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L. Glascoe, C. Noble, J. Reynolds, A. Kuhl, J. Morris

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Securing Infrastructure from High Explosive Threats

Lee G. Glascoe, Ph.D., P.E. [1], **Charles Noble, Ph.D., John G. Reynolds, Ph.D., Allen Kuhl, Ph.D., and Joseph Morris, Ph.D.**
Lawrence Livermore National Laboratory, Livermore, California
1. glascoe@llnl.gov, 925-423-2922

Abstract -- *Lawrence Livermore National Laboratory (LLNL) is working with the Department of Homeland Security's Science and Technology Directorate, the Transportation Security Administration, and several infrastructure partners to characterize and help mitigate principal structural vulnerabilities to explosive threats. Given the importance of infrastructure to the nation's security and economy, there is a clear need for applied research and analyses (1) to improve understanding of the vulnerabilities of these systems to explosive threats and (2) to provide decision makers with time-critical technical assistance concerning countermeasure and mitigation options. Fully-coupled high performance calculations of structural response to ideal and non-ideal explosives help bound and quantify specific critical vulnerabilities, and help identify possible corrective schemes. Experimental validation of modeling approaches and methodologies builds confidence in the prediction, while advanced stochastic techniques allow for optimal use of scarce computational resources to efficiently provide infrastructure owners and decision makers with timely analyses.*

INTRODUCTION

The importance of understanding the failure of vulnerable infrastructure under extreme loading is highlighted by the 9/11 attacks and international attacks on infrastructure and transportation systems of Moscow, Madrid, London and Mumbai. Terrorist penetration risk is relatively high for infrastructure, particularly for infrastructure associated with transportation [1]. Correction of structural vulnerabilities requires close collaboration with infrastructure owners and proper characterization of the structure response to an explosive threat. Up-to-date and informed threat assessments can help prioritize detailed effects modeling and testing, which, in turn, is a necessary precursor to evaluation and deployment of explosives detection and mitigation capabilities. The often complex and computationally challenging analyses require expertise in (1) state-of-the-art testing resources, (2) detailed physics and thermodynamics codes, as well as (3) stochastic approaches to help understand and minimize uncertainty. Building on earlier work on structural response to seismic and shock events [e.g., 2, 3, 4], LLNL scientists and engineers have developed computational capabilities for the evaluation of structural vulnerabilities that can help highlight potential engineered solutions to mitigate structural damage and prevent larger system failure.

BODY

Explosives Characterization

Thermodynamic models are leveraged to predict and survey performance of both ideal and non-ideal explosives. Such physics and chemistry-based modeling helps inform empirical testing of non-idealized and, particularly, thermobaric explosives (see Figure 1). The explosive products are modeled using equations of state (EOS) such as the Jones-Wilkins-Lee EOS, an empirical mathematical expression used to describe the pressure-volume relationship associated with chemical detonation products. Other thermodynamic representations of an EOS are obtained using thermodynamic codes, e.g. LLNL's Cheetah code [5], to predict the performance of ideal and non-ideal high explosives. The EOS is then used in hydrodynamic and structural mechanics codes, briefly described below, to best characterize shock events associated with explosive detonation and airblast.

Characterizing Structural Vulnerabilities

Simulations using high-performance structural and fluid mechanics finite element codes are run on teraflop-class supercomputers to characterize structural response to explosive shock. Appropriate EOS for explosives and structural materials are employed within modeling frameworks of varying complexity that can accommodate computationally demanding fully coupled soil-fluid-structure interactions. Explosive threats under different conditions of confinement or placement have been modeled using the ALE3D [6] and DYNA3D [7] finite element codes, as well as smoothed particle hydrodynamics approaches [8].

Experimental validation of the different computational methods builds confidence in their predictive capabilities. Efforts such as the US Army Engineering Research and Development Center's Precision Test Wall Study, the Defense Threat Reduction Agency's Divine Buffalo test series, and a host of smaller lab and field studies are used to partially validate simulations of air and underwater blasts. Such validation efforts also provide opportunity to evaluate the utility of, for example, faster running simplified approaches to structural response incorporating, for instance, homogenized material assumptions. Sample validation studies, illustrated in Figure 2, include full-scale concrete testing [e.g., 9, 10], and water-tamping/bubble-collapse testing [e.g., 11, 12].

Blast effects and structural response modeling is an integral component of an infrastructure vulnerability assessment, but is most useful when incorporated within a complete systematic framework. Such a systematic analysis evaluates salient aspects of the infrastructure and attempts to establish the overall consequences associated with a range of threats. The system is typically constructed using a set of component level analyses that help bound threats that could initiate a failure mode of concern. Ultimately such analyses can provide the basis for countermeasure prioritization (see below). Relevant assessments may include considerations such as confined and focused explosive assessments within stations or buildings, sustained thermal loading events on structures [13], soil softening and liquefaction considerations, reinforced concrete structural failure, and the progressive collapse of large structures (see Figures 3 and 4).

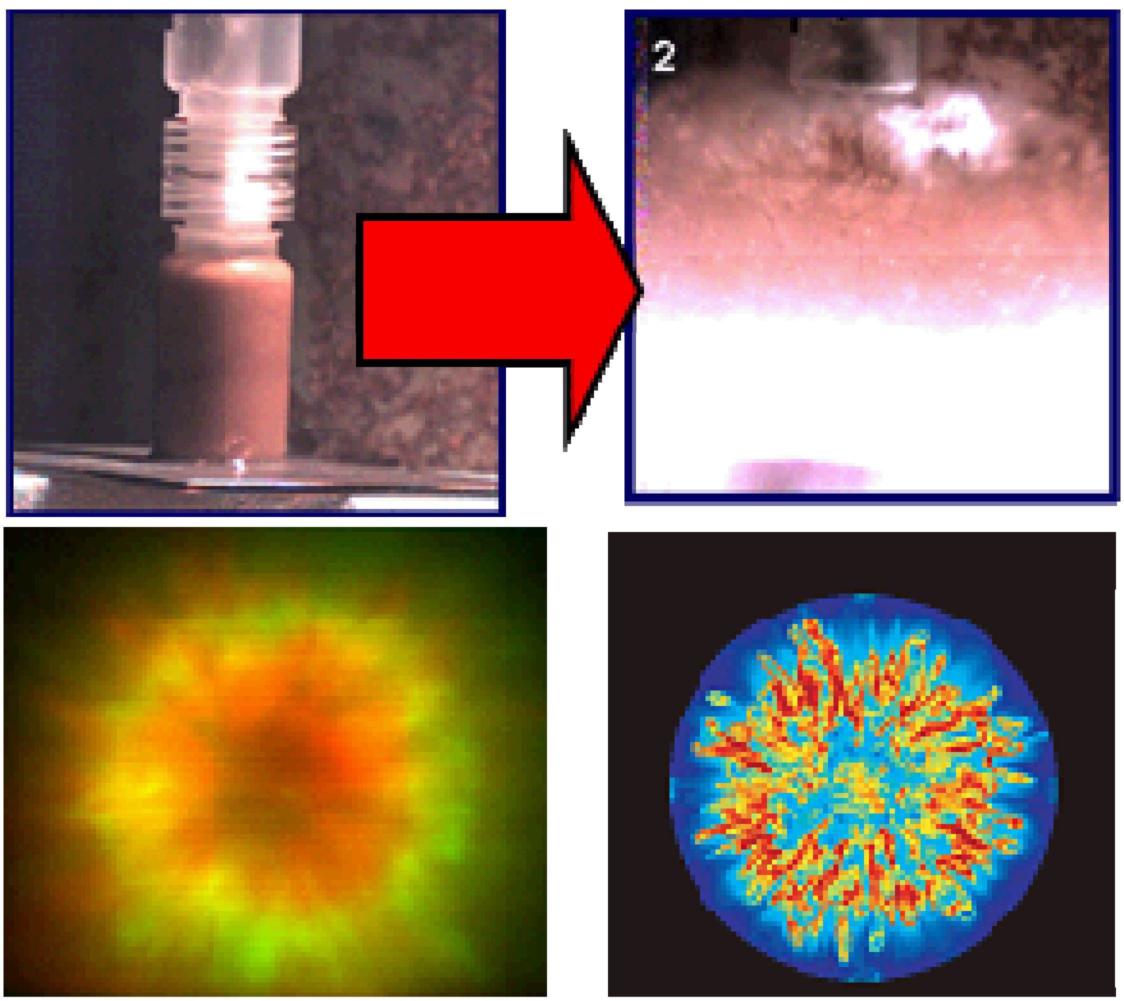

Figure 1 -- Experimental (top and lower left) and numerical characterization (lower right) of non-ideal explosives.

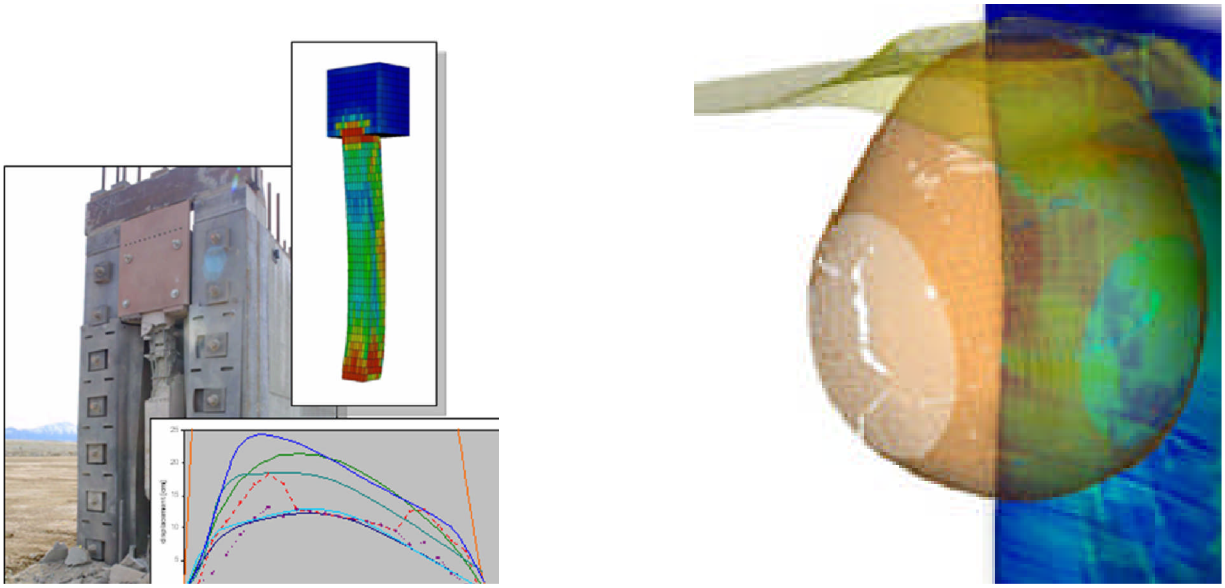

Figure 2 – Component and system experiments are leveraged across programs (DoD, DHS, DOE) to validate structural and hydrodynamic numerical codes and concepts (on the left is a concrete model validation study, the right is a high-fidelity underwater blast study).

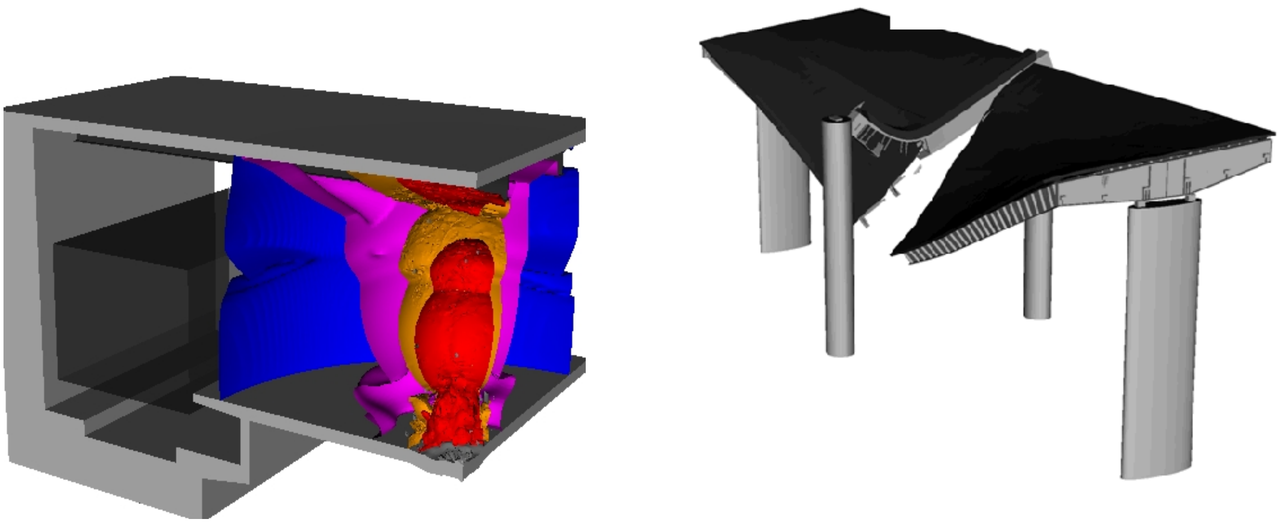

Figure 3 – Examples of structural failure analyses at different time scales: focused explosive blast within a confined station (LEFT), and long duration thermal failure of an overpass (RIGHT).

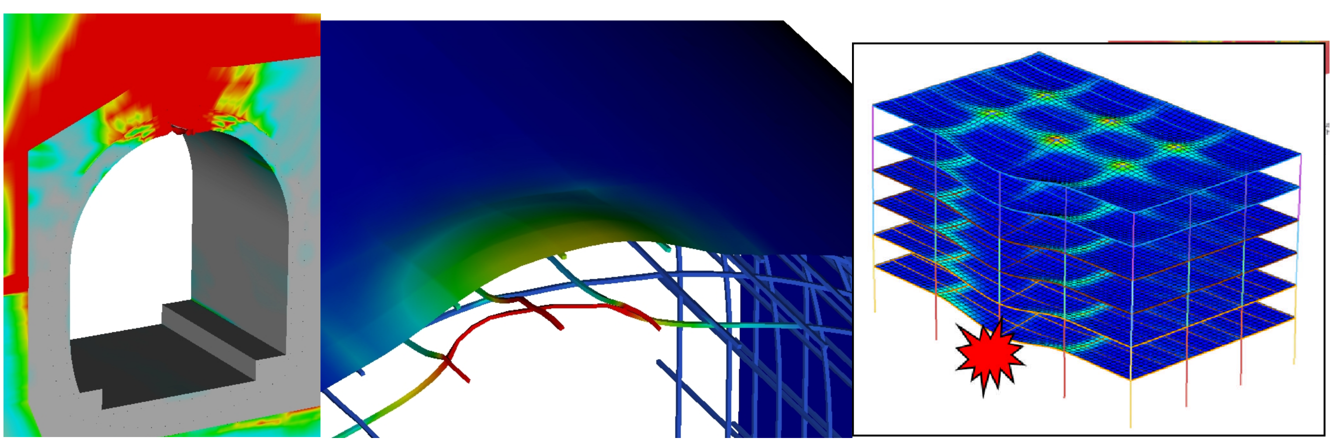

Figure 4 -- Sample high performance simulations: (LEFT) structural-failure in a confined space, (CENTER) detail of steel frame and rebar failure, and (RIGHT) progressive collapse of a large structure.

Structural damage is a function of construction materials and their environment. As an example, one may consider three materials: concrete, steel, and non-cohesive soil media. For a concrete material, finite element codes may incorporate material models developed by Karagozian and Case (K&C) where three independent fixed surfaces define plastic response [14]. In the K&C concrete model once maximum strength has been reached, softening occurs until only a residual strength remains. For analyses of a steel structure, damage may be characterized using a simple bi-linear elasto-plastic material model with a plastic strain failure criterion whereby plastically failed elements are unable to carry or transfer a load. For analyses involving a saturated soil media, material models may account for soil softening and ultimate soil failure associated with, for example, an increase in pore water pressure [15]. These material models and others are typically coupled within the larger finite element code framework for a complete vulnerability assessment. As an example of such coupling, the case of soil bored reinforced concrete structure may be modeled at high resolution with an appropriate finite element code that accounts for concrete materials using a K&C damage criteria, steel rebar within the concrete using a plastic strain to failure criterion, and saturated soil media using an effective stress model (Figure 4, left and center plots).

Structural damage is time-dependent and often requires several levels of analyses over different time-scales to determine the ultimate failure or survival of a structure. During an explosive event, structural damage in the form of a breach may be apparent within milliseconds after the blast and may be best modeled using specific fully-coupled codes. Such may be the case of a focused explosive event within a confined structure, as illustrated in Figure 3. Longer term failure modes may be indirectly associated with a shock event and may occur at timescales on the order of seconds, e.g., longer term structural collapse, soil liquefaction, and the progressive collapse of a structure due to the failure of a critical support (Figure 4, right plot). Such longer term failure modes are likely to be realized by employing less computationally demanding capabilities that allow for longer temporal considerations.

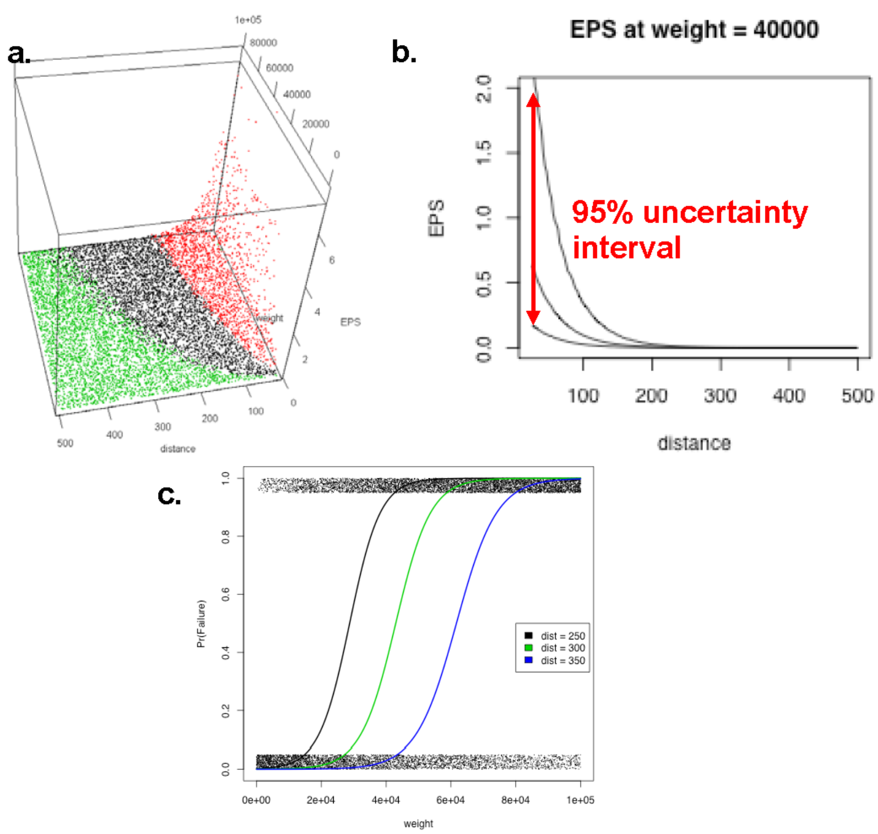

Figure 5 -- A mixture modeling approach can be employed to fit standard logistic regression with regular regression to provide efficient and probabilistic answers to specific questions: (a) threat-standoff-failure space for three regimes of damage; (b) damage with confidence interval in engineering plastic strain (EPS) at different standoff for a specific threat; (c) probability of logistic failure for different threat conditions.

Timely Systematic Evaluation with Uncertainty

Vulnerability assessments employing computationally demanding tools can be difficult to provide in a timely manner, particularly when such assessments account for systematic and structural uncertainty and variability. One possible solution to this difficulty is advanced stochastic modeling techniques that efficiently characterize events in the presence of variability and uncertainty. For example, importance sampling techniques or Bayesian updating techniques can help quantify and bound uncertainty within a parametric response surface with a limited set of numerical realizations [16, 17]. As a specific example, a mixture model approach [18] can be employed to fit standard logistic regression ("failure" versus "no failure") with regular regression ("damage severity") to provide efficient and probabilistic answers to specific questions from decision makers (Figure 5).

Once specific vulnerabilities have been assessed to a sufficient level of detail to address the concern at hand, strategies building from the vulnerability assessment tools described above can be explored for corrective measures and countermeasure prioritization. Such system assessments can accommodate unique site/system characteristics while still leveraging benefits from more generic studies.

SUMMARY AND CONCLUSIONS

Informed use of multi-physics modeling built upon experimental validation can form the basis of an end-to-end capability for analyzing and correcting structural vulnerabilities associated with explosive blast. These techniques are inherently computationally expensive due to the multi-dimensional nature of the problem space and the often necessary requirement for full coupling between fluid, solid and soil media phases. Computational expense can be minimized and results optimized by use of simplified modeling approaches and by leveraging advanced stochastic sampling techniques. Such detailed but timely analyses is particularly useful to accommodate the needs of government agencies and infrastructure owners to guide security efforts for critical infrastructure nationwide.

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