Structural Optimization for Blast Mitigation Using HCA

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**Abstract:**
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Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18
The blast mitigation design problem can be reduced to sub-problems as given:

- Each reduction in problem formulation feeds back into the system above.
- Design objectives for each sub-problem are selected with the overall problem in mind.

- **Vehicle**
  - Design for crew and critical component survivability.

- **Sub System**
  - Design for mechanical isolation between occupant and blast.

- **Component**
  - Design for minimum energy transfer from blast wave.

- **Sub Component**
  - Design for energy dissipation and distribution.

- **Microstructure**
  - Define damage and material parameters for energy absorption.

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**Introduction: Injury Criterion**

- **Injury criteria of vehicle occupants** due to mechanical input taken as the design objective of the vehicle design problem.
- Blast impulse is key the metric which drives injury occurrences.
- Compressive forces and vertical acceleration taken to be defining factor in injury accumulation.

<table>
<thead>
<tr>
<th>HYBRID III Simulant Response Parameter</th>
<th>Symbol (units)</th>
<th>Assessment Reference Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Head Injury Criteria</td>
<td>HIC</td>
<td>750 ~5% risk of brain injury</td>
</tr>
<tr>
<td>Head resultant acceleration</td>
<td>A (G)</td>
<td>150 G (2ms)</td>
</tr>
<tr>
<td>Neck forward flexion moment</td>
<td>+ My (N-m)</td>
<td>190 N-m</td>
</tr>
<tr>
<td>Neck rearward extension moment</td>
<td>- My (N-m)</td>
<td>57 N-m</td>
</tr>
<tr>
<td>Chest resultant acceleration</td>
<td>A (G)</td>
<td>60 G (3ms), 40 G (7ms)</td>
</tr>
<tr>
<td>Lumbar spine axial compression force</td>
<td>Fz (N)</td>
<td>3800 N (30ms), 6672 N (0ms)</td>
</tr>
<tr>
<td>Lumbar spine flexion moment</td>
<td>+ My (N-m)</td>
<td>1235 N-m</td>
</tr>
<tr>
<td>Lumbar spine extension moment</td>
<td>- My (N-m)</td>
<td>370 N-m</td>
</tr>
<tr>
<td>Pelvis vertical acceleration</td>
<td>Az (G)</td>
<td>15, 18, 23 G (low, med, high risk)</td>
</tr>
<tr>
<td>Tibia axial compressive force</td>
<td>F (N)</td>
<td>F/Fc - M/Mc &lt; 1</td>
</tr>
<tr>
<td>combined with Tibia bending moment</td>
<td>M (N-m)</td>
<td>where Fc=35,584N and Mc=225N-m</td>
</tr>
<tr>
<td>Femur or Tibia axial compression force</td>
<td>Fz (N)</td>
<td>7562 N (10ms), 9074 N (0ms)</td>
</tr>
</tbody>
</table>
- Topology optimization process redistributes material in the design domain to obtain a concept design.
- Hybrid Cellular Automata (HCA) algorithm using uniform internal energy density as a design objective.
- Nonlinear transient analysis, utilizing LS-Dyna for finite element analysis (FEA).

\[
\min_{t} \sum_{i} |S_i - S_i^*| \\
\text{s.t. } m_f(t) = M_f^* \\
\text{ } t_{min} \leq t \leq t_{max}
\]

Topology optimization to generate concept designs.
HCA Overview: Algorithm

- A continuum-based topology optimization
  - First utilized for bone remodeling (Tovar'04)
  - Extend bone remodeling technique for crashworthiness design (Patel'07)
- HCA = Cellular Automata (CA) + FEM
- CAs are characterized by local interactions

Global Formulation

\[
\begin{align*}
\text{find } & \quad x \\
\text{s.t. } & \quad h(x) = 0 \\
& \quad g(x) \leq 0 \\
& \quad h(x) = 0 \\
& \quad g(x) \leq 0 \\
& \quad x_i \in \{0, 1\}, \quad i = 1, \ldots, n,
\end{align*}
\]

Local Formulation

\[
\begin{align*}
\text{find } & \quad x_i \\
\text{s.t. } & \quad y_i(x_i) - y^* = 0 \\
& \quad x_i \in \{0, 1\},
\end{align*}
\]

Local CA rules and basic control theory is used to distribute material

Neighborhoods

- von Neumann (2D: \(N=4\), 3D: \(N=6\))
- Moore (2D: \(N=8\), 3D: \(N=26\))
**HCA Overview: Algorithm**

**Algorithm**

1. **Initial design**
   - \( \rho^{(0)} = x^{(0)} \rho_0 \)
   - \( \sigma_y^{(0)} = x^{(0)} \sigma_{y0} \)
   - \( E^{(0)} = x^{(0)} E_0 \)
   - \( E_h^{(0)} = x^{(0)} E_{h0} \)

2. **Crash or Blast analysis**
   - \( U(x^{(k)}) \)

3. **Update material distribution using HCA rule**
   - \( \Delta x = f(U, U^*) \)
   - \( x^{(k+1)} = x^{(k)} + \Delta x \)

4. **Convergence test**
   - Update global setpoint
   - \( S^{(k)} \)
   - Mass control

5. **New design**
   - \( S^{*(j+1)}(x^{(k)}) \)
   - \( \rho^{(j+1)} = x^{(k+1)} \rho_0 \)
   - \( E^{(j+1)} = x^{(k+1)} E_0 \)
   - \( E_h^{(j+1)} = x^{(k+1)} E_{h0} \)

6. **Final design**

**New material model**

"Uniform Internal Energy Density"
Field Variable:

- Original crashHCA algorithm only utilized Internal Energy (IE) at the final time step
  - IE at the final time is highly dependent on the simulation termination time
  - Resulting topology is drastically different depending on the selected end time
- Changed method for blast to use the IE at all time steps.
  \[ S_i = \int_{t=0}^{t_f} U_i(t) \, dt. \]
- Will utilize the concept of a fully stressed design as implemented in the Crash version of the HCA algorithm.
Material Card Selection
- Piecewise-linear elastic plastic material card:
  - Quasi-static
  - Hardening
  - Plastic deformation
- Johnson-Cook:
  - Can be used for dynamic loading situations
  - Strain rate effects
  - Temperature effects

\[ E = E_0 x^p \] and \[ G = G_0 x^p \]
\[ \sigma = [ A + B \varepsilon^n ] [1 + C \ln \dot{\varepsilon}] [1 - T^m] \]
\[ A = A_0 x^q, \quad B = B_0 x^q, \quad C = C_0 x^q \]
Modification of HCA for Blast: CONWEP Blast Model

- Load Type:
  - Began using the CONWEP algorithm for the blast model in the 3-D solid element HCA method.
    - Quick Analysis time (relative to MMALE)
    - Required minimal changes to the HCA algorithm
  - The objective is to design substructure that responds to a blast event in a desired manner. CONWEP can be used in this scenario since we are only looking at the response of a small piece of structure rather than the whole object.

Figure 1. Definition of variables in the US Army TACOM Impulse Model (Adapted from Westine et al., 1985).
As a proof of concept, a rectangular design domain was created to represent a piece of armor.

- Design domain is 40 x 40 x 10 cm aluminum (represents armor substructure)
- Top layer is 40 x 40 x 1 cm ceramic (represents ceramic top plate)
- Domain and top plate have fixed $x$, $y$, and $z$ displacement boundary conditions on all sides.
- Blast is positioned 100 cm up from origin (89 cm from top center of plate)
- Hourglass control is included to help prevent complex sound speeds arising in low density elements
- The target mass is set to be 50% of a full design domain

- Generated Topology to be compared against a baseline model that is full density, but half as thick.
- The top of the baseline design will be 94 cm from the blast source (i.e. the base of the domain will be the same distance in both cases)
Results:
Integrated IE Objective

- Model mesh size to 0.5 cm (a symmetric quarter of the domain was run)
- Simulation end time 800 µs
Results: Integrated IE Objective

- Resulting topology has mass where it would be expected and satisfies the mass target constraint.
- There is an order of magnitude improvement in the mean nodal acceleration of the bottom of the design domain versus the baseline case.
- Peak acceleration is misleading because of nodes that are being unrealistically accelerated relative to their neighbors.
Final Remarks

• This investigation showed that the HCA algorithm could be modified to produce topologies that help to mitigate the acceleration transferred to the occupant from a blast loading

• Future work:
  – Investigate further the use of IE as the field variable in the optimization process
  – Investigation of other field variables to drive the optimization that are more appropriately related to acceleration
  – Mesh refinement study
  – Continued work to improve convergence and to mitigate errors in the LS-DYNA runs (i.e. complex sound speeds arising in low density elements)
Questions?

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Backup
Verification of Monotonic Relationship between SED and Mass Density

- The Piecewise-linear elastic-plastic model was shown by Dr. Patel\(^1\) to have a monotonic relationship between SED and mass density under the SIMP penalization method.

- A similar study was conducted to determine if penalizing the Johnson-Cook model also yielded a monotonic relationship between SED and mass density.
  - Setup as a single solid LS-DYNA cube element under a rapid fixed loading.
  - Mass and penalization factors are varied.

- As in the standard SIMP scheme, elastic modulus (and shear modulus) is penalized according to:
  \[ E = E_0 x^p \text{ and } G = G_0 x^p \]

- Johnson-Cook model calculates a von-mises flow stress according to:
  \[ \sigma = [A + B \varepsilon^n][1 + C \ln \dot{\varepsilon}][1 - T \ast^m] \]

- Penalizing this von-mises flow stress is akin to penalizing the yield stress. This is done by penalizing the parameters \(A, B,\) and \(C.\)
• As in the standard SIMP scheme, elastic modulus (and shear modulus) is penalized according to:

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• Penalizing this von-mises flow stress is akin to penalizing the yield stress. This is done by penalizing the parameters \( A, B, \) and \( C. \)
• Under a constant load, the material does not behave monotonically under any penalization scheme
• Depending on choice of $p$ and $q$, we may have to significantly increase the minimum density allowed in the CA and FE models
• Under fixed displacement the IED appears to have a monotonic relationship with relative density.

Blast loadings, however, are not fixed displacement problems.
Modification of HCA for Blast: CONWEP Blast Model

- CONWEP blast model: Load-Blast function in Ls-Dyna, is an implementation of the hemispherical blast models of Kingery and Bulmash.
- Empirical blast-loading model rather than explicitly simulating the progress of the shock wave from the high explosive through the air and its interaction with the structure.
- Does not account for pressure confinement properties provided by imbedding explosive charge in soil.
- Scaling charge sizes for better agreement accepted, but applications to complete structures limited due to improperly modeled load distributions.
- More complex structures and interaction of detonation products and debris requires a more sophisticated fluid structure formulation.

\[ P(\tau) = P_i \cdot \cos^2 \theta + P_i \cdot (1 + \cos^2 \theta - 2 \cos \theta) \]
Agenda

• Introduction
• Overview of Hybrid Cellular Automata (HCA)
• Methodology
  – Field Variable
  – Material Model
  – Blast Model
• Implementation
• Results