Numerical analysis of blast loaded civilian structures

by Bert Jeffrey Lutzenberger

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Civil Engineering
Montana State University

Abstract:
Malevolent bomb attacks on high profile civilian structures have raised concerns about the vulnerability of multistory civilian structures to terrorist attack. Given the availability of bomb-making materials and the ease with which large explosive devices can be assembled and employed, malevolent bomb attacks on multistory government and civilian structures continue to pose a significant threat to this type of structure. With this in mind, there exists a need within the engineering community for methods to analytically model and predict the response of multistory structures to blast loads.

While classical solutions may be used to analyze the initial response of a structure to a blast type load, they cannot efficiently characterize damage accumulation and failure in areas of extreme stress and strain. Therefore, an alternate approach was presented that used a combination of implicit and explicit finite element methods to characterize structural response before, during and after detonation of an explosive device near a structure of interest.

Public domain versions of the explicit and implicit finite element codes DYNA3D and NIKE3D were used in the following manner. First, the implicit finite element formulation was used to determine the initial stress field in a typical multistory civilian structure due to gravity loads. Then, the nodal data resulting from the implicit code were passed to the explicit code as initial conditions prior to the application of a blast load. Once the static stresses and strains had been transferred and initialized in the explicit formulation, a calculated pressure front was applied to predetermined structural members in the form of a distributed impulse load. The explicit formulation was then used to predict localized structural damage and material failure resulting from the blast load. The resulting state of the structure due to the blast load was then assessed based on post-blast nodal data.

Nodal responses of cantilever beam and two-bay portal test cases showed that the beam-continuum interface used to reduce model size correlated well with similar models that consisted of either continuum or beam elements only. It was also found that transferring nodal data between the two codes did not introduce significant error into the analyses. Finally, the proposed methodology was tested on a model with structural characteristics similar to those of the Alfred P. Murrah federal building. The methodology was found to significantly reduce computational cost while adequately characterizing failure based on the chosen failure material model and prescribed blast load.

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ABSTRACT

Malevolent bomb attacks on high profile civilian structures have raised concerns about the vulnerability of multistory civilian structures to terrorist attack. Given the availability of bomb-making materials and the ease with which large explosive devices can be assembled and employed, malevolent bomb attacks on multistory government and civilian structures continue to pose a significant threat to this type of structure. With this in mind, there exists a need within the engineering community for methods to analytically model and predict the response of multistory structures to blast loads.

While classical solutions may be used to analyze the initial response of a structure to a blast type load, they cannot efficiently characterize damage accumulation and failure in areas of extreme stress and strain. Therefore, an alternate approach was presented that used a combination of implicit and explicit finite element methods to characterize structural response before, during and after detonation of an explosive device near a structure of interest.

Public domain versions of the explicit and implicit finite element codes DYNA3D and NIKE3D were used in the following manner. First, the implicit finite element formulation was used to determine the initial stress field in a typical multistory civilian structure due to gravity loads. Then, the nodal data resulting from the implicit code were passed to the explicit code as initial conditions prior to the application of a blast load. Once the static stresses and strains had been transferred and initialized in the explicit formulation, a calculated pressure front was applied to predetermined structural members in the form of a distributed impulse load. The explicit formulation was then used to predict localized structural damage and material failure resulting from the blast load. The resulting state of the structure due to the blast load was then assessed based on post-blast nodal data.

Nodal responses of cantilever beam and two-bay portal test cases showed that the beam-continuum interface used to reduce model size correlated well with similar models that consisted of either continuum or beam elements only. It was also found that transferring nodal data between the two codes did not introduce significant error into the analyses. Finally, the proposed methodology was tested on a model with structural characteristics similar to those of the Alfred P. Murrah federal building. The methodology was found to significantly reduce computational cost while adequately characterizing failure based on the chosen failure material model and prescribed blast load.

CHAPTER ONE

INTRODUCTION

Background

Bomb attacks at the World Trade Center in New York City, the Alfred P. Murrah Federal Building in Oklahoma City, and American Embassies overseas have raised concerns about the vulnerability of multistory civilian structures to terrorist attack. Given the availability of materials and the ease with which large explosive devices can be assembled and employed, it is reasonable to assume that malevolent bomb attacks on government and civilian structures will continue to pose a significant threat to this type of structure. An increased concern for designing multistory civilian structures to withstand bomb attacks is currently driving the need for a comprehensive method to analytically model the response of civilian structures to blast loads. A numerical methodology capable of predicting the effects of blast loads on multistory, civilian structures would allow scientists and engineers to investigate reasonable defenses in structural design to mitigate possible loss of life resulting from terrorist bomb attacks.

Simulation tools incorporating various numerical approximation schemes have been developed for use in the defense sector to predict the response of mechanical and structural systems to dynamic loads such as air-blasts and projectile impacts. With the proper methodology, public domain versions of these tools, which are readily available, can be applied to analyze blast effects on multistory civilian structures.

Before these tools can be applied, the basic mechanical behavior of multistory civilian structures under dynamic loads must be known. Due to the inherently flexible nature of multistory civilian structures, structural response to blast loading occurs in two distinct and equally important phases. First, within milliseconds after detonation, a blast wave causes permanent local damage to structural members in the immediate vicinity of the blast. Second, after local damage has occurred, new load paths develop as gravitational loads are redistributed to the remaining structural members. In extreme situations, the latter of these phases can lead to buckling and progressive collapse of a structure.

For traditional structural and mechanical response analyses, depending on the particular application, only one of these phases is typically considered. For example, in blast containment and high velocity impact simulations, local damage is the dominant response mechanism, typically occurring within the first few milliseconds of loading. Alternatively, in structural applications involving earthquake and wind loading, overall structural stability is the dominant concern; thus, analyses focus on the overall structural response for many seconds after initial loading. Due to the nature of these distinctly different load cases, different numerical techniques are better suited to model the governing response mechanism of the particular system.

Analyses of blast loaded civilian structures are unique because both phases of response are equally important in the overall instability of the structure resulting from a blast load. Gravity loads must first be initialized and local damage accumulation must be accurately predicted to determine the structural consequences of the initial blast load. Once the localized damage has been predicted, the stability of the newly damaged structure must then be assessed. These distinctly different phases can be predicted using numerical approximation techniques similar to those used to solve the above mentioned examples. However, numerical compatibility between the approximation techniques corresponding to each phase of structural response must be maintained.

This research employs public domain versions of DYNA3D (Whirley, 1993a) and NIKE3D (Maker, 1990), available through Lawrence Livermore National Laboratory, to:

1. Determine initial localized blast damage in a multistory civilian structure subjected to a typical terrorist bomb blast.
2. Predict the resulting redistribution of dead and live loads in the newly damaged structure.
3. Predict the overall structural integrity resulting from 1 and 2.

The proposed methodology combines two different finite element (FE) techniques in the following manner. First, an implicit finite element formulation is used to determine the initial stress field in a typical multistory civilian structure due to gravity loads. Then, stresses, strains and the resulting nodal displacements and velocities from the implicit code are passed to an explicit FE code. Once the static stresses and strains have been transferred and initialized in the explicit formulation, a calculated blast load is applied to predetermined structural members in the form of a distributed impulse load. The explicit formulation is then used to predict localized structural damage resulting from the blast load. Finally, after dynamic vibrations in the structure have dissipated, the new stress, strain and resulting displacement and velocity fields are passed back to the implicit formulation where a dynamic implicit analysis is used to determine the resulting integrity of the structure.

The explicit and implicit modeling capabilities associated with initializing gravity loads, predicting blast damage and tracking the resulting post-blast integrity of a structure are specifically addressed. The translation between the two formulations is discussed and a beam-continuum interface, used to reduce the size of the finite-element mesh, is presented. Analysis results from initial tests on simple steel cantilevered beam models using a linear elastic material model are presented. Analysis results from tests on a steel two-bay portal model using elastic, elastic-plastic, and elastic-plastic-failure material models are also discussed. Compute times are compared between test cases to assess the validity of the proposed methodology. Finally, analysis results from tests on large multistory civilian structure with structural characteristics similar to those of the Alfred P. Murrah Federal Building are presented.

Scope of Work

The goal of this work was to implement explicit and implicit finite element codes in analyses of blast loaded multistory civilian structures. An explicit finite element code was used to study the initial damage phase, while an implicit formulation was used to initialize gravity loads in the static structure and predict the dynamic post-blast response of the damaged structure.

An implicit formulation was chosen for gravity initialization and post-blast analysis because it yields efficient static and low rate dynamic solutions when large time increments can be taken. An explicit formulation was chosen for the initial damage resulting from the blast load because the associated solution method consists of solving multiple uncoupled equations over small increments in time. Explicit formulations are conditionally stable based on the time increment size. This conditional stability requires time increments to be on the order of microseconds or smaller making explicit formulations unsuitable for low rate problems where large time increments will suffice.

Finite Element Codes

Several finite element code sets were considered for this research. Due to the availability of source code, extensive material model libraries and the ability to transfer data between the two codes, public domain versions of the explicit and implicit finite element codes DYNA3D (Whirley, 1993a) and NIKE3D (Maker, 1990) were chosen. These two codes were combined to analytically predict the response of a typical multistory civilian structure to blast loading. As with previous studies, an explicit finite element formulation (DYNA3D) was used to characterize the initial structural damage resulting from a typical bomb blast (Crawford et al., 1997). However, after initial deformation, passing the velocity and strain fields from the explicit analysis to an implicit analysis (NIKE3D), which was used to determine the post-blast performance of the damaged structure, further refined the analysis. The combination of the two finite element codes and the translation between the two formulations provide a numerical methodology to determine the structural consequences of bomb attacks on civilian structures.

Components of Research

Several components associated with the NIKE3D/DYNA3D FE code set were explored. All models used in the research were preprocessed via ANSYS (Revision 5.6). A Perl script was written to translate the ANSYS model database to NIKE3D and DYNA3D database formats. Static solutions of the models were generated in ANSYS5.5 to validate translation of model parameters to NIKE3D and DYNA3D. Static and dynamic analyses of similar test models were run in NIKE3D and DYNA3D to illustrate the computational differences between the two formulations. Computation times were compared between models containing beam elements, continuum elements and hybrid models containing both types of elements. The beam-continuum interface method applied to the hybrid model was also validated using these test cases.

In addition to investigating solution and element formulations, three different material models were compared. A standard isotropic, linear-elastic material model was used in early models to study mesh connectivity and overall model behavior. The models were then refined by the addition of an isotropic-kinematic, elastic-plastic material model. Finally, failure criteria were added to the material model to study the importance of characterizing failure in a blast loaded structure.

NIKE3D and DYNA3D are capable of writing databases during analysis that can be read by their counterparts. For this research, the pre-blast static stress state was initialized via NIKE3D. At the end of the NIKE3D static initialization, the model data was written to a DYNA3D initialization file. The static stress field was then initialized in DYNA3D and a blast load in the form of a uniform distributed load was applied to the structure. After predicting the damage resulting from the blast, the model data was written back to a NIKE3D initialization file. This file was read into NIKE3D where the analysis continued to track the post-blast response of the structure.

The test cases used to explore the primary components associated with the proposed methodology are shown in Table 1.1 and Table 1.2. An elastic cantilever beam model was used for preliminary tests of the beam-continuum interface and code translation validation. A two-bay portal model was introduced to further test these components on a structure with increased geometric complexity. This model offered a comprehensive model to expediently test the solution formulations, material models, beam-continuum interface and data translation between NIKE3D and DYNA3D. The resulting methodology was then applied to the multistory civilian structure model to illustrate its ability to handle large models.

Table 1.1 Analysis Matrix for Cantilever Beam Models

Model	Continuums	Beams	Beams and Continuums
DYNA3D	X	X	X
NIKE3D	X	X	X
NIKE3D-DYNA3D-NIKE3D	X	X	X

Table 1.2 Analysis Matrix for 2-Bay Portal and the Multistory Civilian Structure

Model	2-Bay Portal (continuums)	2-Bay Portal (beams)	2-Bay Portal (beams and continuums)	Civilian Structure (beams and continuums)
DYNA3D Elastic-Plastic	X	X	X	-
DYNA3D Elastic-Plastic-Failure	X	-	X	-
NIKE3D Elastic-Plastic	X	X	X	X
NIKE3D-DYNA3D-NIKE3D Elastic-Plastic	X	X	X	X
NIKE3D-DYNA3D-NIKE3D Elastic-Plastic-Failure	X	-	X	X

The combination of the cantilever beam models, the two bay portal models, and the multistory structure model served to study the methodology on models with increasingly more complex geometries. Finite element material models, a beam-continuum interface and data exchange between the two codes exercised the effects of the methodology on the models. The analyses in Table 1.1 and Table 1.2 were completed to assess the validity of the proposed modeling methodology.

CHAPTER TWO

LITERATURE REVIEW

Introduction

A comprehensive literature review was conducted to assess observations from recent terrorist bomb attacks on civilian structures and identify currently available analysis tools and numerical methodologies capable of predicting the response of these structures to blast loading. Documented terrorist attacks on civilian structures demonstrate the need for analysis tools capable of determining the vulnerability of this type of structure to blast loads. Blast models capable of predicting peak overpressure and impulse duration are presented to provide a method to characterize and apply blast loads to structural models. Finally, current developments and applications of finite element solutions to dynamically loaded structures are reviewed.

Terrorist Threat

World Trade Center

In February 1992, an 1800-lb Ammonium Nitrate-Fuel Oil (ANFO) bomb exploded on an exit ramp inside an underground parking area at the World Trade Center in New York City. The explosion occurred near one of the main columns supporting the 110-story structure. The column did not fail under the direct blast load but lateral restraint provided by two concrete floors was lost. Fortunately, the steel column, measuring 4-ft by 4-ft, did not buckle under the increased effective length. However, several injuries and fatalities occurred due to fragmentation, blast overpressure and smoke inhalation (Longinow, 1996). The fact that the World Trade Center remained relatively stable under the blast load speaks well for structural redundancies in design.

Alfred P. Murrah Federal Building

In April 1995, at 9:00 a. m. a 4800-lb ANFO bomb exploded 20-ft away from the nine-story Alfred P. Murrah Federal Building in Oklahoma City. The explosion collapsed a transfer girder, which supported columns from the seven floors above it. Once the transfer girder failed, all seven floors supported by the columns progressively collapsed. The initial blast and subsequent structural collapse destroyed one third of the building killing 169 civilians and injuring more than 500 (Massa, 1995).

In this case, structural redundancies were clearly inadequate for the blast loading case. Although this building did conform to the government building code at the time it was built, blast load cases were not considered in design. Ultimately, the initial blast damage and the resulting progressive collapse was found to be consistent with what would be expected for an ordinary moment frame of the design available in the mid-1970s subjected to a blast load.

American Embassies

Most recently, two separate bombings occurred at U.S. Embassies in Nairobi and Dar es Salaam in Tanzania. The bombing in Nairobi killed a total 254 initiating one of the largest FBI international-terrorism investigations in history. Although both of these building were designed with consideration of blast loads, the design was based on empirical observations, which were not specific to the particular geometry of each structure (U. S. Department of State, 1989).

Current Methods

Unfortunately, because of the availability of commercial explosives and the ease with which large bombs can be assembled, there is a growing concern in the United States that terrorist attacks on civilian structures may become more common in the future. To avoid further loss of life, reasonable defenses must be employed to minimize the threat of future attacks on civilian structures. In the case of the Oklahoma City bombing, an estimated 80% of the fatalities were caused by structural collapse (Prendergast, 1995). One way to mitigate this type of failure would be to include redundancies in the design of structures so that even with a key structural element removed, the structure would remain stable under alternate load paths (Hinman, 1995). Currently standing structures can be retrofitted with blast walls and established perimeters to increase the standoff distance between the structure and a bomb attack (Chapman et al., 1994). The National Research Council offers similar recommendations to mitigate blast effects on commercial buildings (The National Research Council, 1996). Regardless of the design approach, a thorough analysis of the structure must be performed to assess vulnerable areas within the structure and determine the consequences of a malevolent bomb attack (Prendergast, 1995).

Until recently, the effect of blast loading on structural systems has been a concern of almost exclusively the military. Additional research has been pursued by process industries dealing with explosive materials and the blast mining industry. Consideration of blast loads from terrorist bomb attacks on civilian structures has been addressed for

American Embassies overseas (Ettouney, 1996). However, the current design philosophy for civilian structures in the United States does not include the same consideration.

The bombings of the World Trade Center in New York City and the Alfred P. Murrah Federal Building in Oklahoma City clearly demonstrate a need to design multi-story civilian structures with future terrorist threat in mind (Longinow, 1996). Present research in this field consists mostly of deterrence and prevention of terrorist attacks in the form of physical security with little effort being expended on analytically assessing the response of this type of structure to blast loading. One noted exception is the work of Crawford et al. (1997), which used the Lagrangian finite element code DYNA3D (Whirley, 1993a) to study the effectiveness of jacketing columns on multistory reinforced concrete structures to resist blast loads. The focus of the analysis, however, was on the localized response of lower-story perimeter columns only.

Blast Modeling

The development and propagation of blast waves has been well characterized by the military. When a high explosive material is initiated it can burn, deflagrate or detonate (DOE/TIC, 1981). Detonation, the most severe of these reactions, initiates a blast wave. In general, a blast can be defined as a process whereby a pressure wave is generated in air by a rapid release of energy (*Major*, 1994). A blast front is generated when the air surrounding an explosion is compressed by the release of energy immediately after detonation. The blast wave propagates away from the point of detonation at a sonic velocity with a peak overpressure proportional to the charge type and weight. When the blast front encounters a solid object, it reflects back onto itself which has the effect of reinforcing the pressure imposed on the object (Dharaneepathy, 1995; Ettouney, 1996; Beshara, 1994a).

In addition to a blast wave, an explosive source detonated near the ground may also produce ground vibrations. The amount of explosive energy partitioned for the ground vibration is a function of the characteristics of the ground and the shape of explosive (DOE/TIC, 1981). Structural damage resulting from blast induced ground vibrations has been classified by the blast mining industry by means of the "peak particle velocity" (PPV). The PPV is related to the charge weight and distance from the point of interest by a power function. Extensive research on damage resulting from blast induced ground motion has been conducted by the blast mining community (Singh and Thorte, 1985; Favreau et al., 1989; Dowding, 1994; Yu and Vongpaisal, 1996).

Although blast induced ground vibrations play a significant role in both military and blast mining applications, a majority of the energy of a typical terrorist bomb blast is partitioned to the blast wave. Therefore, the ground motion is of little consequence to the overall behavior of a multistory civilian structure (Mlaker et al., 1998). Thus, ground motion was neglected in this study.

Undisturbed Blast Profile

Blast wave properties are traditionally defined and measured for an undisturbed or side-on wave as it propagates through air. Figure 2.1 shows a typical blast profile. The peak overpressure (peak blast pressure above ambient air pressure) occurs almost instantaneously after the blast shock wave passes a point. This is followed by a decrease in the positive phase to a pressure below ambient air pressure; and finally, a gradual increase back to the ambient air pressure.

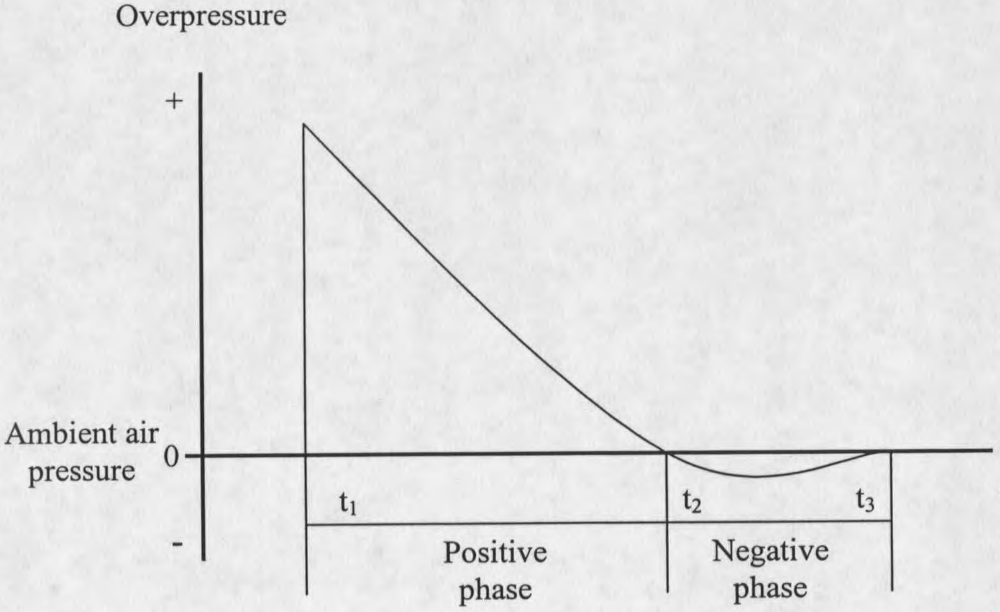

Figure 2.1 Typical undisturbed blast profile.

Military Design Aids

Much of the current literature available on blast characteristics originates from military research. Research conducted by the military after World War II has, however, focused primarily on blast loads resulting from nuclear weapons. Although magnitudes differ dramatically, conventional blast characteristics are similar to those of nuclear weapons. Current military design aids include generalized empirical formulations to estimate ground motion characteristics and blast wave properties for both nuclear and conventional weapons (TM5, 1965).

Scaling of blast wave properties from an explosive source is a common practice. Scaling laws allow the prediction of blast wave properties for large-scale explosions to be based on tests of a much smaller scale. The most common form of blast scaling is Hopkinson-Cranz or "cubed-root" scaling. This law states that two self-similar explosive charges, differing only in size, produce identical blast waves of different size, scaled proportional to the difference in size between the two explosive charges. The scaling laws are written as follows:

Equation 2.1
$$Z = \frac{R}{E^{1/3}}$$

Equation 2.2
$$Z = \frac{R}{W^{1/3}}$$

where Z is the scale factor, R is the distance from the center of the explosive source, E is the total heat energy of detonation, and W is the weight of the charge (Hopkinson, 1915, Cranz, 1926).

Furthermore, an object located at a point some distance R from the center of the explosive charge of characteristic dimension d will be subjected to a blast wave with amplitude P, duration t_d, and a characteristic time history. The Hopkinson-Cranz scaling law states that for the same object in the same atmosphere at a point some distance λR from the center of the same charge with a characteristic dimension of λd will be subjected to a blast wave with amplitude λP, duration λt_d, and a characteristic time history scaled by λ. Figure 2.2 shows the implications of the Hopkinsin-Cranz scaling law.