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**EXPLOSION DAMAGE AND INJURY ASSESSMENT MODELLING:
BALANCING MODEL SOPHISTICATION WITH FINITE RESOURCES**

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Abstract: Explosion consequence modelling (ECM) techniques vary significantly in computational complexity. At one end of the spectrum, simple distance-from-blast calculations such as TNT-equivalency and multi-energy methods have utility and are very efficient in terms of computational and labor effort, but have limitations. On the other extreme, computational fluid dynamics (CFD) tools provide a valuable refined modelling capability and are applicable to a wide range of situations, but require a level of resources for a detailed analysis that may be prohibitive for some users.

This paper will present the technological foundations of the BREEZE Explosion Damage Assessment Model (ExDAM), which seeks to fill the “sophistication gap” between purely distance-based simple models and CFD tools. ExDAM builds on a basic empirical phenomenological pressure-impulse vulnerability framework in several ways:

- Explicit estimation of damage and injury effects based on the Physical Vulnerability System (PVS), a phenomenological-based ECM method developed by the DOD after WWII to predict the damage levels of nuclear explosions.
- Accounts for the role of pulse duration in determining the damage incurred by different materials.
- Models the protective shielding effects of structures/individuals on other structures/individuals using finite line doublets from potential theory.
- Able to estimate the secondary fragmentation of materials and resulting injury potential, as well as primary fragmentation from an explosive device.
- Applicable to both vapor cloud and high explosive situations.

Discussion of the model’s capabilities will include the types of situations it is and is not appropriate for, the level of effort required in comparison to other modelling approaches, and the strengths and weaknesses of this approach. Some sample real-world applications of the model will be presented, including both a high explosive and vapor cloud explosion case.

Key words: *ExDAM; Explosion Modelling; High Explosive; Vapor Cloud Explosion*

INTRODUCTION

Explosion Consequence Modelling (ECM) techniques vary widely in complexity, from very simple algorithms relying only on distance and explosive type to computational fluid dynamics (CFD) techniques which model the physics of an explosion in great detail. While the most basic pressure-impulse (P-I) curve-based techniques, such as TNT equivalency models, are most appropriate only for explosions of certain materials occurring in flat, open areas, more advanced techniques such as CFD can account for shielding, channeling, reflection, and vapor cloud explosion characteristics such as ignition location, flame speed, and congestion/confinement. However, the time, effort, and expertise required to effectively utilize a model is significantly higher for these more complex modelling approaches. Each type of model is appropriate for certain circumstances. For example, a simple hazard assessment of a chemical stockpile, such as that mandated by the U.S. EPA’s Risk Management Program (RMP) could be conservatively performed using

several simple models and does not require the refinement of a CFD analysis. Accurate analysis of a vapor cloud explosion in an offshore platform compartment, on the other hand, requires the consideration of complex geometry that a CFD model can provide.

For some applications, basic modelling approaches are overly simplistic, but a full CFD analysis provides more detail than necessary at a cost that may be prohibitive. The Explosive Damage Assessment Model (ExDAM), originally developed by Dr. Frank Tatom and presently maintained by the BREEZE Software division of Trinity Consultants, takes a high explosive (HE) or vapor cloud explosion (VCE) P-I model as its basis, and adds the ability to model both shielding effects of structures/people and damage and injury to structures/people. As such, ExDAM provides an intermediate ECM tool for predicting incident pressure/impulse that provides more refinement and detail than simple P-I models while requiring less time and specialized expertise than CFD models.

This paper will describe BREEZE ExDAM's HE and VCE models, HExDAM and VExDAM, and discuss application examples with the objective to understand the characteristics, capabilities, and limitations of the model and to demonstrate that the types of scenarios described can be accurately modeled and analyzed using a relatively fast and simple process.

ExDAM EXPLOSION MODELS – HISTORY AND COMPUTATIONAL METHODOLOGY

BREEZE ExDAM provides a phenomenological method to predict damage and injury levels for open-air explosions. Historically, since the mid-1980s, organizations involved in the development of this method include the Strategic Defense Command, U.S. Army Corps of Engineers, Southwest Research Institute, Facility Army System Safety (FASS) Office, the Naval Civil Engineering Laboratory, Engineering Analysis, Inc. (EAI), and BREEZE Software / Trinity Consultants, Inc.

The predecessors to HExDAM, the Nuclear Damage Assessment Model (NDAM) and the Enhanced Nuclear Damage Assessment Model (ENDAM), were originally developed to predict large-scale structure damage for nuclear blasts using the Physical Vulnerability System (PVS) (Defense Intelligence Agency Production Center, 1969). The mathematical and computational aspects of this system are provided in a companion public/unclassified document (Defense Intelligence Agency, 1974). ENDAM evolved into HExDAM when the blast pressure profiles and structure vulnerability data were modified to accommodate conventional high explosives. The overpressure and impulse fields in HExDAM are computed according to Glasstone (Glasstone and Dolan, 1977).

To accommodate the need for modelling vapor cloud explosions (VCEs), VExDAM was developed. VExDAM uses Van den Berg's Multi-Energy Method (Van den Berg, 1985) to generate 3D overpressure and impulse profiles for spherical vapor clouds. Multiple spherical vapor clouds are used to model more complex vapor cloud geometries, and the effects of these sub-clouds are combined to produce cumulative overpressure/impulse fields. Once the initial overpressure and impulse fields are calculated, both HExDAM and VExDAM use the same methodology to compute shielding effects and injury/damage.

For open-air explosions, particularly with conventional high explosives, unshielded peak pressure distributions are well understood. However, damage levels to larger, more complex structure scenarios are increasingly a function of shielding effects. Incident pressures and subsequent damage levels are significantly lower for structures and persons located behind other structures/persons. For this reason, ExDAM's 'shielding algorithm' was developed (Tatom and Norman, 1993). Most generally, the shielding algorithm reduces the peak pressures behind structures based on a dipole-flow-field distribution. Each component of a structure is evaluated separately, such that if an explosion is sufficient to destroy glass windows but not masonry walls, the shielding effect of the walls will be accounted for but little or no shielding will be produced by the window area.

Once an incident pressure/impulse field is calculated, ExDAM computes structure damage based on a Master Structure Data set (Glasstone and Dolan, 1977; Ferritto and Hager, 1988), providing a list of common structures and materials, each with six ‘Vulnerability Parameters’ (VPs) which directly correlate incident pressures to ‘percent’ damage. These vulnerability parameters include vulnerability type, which determines whether the material is most sensitive to overpressure, P, or dynamic pressure, Q, and K-factor, which is used to account for the different pressure-time pulse shapes (i.e. pulse duration) of various explosion yields. HExDAM’s structure VPs are derived from empirical data.

To allow for the injury potential of an explosion to be quickly evaluated, ExDAM also incorporates model male, female, and child bodies. The ExDAM body models are composed of 28 total body components and 19 different body component types. Like structure materials, empirical vulnerability data was used to develop the body component VPs (Mercx, 1989; Evans, 1957; Messerer, 1880).

SCALABILITY, APPLICABILITY, AND LIMITATIONS OF ExDAM ANALYSES

ExDAM can be applied to a wide range of spatial scales, from near-field effects of an explosion on a single nearby structure to effects on a large area with numerous structures. The primary limitation of ExDAM lies in the fact that the model relies on P-I relationships, with modifications to account for shielding effects and to allow damage and injury calculations. ExDAM does not explicitly model flame front or blast wave propagation, and does not account for channeling or reflection (other than interactions with the ground). As with other multi-energy models, some details of a VCE, such as the degree of confinement and congestion and the fuel’s characteristic flame speed, can be accounted for by an explosion strength adjustment factor, but fluid flow is not explicitly modeled as in a CFD application. Thus, the model is generally not appropriate for small-scale modelling of internal explosions such as an offshore platform compartment. The model is, however, still suitable for a large variety of applications, and has been used to model situations ranging in spatial scale from a subway car to large petrochemical facilities and entire towns.

PROJECT EXAMPLES

As noted above, while ExDAM is not suitable for every explosion scenario, it can and has been used to model a wide range of HE and VCE cases. Four example case-study projects are listed below, two of which will be presented instead of discussed in this paper due to the extended abstract page restriction:

1. An industrial plant siting analysis involving multiple potential VCE scenarios
2. A large-scale city/residential HE scenario (the West, Texas event)
3. An urban multi-story building external HE scenario
4. A small-scale IED terrorism event (one of the London 7/7 subway bombings), as modeled by researchers at the University of Salzburg.

Example 1: Industrial Plant Siting Analysis

Explosion consequence modelling at industrial and military facilities has historically been the most common use of ExDAM. By modelling the worst-case explosion scenarios across the facility, worst-case peak overpressures/impulses and subsequent worst-case damage and injury levels can be estimated across the facility. In the case presented here, modelling was performed for a petrochemical client to determine the potential VCE hazard posed to existing process and office buildings, as well as a safe location for siting of a future portable building (as in API 753).

ExDAM model results predicted broken windows and minor structural damage to exposed faces of several of the permanent structures. Predicted injuries to personnel were slight for personnel in shielded locations, but broken bones and other injuries were predicted for personnel in poorly shielded locations such as near windows. An area for safe placement of portable buildings was defined based on areas with low modeled overpressure. The location of this area was dictated primarily by distance from explosion sources and shielding from permanent structures. A plot plan illustrating some of the shielding effects, structure damage,

and occupant injury is shown in Figure 1. Creation and execution of this modelling scenario required approximately two days of time from an experienced user.

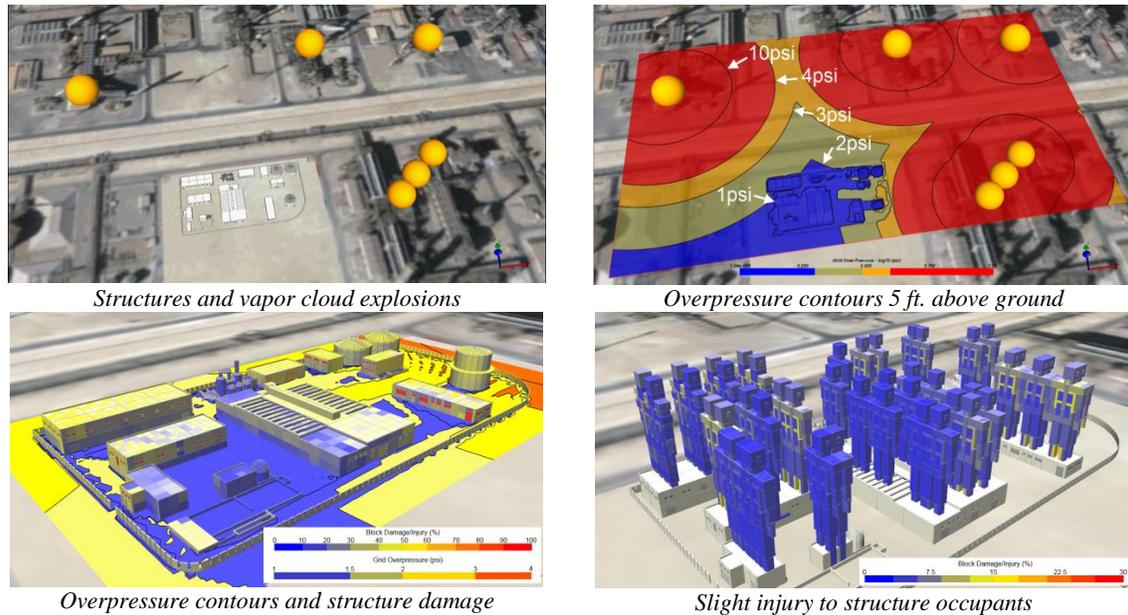


Figure 1. Example 1 project results from all possible explosion sources to single building.

Example 2: City/Residential HE Event (West, Texas)

ExDAM can also be used for highly macro-scale explosion consequence analyses, such as the effects on a large number of surrounding structures in an urban area. The April 17, 2013 West, Texas fertilizer company explosion is an example of this application. Almost 200 buildings were created in ExDAM based on satellite imagery and street-level photographs. Setup and execution of the model scenario was completed in approximately three days. The model analysis was completed with an assumed TNT-equivalent mass of ammonium nitrate (AN) of 30 tons.

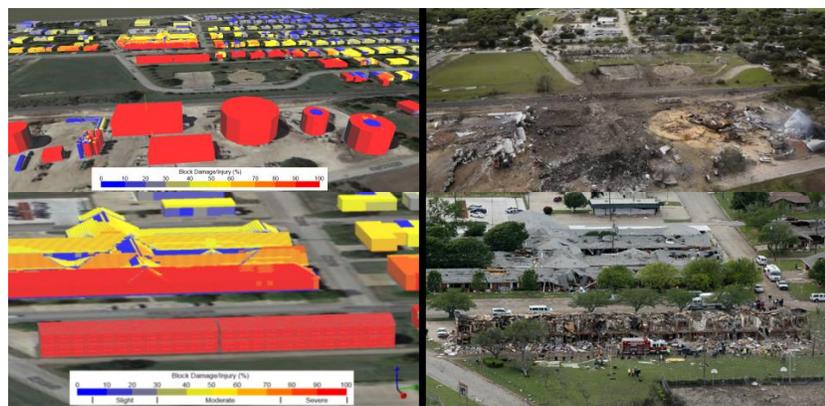


Figure 2. Comparison of actual to predicted damage for one portion of the affected area.

CONCLUSIONS

The BREEZE ExDAM model provides an intermediate-complexity solution, which is well-suited to modelling explosions of both vapor clouds and high explosives in environments where effects such as reflection and channeling are not expected to have a significant effect, but where shielding caused by structures and people may have an effect.

The model is relatively simple to use and understand in comparison to approaches such as CFD. Thus, while in no way a replacement for applications in which CFD modelling is required, ExDAM is potentially accessible to a wider audience of safety professionals, first responders, etc. than CFD modelling. The ability of the model to correlate predicted overpressure and impulse into predictions of injury and damage adds to the potential utility of the model for these groups – impacts are translated into terms that can be readily understood by those without formal training in interpretation of overpressure and impulse data. However, some expertise is still required to properly use the model, particularly when modelling vapor cloud explosions as these can be more difficult to quantify. Thus, for many persons and applications, a simpler model, and particularly one targeted at non-specialist personnel such as the NOAA ALOHA model, is more appropriate.

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