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# Assessing the Vulnerability of Large Critical Infrastructure Using Fully-Coupled Blast Effects Modeling

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## Disclaimer

# Assessing the Vulnerability of Large Critical Infrastructure Using Fully-Coupled Blast Effects Modeling

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## Abstract

Structural failures, such as the MacArthur Maze I-880 overpass in Oakland, California and the I-35 bridge in Minneapolis, Minnesota, are recent examples of our national infrastructure's fragility and serve as an important reminder of such infrastructure in our everyday lives. These two failures, as well as the World Trade Center's collapse and the levee failures in New Orleans, highlight the national importance of protecting our infrastructure as much as possible against acts of terrorism and natural hazards. This paper describes a process for evaluating the vulnerability of critical infrastructure to large blast loads using a fully-coupled finite element approach. A description of the finite element software and modeling technique is discussed along with the experimental validation of the numerical tools. We discuss how such an approach can be used for specific problems such as modeling the progressive collapse of a building.

## Introduction

The ramifications of structural failures extend far beyond the lost physical use of the structure. The World Trade Center collapse, New Orleans levee failure, and Minneapolis I-35 bridge failure are just three recent examples of the psychological and financial impacts that the loss of critical infrastructure can have on regional and national economies. The MacArthur Maze I-880 overpass collapse from a gasoline tanker collision and resulting fuel fire highlights our infrastructure vulnerability to accident scenarios that can result from its normal everyday use. The terrorist use of explosives against buildings and transit systems is illustrated by the bombings at the Marine barracks in Beirut (1983), Murrah Federal Building (2000), and U.S. embassies in Kenya (1998), Tanzania (1998), and Yemen (2008) and train bombings in Madrid (2004), Mumbai (2006), and Russia (2007). Understanding critical infrastructure vulnerabilities to accidents, natural hazards and directed terrorist attack is recognized as a topic of national concern.

Considerable efforts have been made to understand the evolution of progressive damage in large infrastructure (e.g. NIST, 2005), the uncertainty in failure analysis (Fong, 2006), and the probabilities associated with system reliability during progressive failure (Guers, 1988). The federal government has adopted design guidelines (GSA, 2005 and DoD, 2005) that use a threat independent methodology to reduce the progressive collapse potential for new and retrofitted federal facilities. These efforts reflect the need to understand how blast energy is imparted to a structure, the initiation of local (component) failure, damage evolution as loads are redistributed, and the overall structural stability of a damaged structure.

**Vulnerability Assessment Process**

Modeling the nonlinear, dynamic response of large-scale infrastructure from explosive detonation to final structural stability is a computationally demanding endeavor. As a national science and technology laboratory operated for the Department of Energy (DOE), Lawrence Livermore National Laboratory (LLNL) has the computational resources and finite element software capabilities that enable high-fidelity simulation of critical infrastructure to a range of dynamic insults. LLNL's approach for assessing the terrorist threat to structures leverages a history of high-fidelity infrastructure analysis that extends back to the 1970s with assistance to the Nuclear Regulatory Commission (e.g. Bohn et al 1984) and DOE complex (e.g. Coats et al 1981) on earthquake safety. LLNL has also been actively involved in assessing the seismic safety of buildings, bridges and dams (e.g. McCallen and Romstad 1994; McCallen and Astaneh-Asl 2000; and Noble and Nuss 2004). The approach used by LLNL engages a multi-disciplinary team of engineers (civil, mechanical, geotechnical), physicists, computer scientists, geoscientists, and statisticians. Extensive experimental facilities for high explosive research, development, and testing at LLNL's High Explosives Applications Facility complement the available computational resources. This unique combination of personnel, computational resources, and experimental facilities enables LLNL to perform a complete characterization of threats, vulnerabilities, and countermeasures for critical infrastructure.

Blast effects modeling is an integral component of the vulnerability assessment process which uses a systematic approach to determine infrastructure vulnerability and assist stakeholder decisions. A system level analysis evaluates the system as a whole and establishes the overall consequences from a particular, local, component failure. Component level analysis determines the threat required to initiate a specific failure. Risk, adversary and consequence analysis allows for countermeasure prioritization. This approach allows threat considerations to be tailored to the type of infrastructure and any unique site/system characteristics.

The process begins by identifying what kinds of threats are of concern (explosives, shaped charges, fire events), what structures are likely to be the most vulnerable (age, construction technique and materials, accessibility), and which vulnerabilities have the highest consequence (casualties, economics). Threat size and type are influenced by facility access and physical constraints. For example, a transit system may be more susceptible to a man portable explosive, while a building might be easily subjected to a vehicle borne explosive. A detailed vulnerability assessment is then performed to determine how vulnerable a specific structure is to high consequence threats. A finite element model of the structure is developed and high-fidelity, physics based, structural analysis is performed to simulate exposure to a variety of dynamic insults, e.g. vehicle impact, explosive detonation, explosively formed projectile. Stochastic inferences can be made from analysis results to evaluate confidence levels and estimate uncertainty (Glascoe et al 2009; Koutsourelakis et al 2006). The process continues by identifying practical countermeasures and the Concept of Operations (CONOPS) required to effectively protect the structure. Countermeasures for structurally robust structures may focus on security and response enhancements, while countermeasures for weaker structures will also include bounding vulnerabilities and developing actionable mitigation strategies. A detailed countermeasure evaluation is performed using systems analysis, high-fidelity modeling, and stochastic inference to determine the effectiveness of a particular countermeasure. The countermeasure is evaluated not only with respect to its effectiveness to mitigate a threat, but also how well it works with CONOPS and maintains system functionality.

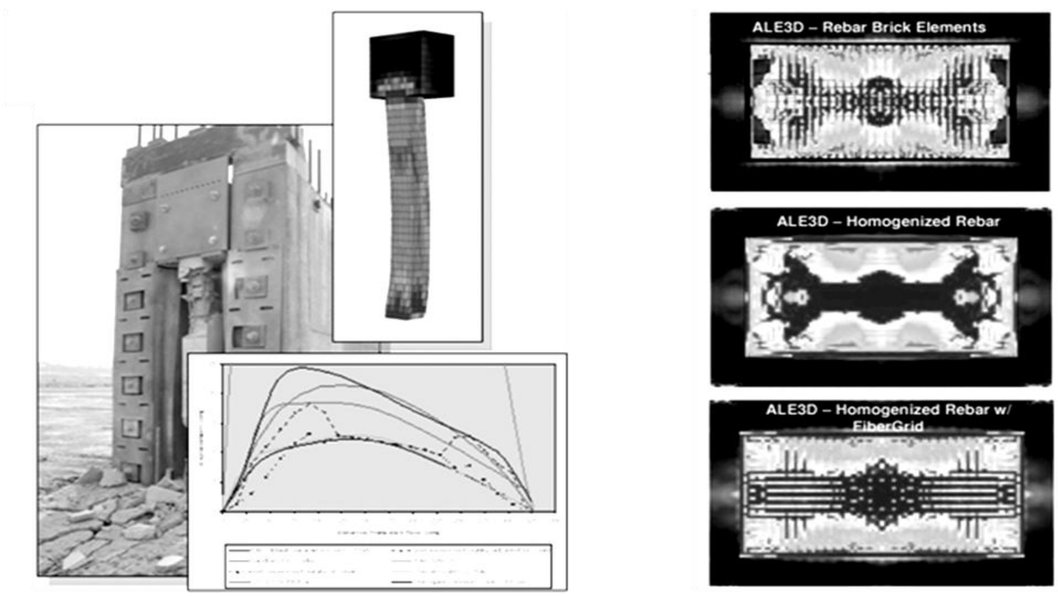
**Finite Element Analysis Software**

Vulnerability assessments are performed using two finite element analysis codes developed by LLNL: ParaDyn (DeGroot et al 2008) for system level response to structural failures and ALE3D (Nichols 2008) for fully coupled blast analysis. ParaDyn, the parallel version of DYNA3D (Lin 2007), is an explicit, transient dynamic analysis code for solid and structural mechanics which uses a Lagrangian formulation. Component failures can be accommodated through element erosion and the conversion of failed elements into SPH particles which preserve the system’s mass and momentum balances. The SPH particles can interact with other particles and intact elements which provides a means to transfer the kinetic energy of failed components into other parts of the structure.

ALE3D is an arbitrary-Lagrangian-Eulerian hydrodynamic analysis code that simulates the fluid and elastic-plastic material response. The code incorporates continuum mechanics, thermal diffusion, chemistry, incompressible flow, multiphase flow, and magneto-hydrodynamics. The detonation energy released by the explosive is represented using a Jones-Wilkins-Lee (JWL) equation of state (Dobratz 1981). The resulting shock wave is propagated through the surrounding medium (e.g. air or water) using advection and mesh relaxation techniques to allow material flow through the mesh without tangling elements. The code tracks the wave propagation and interactions (reflections), so the blast pressures applied to the structure vary temporally (arrival time) and spatially (stand-off distance) as the blast wave travels over and around the structure. The materials representing the structure can be held Lagrangian to best preserve material history parameters or allowed to advect if extensively damaged.

Several material models are available in both codes to represent the component materials' deviatoric strength and pressure-volume relationship (i.e. equation of state). Structural components can be modeled using a combination of beam, shell, and solid elements. Steel members are often modeled using beam elements with user defined integration rules to represent the joist, girder, and column cross-sections and account for partial yielding through a cross-section. The constitutive response is represented by an isotropic plasticity model; there are options for bilinear, power law, and piecewise linear hardening relationships and strain rate dependent yield strength. Concrete members are typically modeled with solid elements and often use the Karagozian & Case (K&C) concrete model (Malvar et al 1997; Malvar et al 2000). The K&C model determines concrete strength with respect to confining pressure, damage, and strain rate. The K&C model also allows a homogenized representation of reinforcement using volume fractions.

Considerable efforts have been made to validate the blast responses predicted by these simulation tools (e.g., Noble et al 2005). The experimental studies used for the validation efforts include, among others, the U. S. Army Engineer Research and Development Center Precision Test Wall Study and the Defense Threat Reduction Agency Divine Buffalo test series. Validation efforts include simulations of air blasts (Figure 1a), underwater explosions, and comparisons of discrete and homogenized rebar models (Figure 1b).




(a) (b)

**Figure 1. Validation efforts include comparing numerical results against experimental data (a) and verifying modeling assumptions like the use of homogenized rebar (b).**

**Evaluating Structural Stability**

The consequences that a particular threat has on a structure can range from cosmetic damage to initiating progressive collapse. If a structural breach (localized failure) does occur, the effects may extend to a single structural component, a section of the structure (localized collapse), or a large portion of the structure (progressive collapse). Evaluating a threat's consequences requires determining the energy released by the threat and imparted to the structure, the resulting structural damage and potential structural component failures, and the damaged structure's ability to redistribute the loads that had been carried by failed members. Typically, the threat is generalized as a sphere of trinitrotoluene (TNT). This allows other explosives and shapes to be converted to an equivalent weight of TNT and be related to the results obtained. Alternatively, other explosives and shapes can be explicitly represented to account for differences in the energy release rate and focusing effects. Two approaches are used at LLNL to evaluate a damaged system's structural stability.

The first approach initially uses a threat independent technique that presupposes a localized component failure and evaluates the system impact of that failure. For the high consequence failures, i.e. where a local component failure propagates into localized or progressive collapse, the threat required to cause the initial failure is determined with respect to charge weight and stand-off distance. An example application of this approach is looking at the potential for progressive collapse of a building. The building is represented using beam, shell, and solid elements as appropriate (refer to Figure 2a) and ParaDyn is used to determine the system response. The first analysis step is to statically initialize the building with gravity loads and create a restart file (which allows the static initialization to be performed only once and provides a starting point for all the subsequent failure analyses). The failure of one or more structural members is represented by specifying the elements to be removed and restarting the analysis. The element deletion causes an imbalance between the external applied loads and internal stresses which forces the structure to attempt to redistribute loads. If the redistributed loads cause additional component failures (e.g. excessive plastic strain, damage or buckling), then the code tracks the failure propagation until an alternative load path with adequate strength is reached or

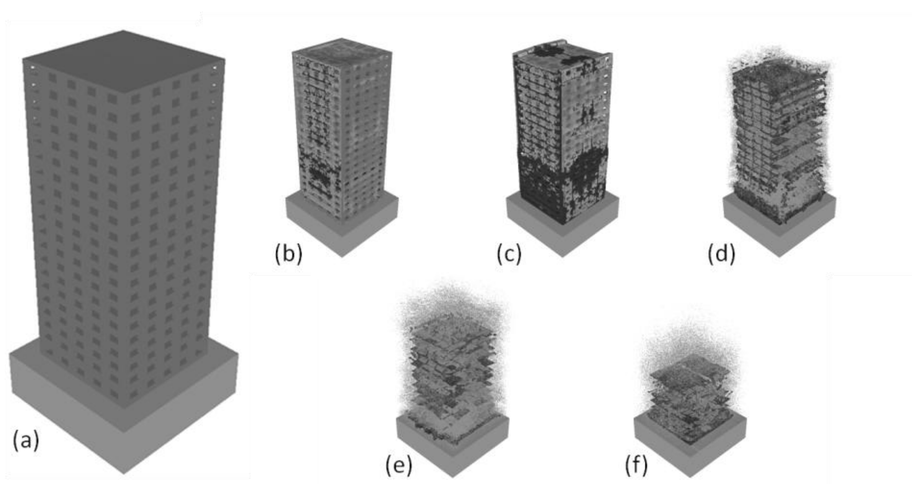



**Figure 2. When a basement column failure is simulated, the building (a) experiences large deformations and extensive concrete damage which leads to structural collapse (b-f).**

the structure collapses (refer to Figure 2 b to f). Metrics for evaluating the structure's damaged state include equivalent plastic strains (EPS) in the steel, damage parameter in the concrete and nodal displacement time histories. Displacement time histories with continually increasing magnitudes indicate failure propagation, while displacement time histories that oscillate about a stable value indicate that the structure has stabilized and is just ringing from the dynamic loading.

The second analysis step is to determine the threat required to cause the initial failure by performing a fully coupled blast analysis using ALE3D. The finite element model might contain only the component of interest to evaluate a single point failure mode, or a subsection of the structure to evaluate a multi-point failure mode or floor heave (refer to Figure 3). The model can represent the structural members using a combination of beam, shell, and solid elements. The metrics used for evaluating damaged components is similar to those used for the system analysis, including EPS for steel, concrete damage, and displacement time histories.

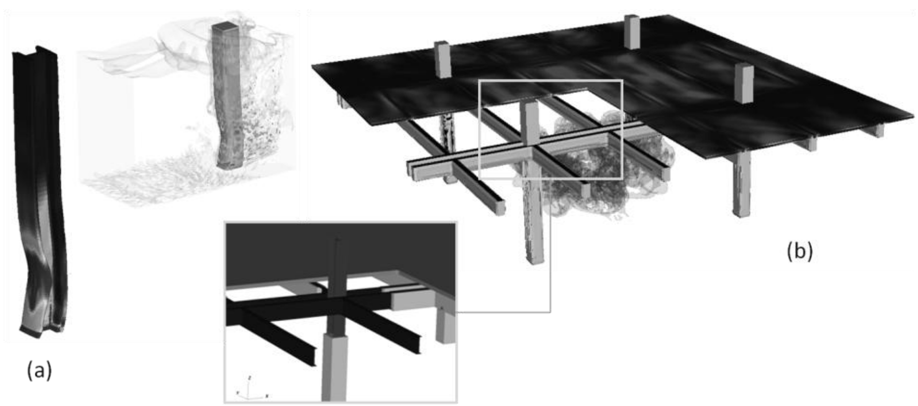



**Figure 3. A component model (a) provides a good estimate for a single point failure mode, while multi-point (multi-component) failure modes or floor heave require a section of the structure to be modeled (b).**

The second approach performs a fully coupled blast analysis on a full system model. The domain space can be limited by symmetry planes and boundary conditions where appropriate to reduce model complexity. The resulting finite element model is typically much larger than a corresponding model in ParaDyn due to the necessity to include the medium propagating the blast wave. This approach is used when specific threat scenarios are being considered or component failures are intimately connected to the overall structure geometry. An example application of this approach is the tunnel vulnerability assessment shown in Figure 4. The tunnel is constructed from reinforced concrete waffle sections (Figure 4b) and subjected to the detonation of a high explosive charge near the tunnel wall (Figure 4a). The concrete shelf acts as a reflecting surface and increases the damage caused by the high explosive. Figure 4c shows a simulation result where the explosion directly breached the tunnel wall near the charge location and the reflected blast waves caused secondary breaches near the tunnel top and on the opposite tunnel wall.

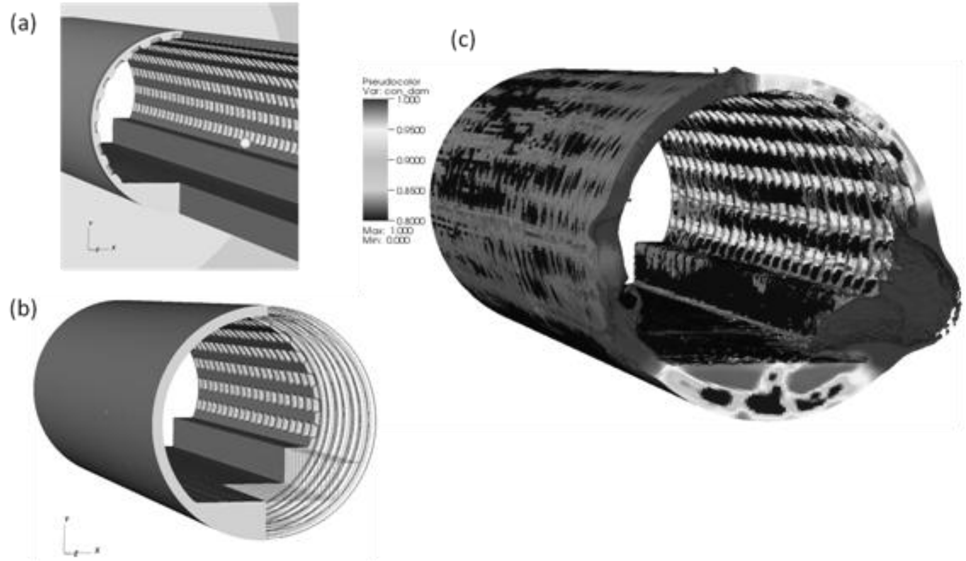



**Figure 4. A spherical TNT charge is placed near the wall (a) of a reinforced concrete tunnel composed of waffle sections (b). The explosion breaches the tunnel in three locations (c).**

In addition to characterizing the structural damage from an explosive detonation, ALE3D can be used to predict personnel injuries from the blast. The simplest indicator is to track the peak overpressure over the problem domain and construct casualty contours based on those peak pressures (refer to Figure 5). This approach neglects the relationship between pressure and exposure duration with respect to injury and lethality (Bowen, 1968), but provides the stakeholders with a conservative injury estimate that can be used for emergency planning and mitigation assessment.

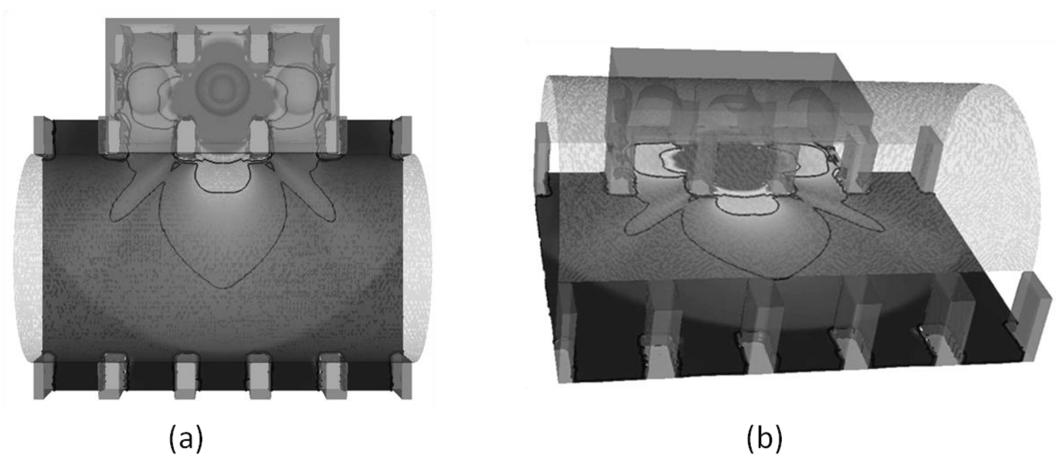



**Figure 5. Personnel injury estimates are shown for a particular threat scenario from a top view (a) and oblique view (b) of the structure.**

**Basing Stochastic Inferences on High-Fidelity Simulations**

A single analysis provides a deterministic approximation for the structural response for a given threat and set of material parameters. If a series of analyses are performed, with carefully chosen variations in input parameters, then stochastic inferences can be made regarding result uncertainty and sensitivity to constitutive parameters, threat size, etc. An example application of this technique is shown in Figure 6. A series of high-fidelity hydrodynamic analyses were performed using ALE3D's fully coupled physics models to determine the predicted breach diameter in the tunnel for a subset of material parameter variations. A multivariate regression technique can then be used to establish confidence levels and predict the breach diameter for a range of charge stand-off distances (Glascoe et al 2009; Koutsourelakis et al 2006).

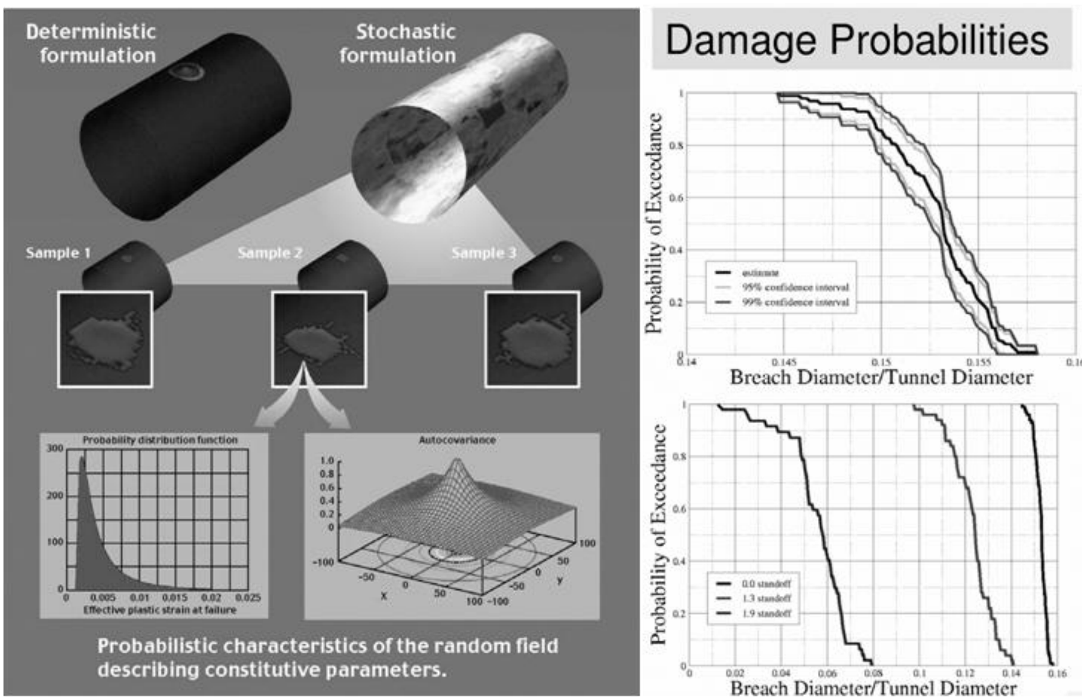



**Figure 6. Stochastic inferences predict the breach diameter for several stand-off distances based upon the results of several high-fidelity, hydrodynamic analysis realizations.**

## Conclusions

Critical infrastructure protection requires a systematic approach that identifies credible threats, evaluates the overall consequences from vulnerabilities being exploited, determines the threat required to initiate a failure and deploys actionable countermeasures to protect the system. By combining high-fidelity, multi-physics modeling and materials testing capabilities with expertise in understanding emerging terrorist threats, LLNL provides end-to-end analysis of critical infrastructure with resultant assessments of likely vulnerabilities and potential consequences as well as recommendations for the development and deployment of mitigation strategies. Such analyses are used by government agencies and infrastructure owners to guide security efforts nationwide.

## Acknowledgements

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