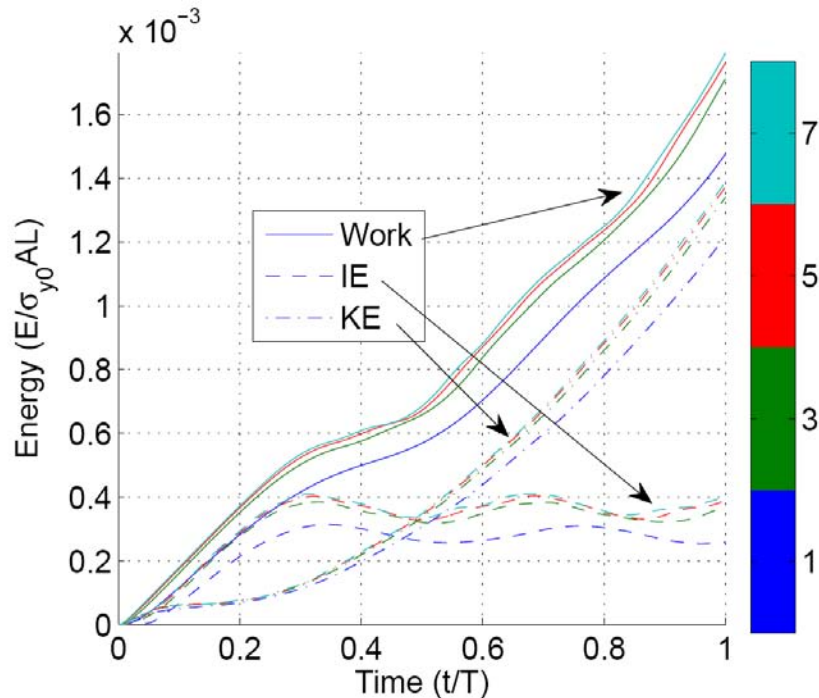
Model Parameters/Convergence

Total system length: $L=.1\text{m}$

Pressure Pulse duration: $T=150\mu\text{s}$

Protected Mass: $M=100\text{kg}$

Parameter	C_0	C_1	n
σ_p	0 (MPa)	720 (MPa)	2.33
γ	0 (MPa)	42 (MPa)	1.42
α	0 (MPa)	251 (MPa)	1
$1/\beta$.1	15.7	3



$$\sigma_{y0} = 276 \text{ MPa}$$

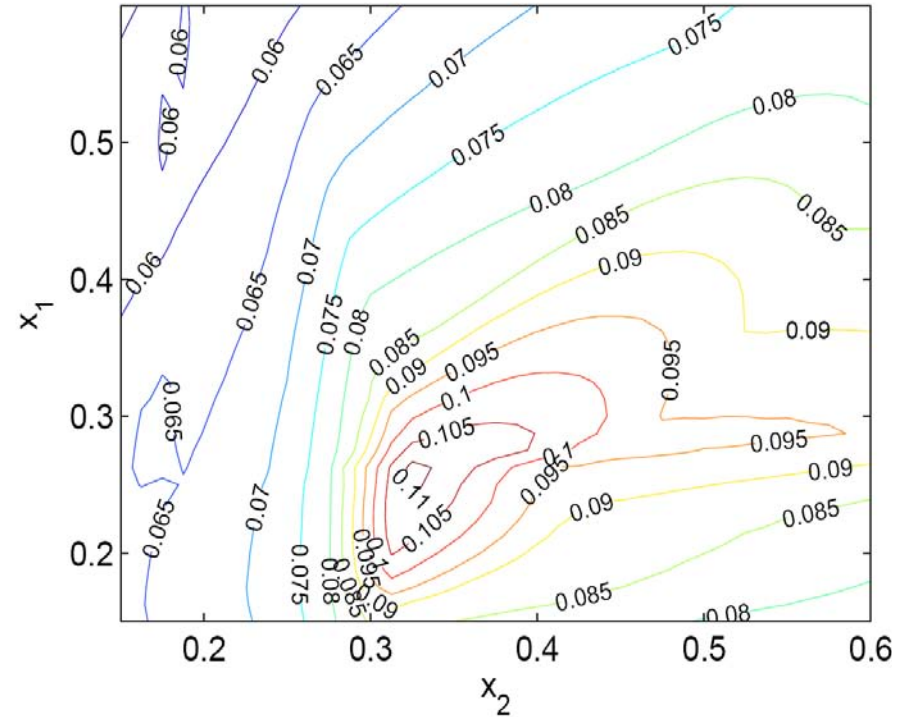
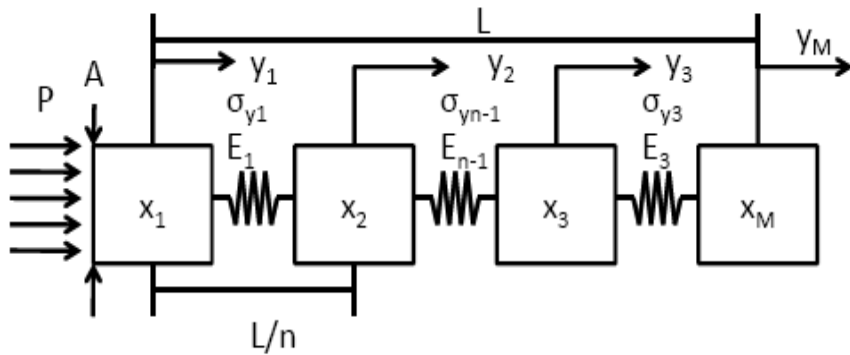
$$E_0 = 68.9 \text{ GPa}$$

$$\rho_0 = 2700 \frac{\text{kg}}{\text{m}^3}$$

LOAD CASE 1: $P = 0.1\sigma_{y0}$

$$\min_x \{ \max \ddot{u}_M \}$$

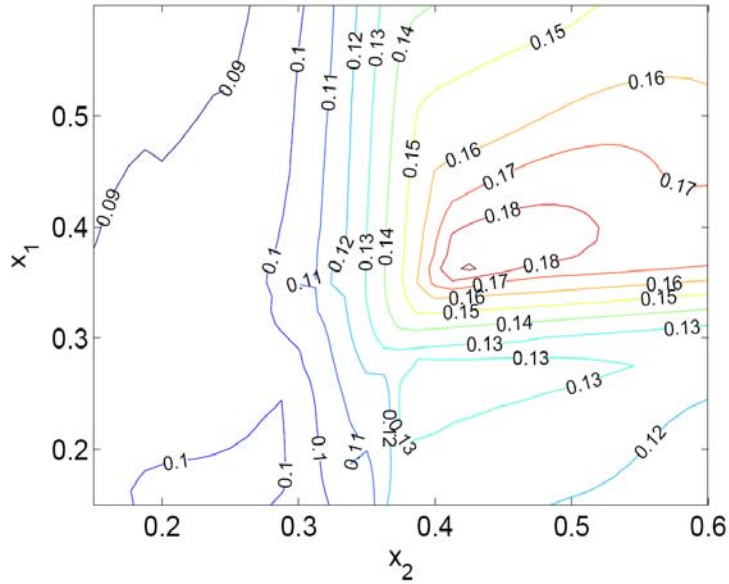
s.t. $x_L \leq x_i \leq x_U$



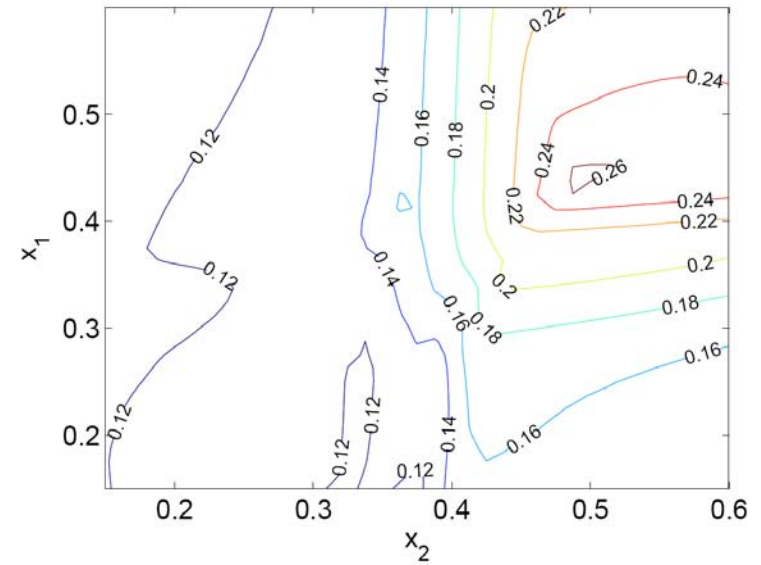
	x_1	x_2	
Graphical Solution:	0.6	0.15	0.05423

Higher Load Values

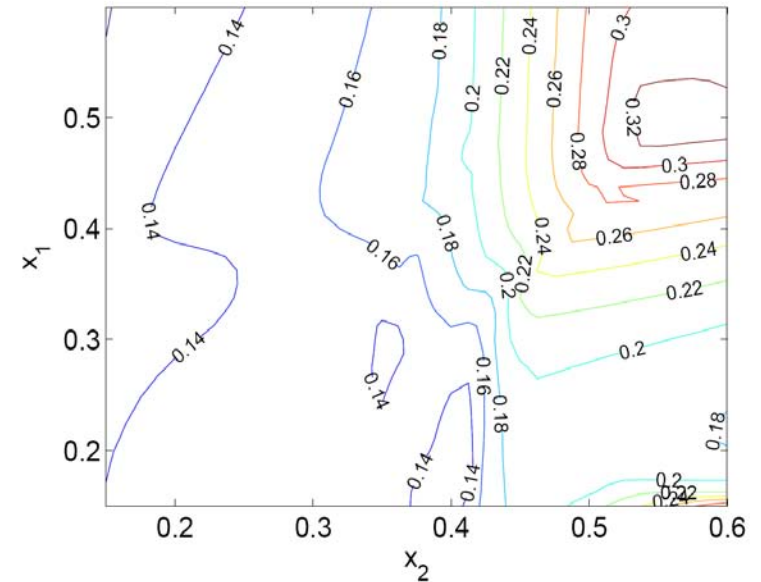
LOAD CASE 2: $P = 0.2\sigma_{y0}$



$x_1 = 0.60$ and $x_2 = 0.15$



Solution space of 2DV acceleration minnimax problem with $P = 0.3\sigma_{y0}$

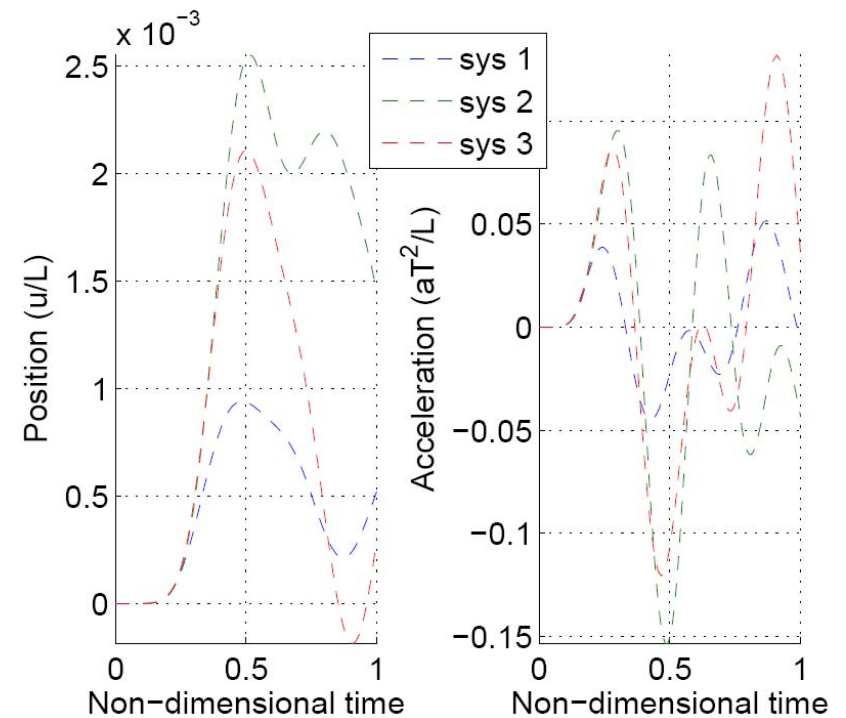
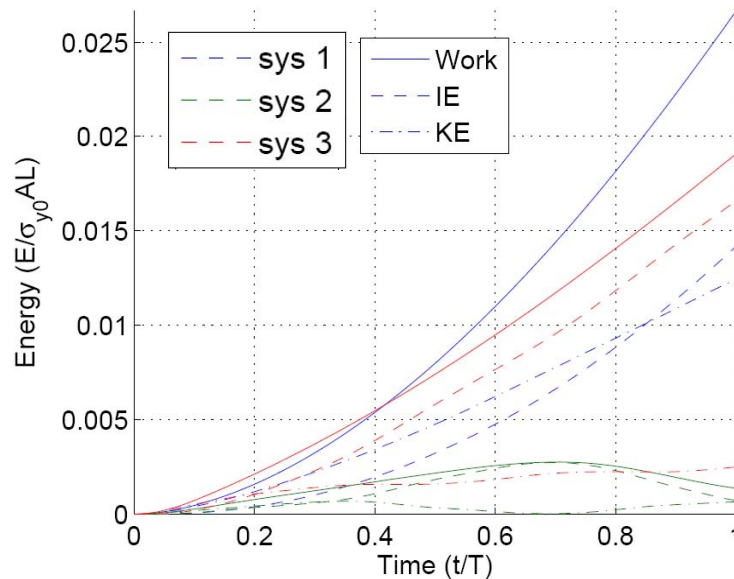
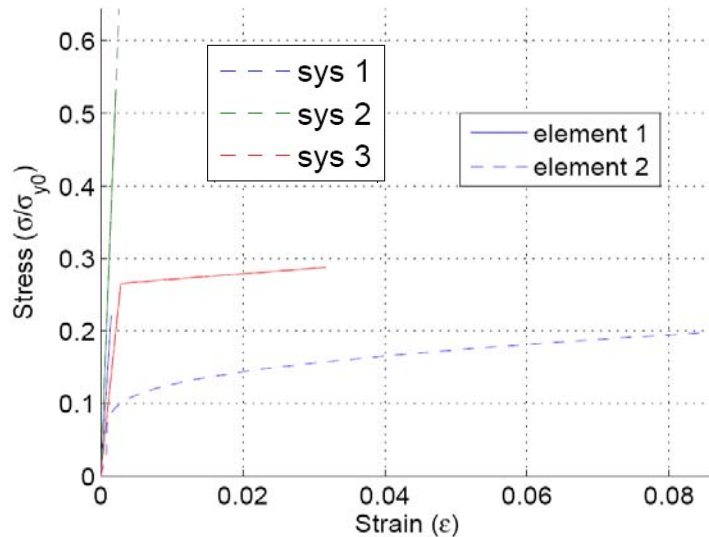


Solution space of 2DV acceleration minnimax problem with $P = 0.4\sigma_{y0}$

System Response Comparison

Relative densities of comparison systems

System->	1	2	3
x_1	0.6	1	0.375
x_2	0.15	1	0.375
x_3	1	1	1



Conclusions

- Found optimal design for 2 elements of foam
 - $x_1 = .6$ (highest density)
 - $x_1 = .15$ (lowest density)
- Observed that
 - More energy absorbed does not necessarily give the best result
 - Less work done by the blast can be worse than more work
 - Having more system kinetic energy

QUESTIONS?



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Any opinions, findings and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the U.S. Army TACOM Life Cycle Command.

BACKUP

Material properties

- Yield stress and elastic modulus depend on
 - Relative density (density of foam/density of solid)
 - Distribution constant (open cell vs closed cell)
- Compaction strain is only a function relative density

Relative density

$$\frac{\sigma_p}{\sigma_{y0}} = 0.3\phi^{3/2} \left(\frac{\rho_f}{\rho_0}\right)^{3/2} + (1 - \phi) \left(\frac{\rho_f}{\rho_0}\right)$$

$$\frac{E_f}{E_0} = 0.3\phi^2 \left(\frac{\rho_f}{\rho_0}\right)^2 + (1 - \phi) \left(\frac{\rho_f}{\rho_0}\right)$$

$$\varepsilon_d = 1 - 1.4 \left(\frac{\rho_f}{\rho_0}\right)$$