Shock-driven Fluid Structure Interaction Simulation for Civil Design

https://sites.google.com/site/stephenwoodornlrams2011/

Research Alliance in Math and Science intern:
Stephen Wood
Florida International University

Research Alliance in Math and Science mentor:
Dr. Ralf Deiterding
Computer Science and Mathematics Division

Abstract

The multiphysics fluid-structure interaction simulation of shock-loaded structures requires the dynamic coupling of a shock-capturing flow solver to a solid mechanics solver for large deformations. This poster gives an overview of the computational approach and presents the first simulations that couple the software to the general purpose solid dynamics code DYNA3D for complex 3D structures.

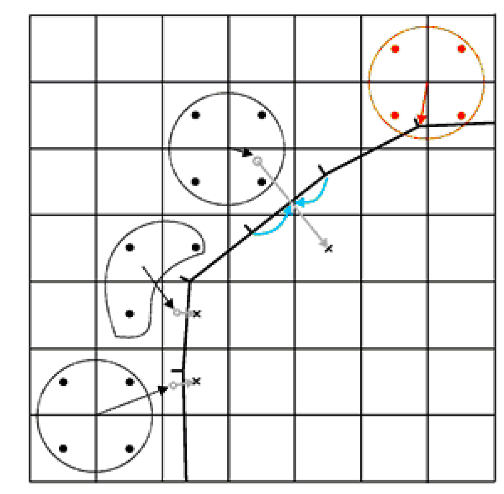
Introduction

- Bomb attacks on city centers by terrorist organizations
- Explosions within or adjacent to buildings can cause catastrophic damage
  - External and internal structural frames
  - Wall collapse
  - Window blow out
  - Shutdown of critical life-safety systems
- Analysis and design of structures to survive blast loading
  - Blast phenomenon
  - Dynamic response of structural elements

Method of solution

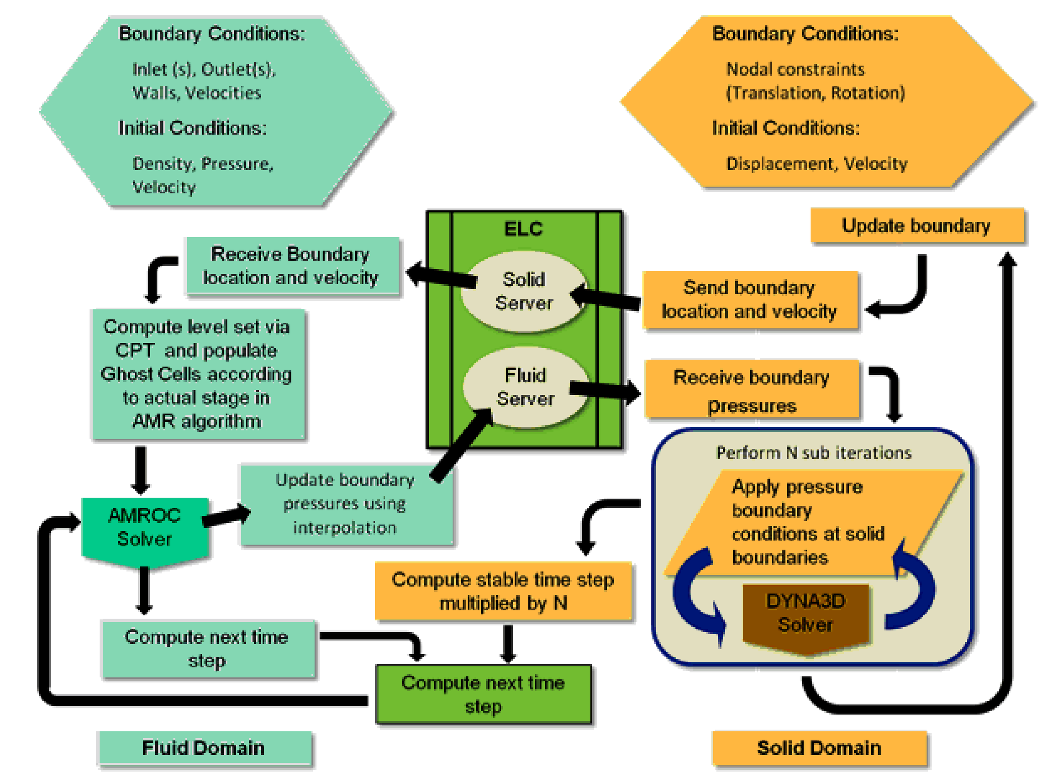
Fluid - structure coupling

- Compatibility conditions between inviscid fluid and solid at a slip interface
  - Continuity of normal velocity: $u^S_n = u^F_n$
  - Continuity of normal stresses: $\sigma^S_{nn} = -p^F$
  - No shear stresses: $\sigma^S_{n\tau} = \sigma^S_{n\omega} = 0$
- Time-splitting approach for coupling
  - Fluid:
    - Treats evolving solid surface with moving wall boundary conditions in fluid
    - Uses solid surface mesh to calculate fluid level set
    - Uses nearest velocity values $\mathbf{u}^S$ on surface facets to impose u^F_n in fluid
  - Solid:
    - Use interpolated fluid-pressure p^F to prescribe σ^S_{nn} on boundary facets
- Ad-hoc separation in dedicated fluid and solid processors



Mapping of to fluid cell centers (dots) to solid surface cell centers (x).

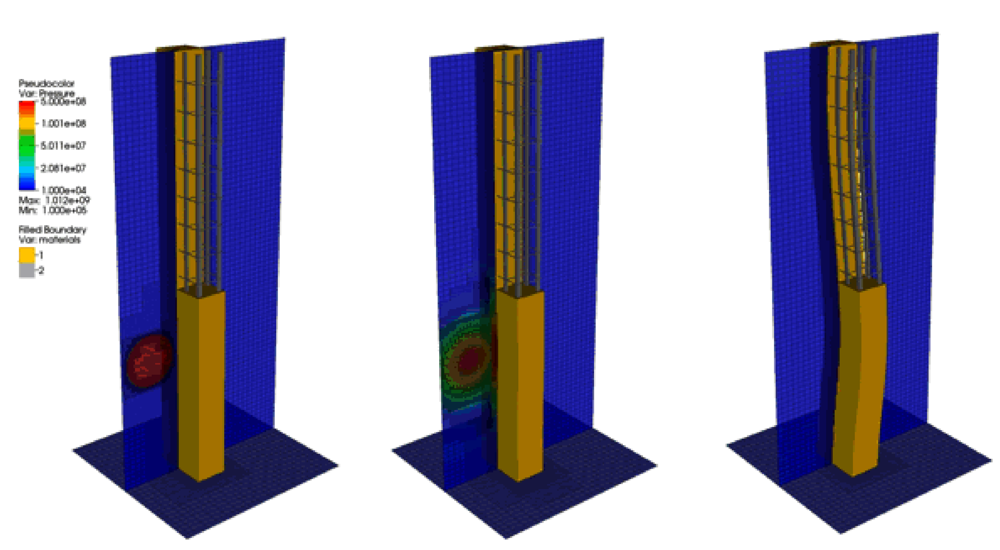
Algorithmic approach for coupling



Flow of applied boundary pressure, location and velocity data exchanged between AMROC and DYNA3D at each time step through the Euler-Lagrangian Coupler (ELC).

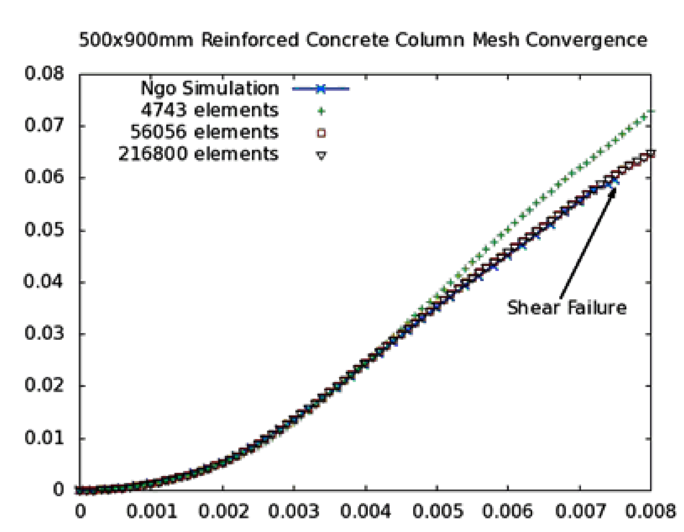
Results and Discussion

Reinforced concrete column



Time = 0.0000 s　Time = 0.0005 s　Time = 0.0036 s

Air pressure shown on slice planes around deforming column (tan) shown in cutaway to reveal steel rebar (grey) for three time steps.

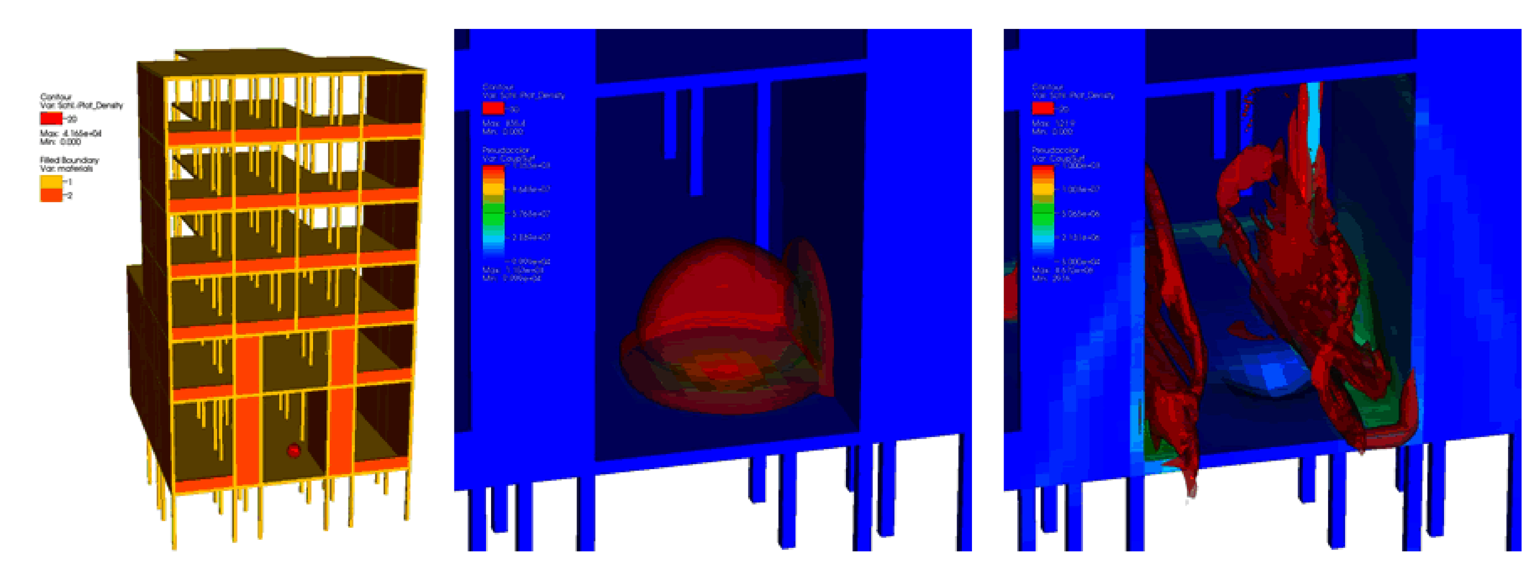


Solid mesh convergence and comparison with simulation results by Ngo et al.

- Detonation of 150kg of TNT positioned 0.5m in front of column, 2m above the ground plane along centerline
- Flexure of concrete and rebar is considered but rebar pull out is not.
- Less than 5% discrepancy between medium and fine solid mesh refinement levels and results published by Ngo et al. (2007)

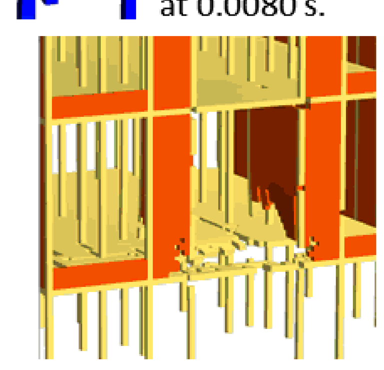
297 CPU hours on 34 3.4 GHz Xenon EM64T Processors in the Oak Ridge Institutional Cluster (OIC)

Multistory building



Time = 0.0000 s　Time = 0.0010 s　Time = 0.0042 s

Contour of air density gradient (red) shown around deforming building of high strength (yellow) and low strength (orange) concrete for three time steps.

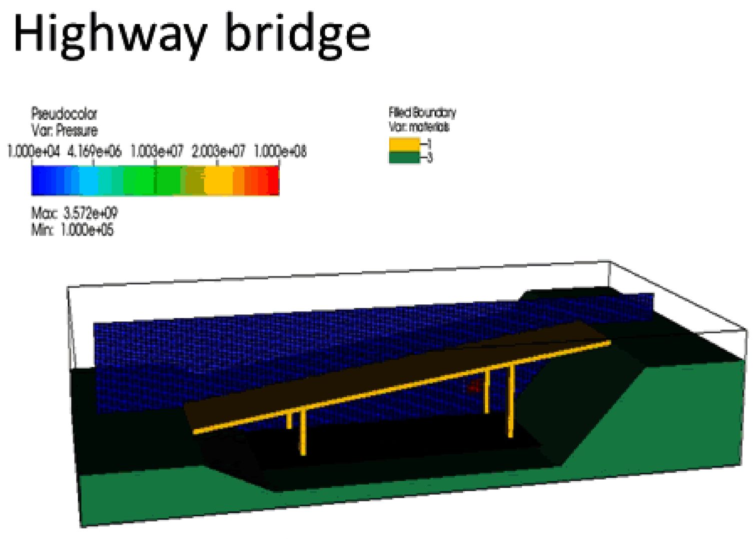


Detail: local failure of floors and walls adjacent to detonation at 0.0080 s.

- Detonation of 400kg of TNT positioned 1m above ground level, 1m inside lobby and 1m to the right of the centerline
- Good agreement with observations and qualitative simulation results published by Luccioni et al. (2004)

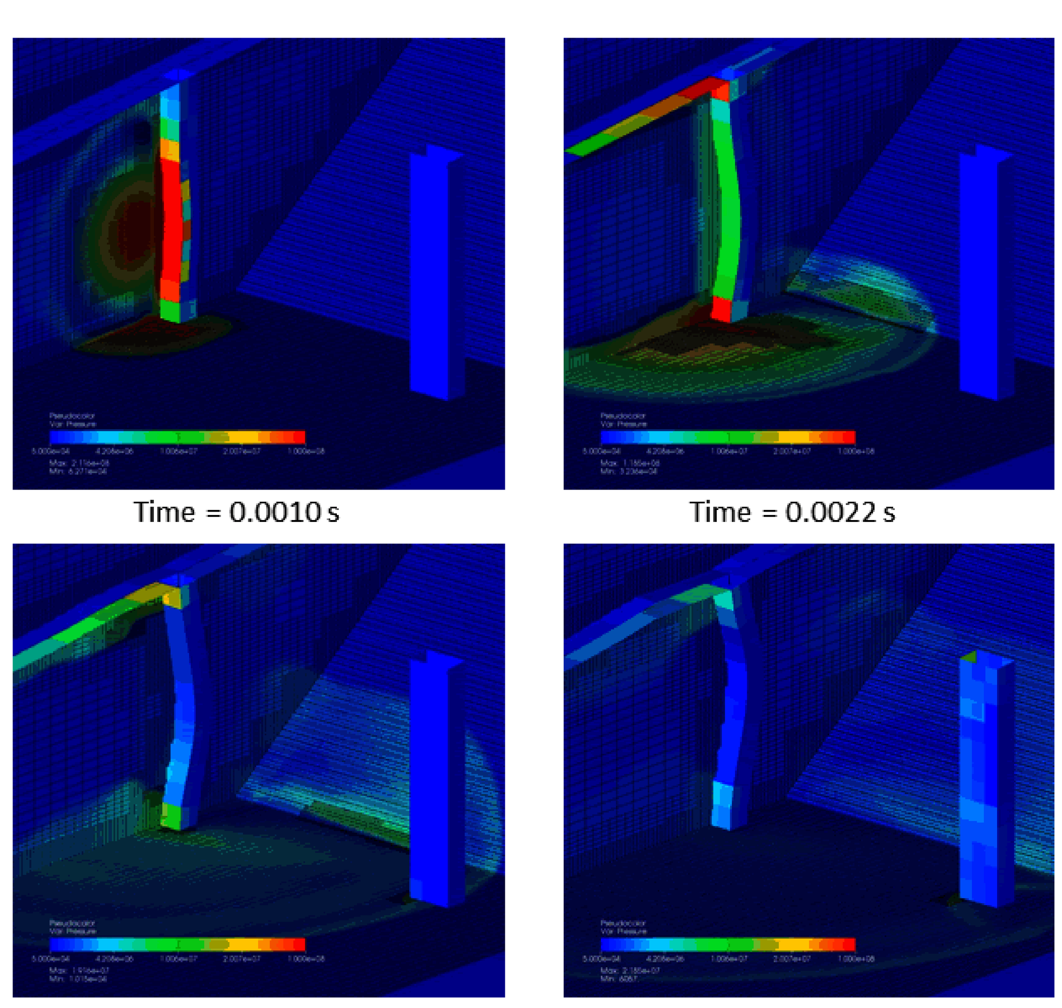
37 CPU hours on 32 3.4 GHz Xenon EM64T Processors in the Oak Ridge Institutional Cluster (OIC)

Highway bridge

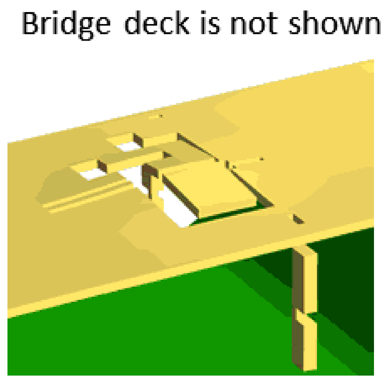


Time = 0.0000 s

Air pressure shown on slice plane and surfaces above rigid ground (green) and around deforming bridge (tan) shown for five time steps. Bridge deck is not shown in later time steps.



Time = 0.0010 s　Time = 0.0022 s　Time = 0.0034 s　Time = 0.0045 s



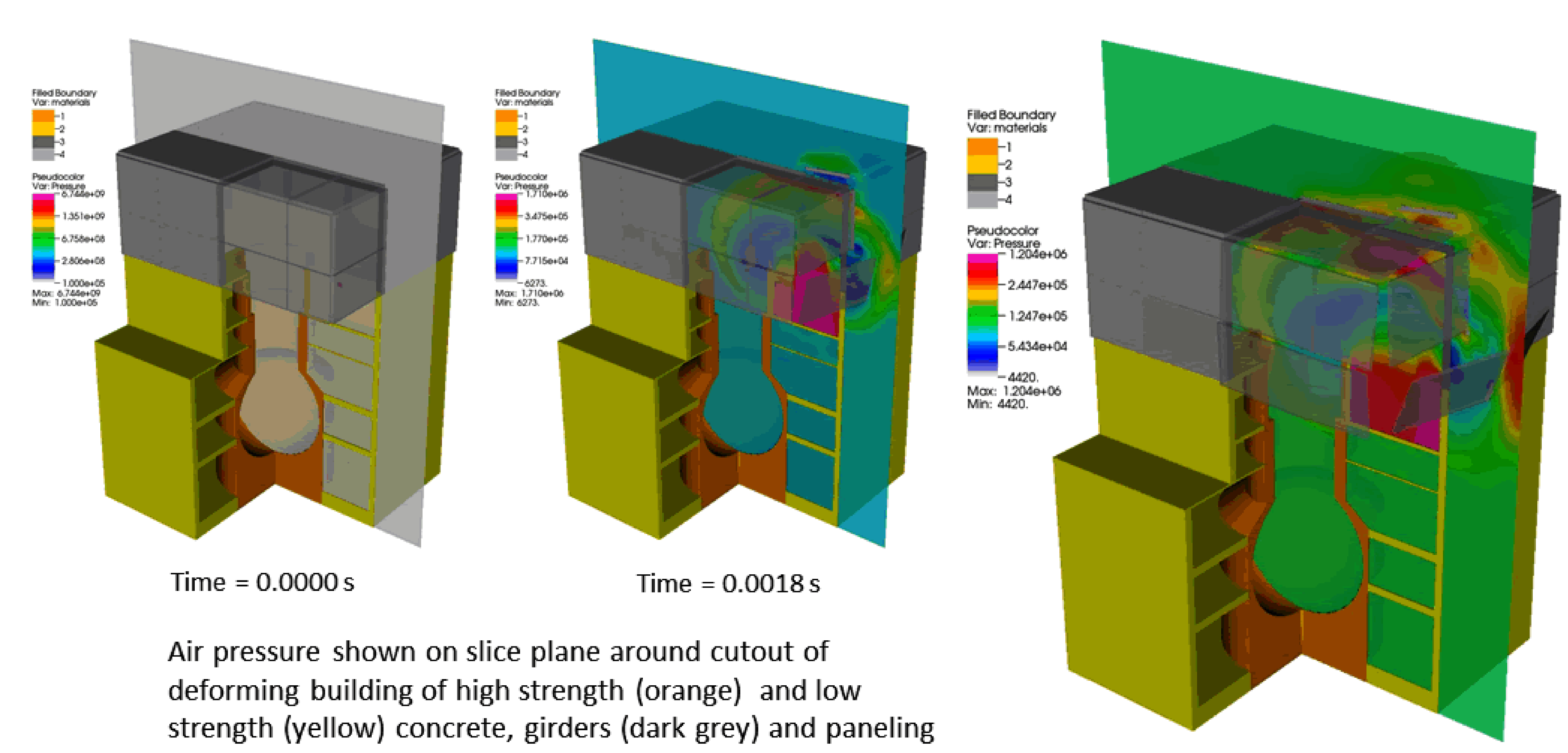
Time = 0.001865 s

Detail: local failure in bridge deck and columns adjacent to detonation.

- Detonation of 450kg of TNT positioned 0.5m in front of column, 2m above the ground plane along centerline
- Good agreement with simulation results published by Agrawal and Yi (2009)

363 CPU hours on 32 3.4 GHz Xenon EM64T Processors in the Oak Ridge Institutional Cluster (OIC)

Reactor building



Time = 0.0000 s　Time = 0.0018 s　Time = 0.0025 s

Air pressure shown on slice plane around cutout of deforming building of high strength (orange) and low strength (yellow) concrete, girders (dark grey) and paneling (light grey) for three time steps.

- Detonation of 1000kg of TNT positioned on reactor floor above the spent fuel storage pool along the centerline
  - Prototypical representation of hydrogen explosion
- Complexity of structures and attachments can be accurately modeled

3405 CPU hours on 64 3.4 GHz Xenon EM64T Processors in the Oak Ridge Institutional Cluster (OIC)

Conclusions

- AMROC-DYNA is capable of simulating FSI on complex 3D structures
- Results agree with limited experimental measurements and observations
- Material failure and fracture can be modeled and simulated
- AMROC-DYNA can be utilized in design and optimization of blast mitigation structures
- AMROC-DYNA can be utilized in forensic investigation

Future work

- Continue development of coupling surface routine to enable large deformations and fragmentation following failure
- Further development of Hydrogen detonation and deflagration models
- Incorporation of case appropriate fluid and material properties into required models
  - Parameter study to be conducted

Selected References

Agrawal, A. K. & Yi, Z. (2009). *Blast Load Effects on Highway Bridges.* New York: University Transportation Research Center City College of New York.

Deiterding, R., Cirak, F., & Mauch, S. P. (2008) Efficient fluid-structure interaction simulation of viscoplastic and fracturing thin-shells subjected to underwater shock loading. In S. Hartmann, A. Meister, M. Schäfer, and S. Turek, editors, *Int. Workshop on Fluid-Structure Interaction. Theory, Numerics and Applications, Herrsching am Ammersee 2008,* pages 65–80. kassel university press GmbH, 2009.

Hallquist, J. & Lin, J. I. (2005). A nonlinear explicit three-dimensional finite element code for solid and structural mechanics. Technical Report UCRL-MA-107254, Lawrence Livermore National Laboratory, 2005. Source code (U.S. export controlled) available for licensing fee from http://www.osti.gov/estsc.

Luccioni, B. M., Ambrosini, R. D., & Danesi, R. F. (2004) Analysis of building collapse under blast loads. Engineering Structures 26, pages 63-71

Ngo, T., Mendis, P., Gupta, A., & Ramsay, J. (2007). Blast Loading and Blast Effects on Structures - An Overview. *Electronic Journal of Structural Engineering* .

U.S. DEPARTMENT OF ENERGY | Office of Science

The Research Alliance in Math and Science program is sponsored by the Office of Advanced Scientific Computing Research and the U.S. Department of Energy. The work was performed at the Oak Ridge National Laboratory, which is managed by UT-Battelle, LLC under Contract No. De-AC05-00OR22725. This work has been authored by a contractor of the U.S. Government, accordingly, the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for U.S. Government purposes. I would like to thank Ms. McCoy for bringing me to ORNL through the RAMS program and giving me the opportunity to conduct research with guidance from Dr. Ralf Deiterding. I would also like to express my gratitude for all the mentoring Dr. Deiterding has provided without which this work would not have been possible.

UT-BATTELLE
OAK RIDGE NATIONAL LABORATORY