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Finite Element Modeling of Explosion in Confined Geometries of A Building

[1]Mohammad Aghaei Asl, [2]Kambiz Kangarlou

[1]*Assistant Professor, Department of Civil Engineering, Payame Noor University of Tabriz, Iran.*
[2]*Postdoctoral Researcher, Biomedical Engineering Department, Amir Kabir University of Technology, Tehran, Iran.*

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ABSTRACT

In recent years high explosive bomb attacks have been increasingly directed against civil structures by various terrorist organizations. This paper describes a numerical method for assessing the interaction of high explosive air blast within the complex geometries typical of a congested urban environment. The first step in predicting blast effects on a target is to predict blast loads on it. In this study a Computational Fluid Dynamics (CFD) computer programs and analytical methods developed by the Federal Emergency Management Agency (FEMA) used to solve 2 and 3 dimensional air blast problems. In order to better understand the behavior of high explosive blast waves in confined geometries of a building, a numerical calculation carried out using the Ansys-cfx sotware is presented. The extent and severity of damage and injuries in an explosive event cannot be predicted with perfect certainty. Despite these uncertainties, it is possible to give some general indications of the overall level of damage and injuries to be expected in an explosive event, based on the size of the explosion, distance from the event, and assumptions about the construction of the building.

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INTRODUCTION

International economic pressures and unbalance of power caused by globalization leads to increased number of terrorist activities, which primarily targets civil infrastructure such as strategically important buildings and environmental public. Attacking strategically important buildings is not a new issue but events occurred during the last decades show the importance of this topic.

Figure 1 shows the bombing of the Federal Building in Oklahoma City. The Oklahoma City bombing was a domestic terrorist bomb attack on the Alfred P. Murrah Federal Building in downtown Oklahoma City on April 19, 1995. The bombing killed 168 people and injured more than 680 others. The blast destroyed or damaged 324 buildings within a 16-block radius, destroyed or burned 86 cars, and shattered glass in 258 nearby buildings, causing at least an estimated 652 million dollar worth of damage. Extensive rescue efforts were undertaken by local, state, federal, and worldwide agencies in the wake of the bombing, and substantial donations were received from across the country. The Federal Emergency Management Agency (FEMA) activated eleven of its Urban Search and Rescue Task Forces, consisting of 665 rescue workers who assisted in rescue and recovery operations [1].

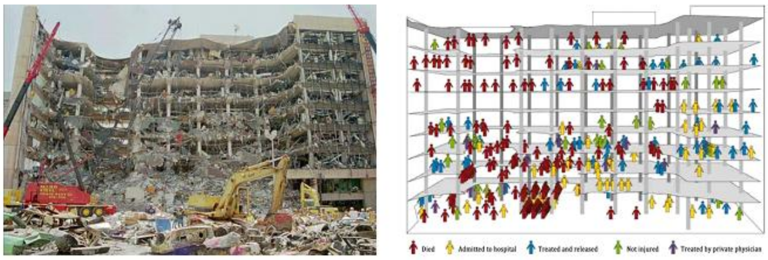

Fig. 1: The Alfred P. Murrah Federal Building, Oklahoma City, Oklahoma, U.S, in the wake of the terrorist bombing on April 19, 1995.
(http://www.britannica.com/EBchecked/media/70968/The-Alfred-P-Murrah-Federal-Building-Oklahoma-City-Oklahoma-US.)

Corresponding Author: Kambiz Kangarlou, Postdoctoral Researcher, Biomedical Engineering Department, Amir Kabir University of Technology, Tehran, Iran,
E-mail: kangarloo_kambiz@yahoo.com

Blast injuries are generally categorized as primary, secondary, tertiary and quaternary or miscellaneous. A primary blast injury occurs as the shock front and the overpressure blast wave move through the body. Differences in densities of the body's anatomic components (particularly at air/fluid interfaces) are susceptible to spalling (the forcible, explosive movement of fluid from more dense to less dense tissues, such as in the human lung) and implosion (when areas of gas are rapidly compressed at the time of shock-front impact and then rapidly re-expand after it passes, causing tissue injury). The latter frequently occurs in the ear/tympanic membrane and intestine. Acceleration/deceleration forces can cause tearing of organ pedicles and mesentery when there is an inertial difference between organ structures. Also, pressure differentials (wherein there is a liquid/gas interface and incompressible, water-filled organs, such as vessels, have fluid forced into the less compressible adjacent structure) can also cause internal injury[2,3]. The most susceptible organs to primary blast injury are ears, lungs, and gastrointestinal tract. The ear is the most sensitive, and tympanic membrane rupture can be used as a marker of overpressure exposure. The lungs are moderately more resistant; however, with enough energy exposure, disruption of the capillary–alveolar interface can lead to parenchymal hemorrhage and destruction of the alveolar walls. Emphysematous spaces, as well as pneumothorax, can be created. The interstitial changes of blast lung can lead to acute respiratory distress syndrome. Infiltrates can be seen on a chest radiograph within 90 minutes of the blast [4]. In rare instances, air embolism of the vascular tree is believed to lead to sudden death [5,6] As a gas-filled organ, the gastrointestinal tract can be injured by implosion and ruptured. The mucosal wall can become bruised. Shearing injuries can occur due to acceleration/deceleration relative to more solid, adjacent structures. Other organ systems have varying degrees of response to injury from primary blast, and models have been developed to better study the overall pathophysiologic effects [7,8]. The lungs tend to be the predominant nonauditory system injured in most air blasts, whereas the gastrointestinal tract is more susceptible to underwater blasts. Markers are being sought to better diagnose and treat blast overpressure injury [9,10].

Secondary blast injuries occur from objects that have been energized by the explosion to become projectiles. These projectiles, which can be intentionally imbedded into the explosive device to cause wounding, may be a part of the bomb's housing (primary fragmentation), or they may be local material, such as rocks or glass, that became airborne due to their proximity to the explosion (secondary fragmentation). Most penetrating injuries caused by blast-driven projectiles should be considered as contaminated. Instances of the wounding of victims by bone fragments from the bodies of suicide terrorists or other blast victims have been reported; these injuries require special management.[11,12].

Tertiary blast injury occurs when a victim is thrown against the ground or an object. Quaternary injury is the result of structural collapse or burns secondary to the detonation. Crush, traumatic amputation, compartment syndrome injuries, and other blunt and penetrating injuries can be common sequelae of structural collapse. Flash burns to exposed skin can occur as a result of the thermal component of the detonation. Secondary fires can cause additional burns and injury from smoke inhalation.[2].

Experimental data and analysis of actual exposure of personnel to blast waves, has provide researchers with a general understanding of the body's ability to withstand pressure waves associated with explosive blasts. These references are typically based on conditions that are easily diagnosed (e.g. eardrum rupture, lung damage, and death). Figure 2 is an example of a chart originally produced in 1988 by the Government Printing Office [13]. Charts such as this provide a reasonable means to evaluate the survivability of a specified blast.

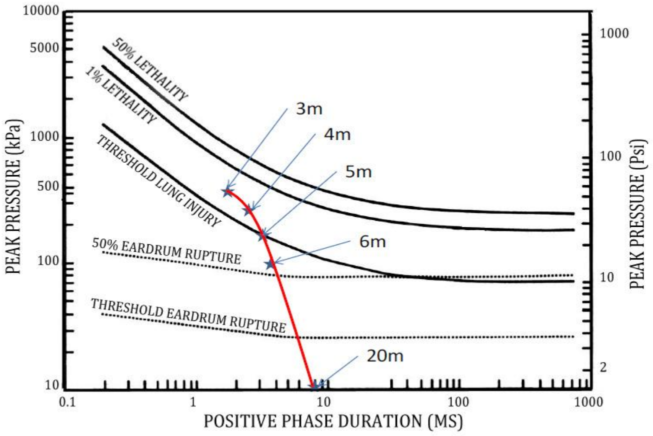

Fig: 2. Human Injury Thresholds. Reprint of chart from Government Printing Office depicting human thresholds for injury based on peak over-pressure and duration of the positive phase [20]. Superimposed red line illustrates pressure and duration associated with 10kg TNT at distances from 3 to 20 meters from point of detonation.

MATERIALS AND METHODS

Blast wave parameters:

Explosions are physical phenomena that result in the sudden release of energy; they may be chemical (typical rapid exothermic oxidation of a solid or liquid material into gaseous reaction products), nuclear or mechanical (e.g. pressure driven by rupture of a membrane or vessel). A typical pressure-time profile of an explosion in a free field is shown in Figure 3.

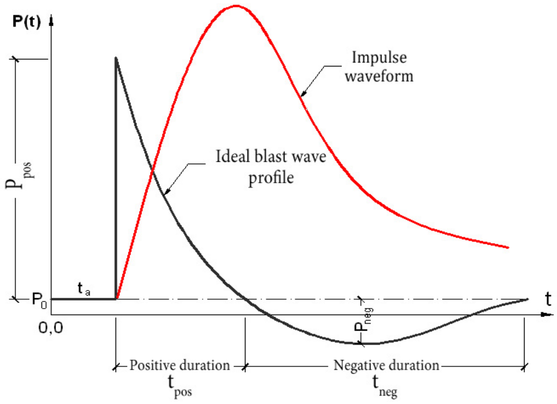

Fig. 3: A typical pressure-time profile of an explosion in a free field.

Generally, explosion reactions are completed within a few microseconds. The principal parameters required to define the blast loading are the peak overpressure, P_S, and the duration of the blast impulse, t_d. Simple expressions can be used to relate these parameters to the weight of charge and the standoff distance expressed as *W* and *R*, respectively. The peak overpressure can be expressed as a function of Z=R/$W^{1/3}$ (m/$kg^{1/3}$), which is designated as the blast load scaled distance [14].

$$P_s = \begin{cases} \frac{6.7}{Z^3} + 1\,(bar) & (P_s \geq 10\ bar) \\ \frac{0.975}{Z} + \frac{1.455}{Z^2} + \frac{5.85}{Z^3} - 0.019\,(bar) & (10 \geq P_s \geq 0.1\ bar) \end{cases} \tag{1}$$

The duration of the blast impulse, *td*, can be determined as a function of *W* and *R*, given by [15].

$$\begin{cases} log_{10}\left(\frac{t_d}{W^{1/3}}\right) \approx -2.75 + 0.27.\,log_{10}\left(\frac{R}{W^{1/3}}\right) & (Z \geq 1.0) \\ log_{10}\left(\frac{t_d}{W^{1/3}}\right) \approx -2.75 + 1.95.\,log_{10}\left(\frac{R}{W^{1/3}}\right) & (Z \geq 1.0) \end{cases} \tag{2}$$

When the incident pressure wave impinges on a structure that is not parallel to the direction of the wave's travel, it is reflected and reinforced, producing what is known as reflected pressure. The reflected pressure is always greater than the incident pressure at the same distance from the explosion. Kingery and Bulmash [16] note that the following relationship is used for calculating the peak reflected overpressure (P_r):

$$P_r = (P_s + P_0)\frac{\left(2 + \frac{\gamma + 1}{\gamma - 1}\right)\left(\frac{P_s + P_0}{P_0}\right) - 1}{\frac{\gamma + 1}{\gamma - 1} + \frac{P_s + P_0}{P_0}} - P_0 \tag{3}$$

Where P_S is the peak side-on overpressure, P_0 is the ambient pressure and γ is the variable ratio of specific heats (for air $\gamma=1.4 \rightarrow P_r=2P_s(7P_0+4P_s)/(7P_0+4P_s)$).

The reflected pressure varies with the angle of incidence of the shock wave. Figure 4 shows reflected pressure coefficients versus the angle of incidence for four different peak incident pressures. The reflected pressure coefficient equals the ratio of the peak reflected pressure to the peak incident pressure (C_r = P_r / P_s). This figure shows that reflected pressures for explosive detonations can be almost 13 times greater than peak incident pressures and, for all explosions, the reflected pressure coefficients are significantly greater closer to the explosion.

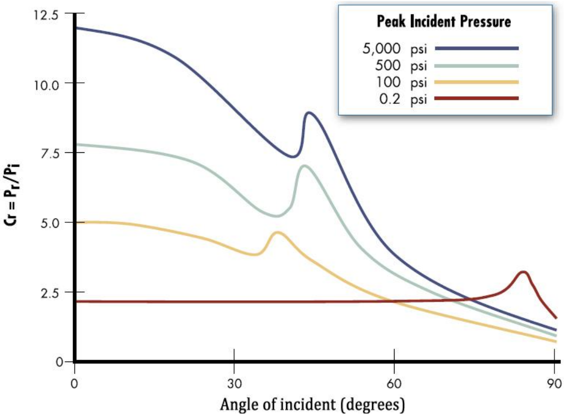

Fig. 4: Reflected pressure coefficients versus the angle of incidence [17].

In most cases, especially for design purposes, more simplified methods may be used by blast consultants to predict blast loads. The overpressure is assumed to instantaneously rise to its peak value and decay linearly to zero in a time known as the duration time. In order to obtain the blast load, a number of different tools can be used. Figure 5 shows an example of a range-to-effect chart that indicates the distance or stand-off to which a given size bomb will produce a given effect. This type of chart can be used to display the blast response of a building component or window at different levels of protection. It can also be used to consolidate all building response information to assess needed actions if the threat weapon-yield changes [17].

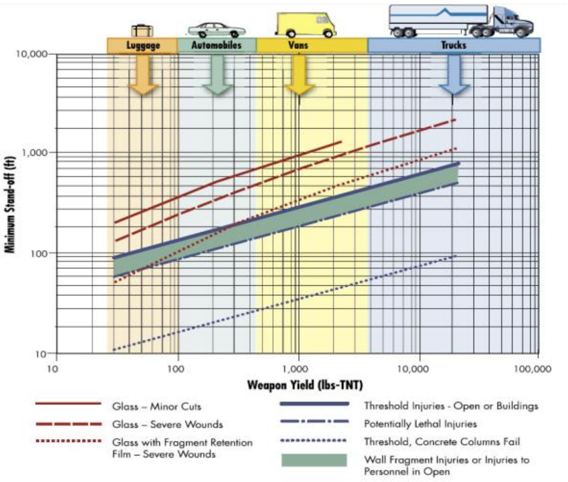

Fig. 5: Explosives environments - blast range to effects.
(Source: Defense Threat Reduction Agency) [17]

Numerical analysis:

For complex structures requiring refined estimates of blast load, blast consultants may use sophisticated methods such as Computational Fluid Dynamics (CFD) computer programs to predict blast loads. In this study a series numerical analyses were performed using Ansys-cfx. In all of the analyses TNT charge was modelled using published JWL data[18], with the surrounding air modelled using ideal gas material with a constant gamma of 1.4 and initial conditions set to give atmosphere pressure. The building was assumed to be rigid in all cases.

RESULTS AND DISCUSSION

An explosive event inside a building is different from an external explosive event. First, the standoff distance between the explosive and an internal surface is much smaller so that incident and reflected pressures are greater and multiple reflections occur off all surfaces, resulting in more extreme loading. Second, because the internal explosion is confined compared to the free movement of air in an external explosion, the detonation and deflagration products continue to add gas pressure in the afterburning process behind the blast wave. This gas pressure adds to and sustains the shock wave pressure for longer positive phase duration, greatly increasing the impulse of the internal blast. Thus, an internal explosion of the same size bomb will result in more building damage than an external explosion.

In order to better understand the expansion of high explosive blast waves in confined geometries of a building (Figure 6), 3D finite element modeling using the Ansys-cfx sotware was performed. The results are shown in Figures 7 and 8.

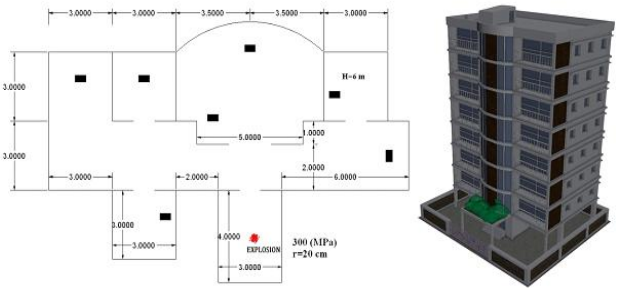

Fig. 6: The plan of the building geometry used in finite element modeling.

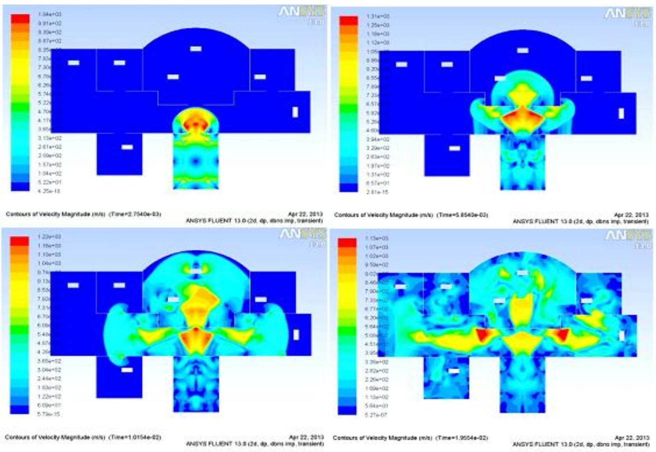

Fig. 7: Static pressure contours at various time steps.

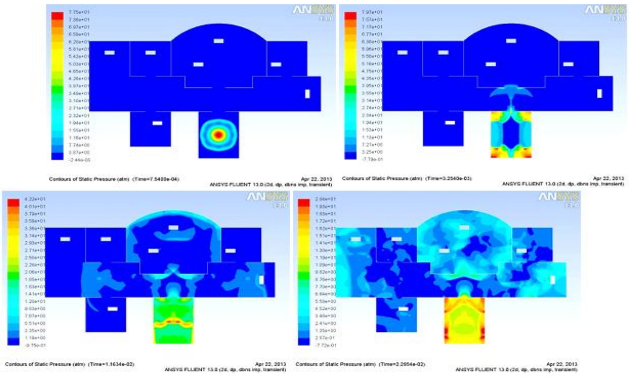

Figure 8: The velocity contours at various time steps.

Conclusion:

This paper presents methodologies for administrators, planners, architects, engineers, and other building science professionals to identify and quantify the security risks to which a place may be exposed. The ultimate objective of the risk assessment process is to find the most effective mitigation measures to achieve a desired level of protection against terrorist and other kinds of attacks. These methodologies will help both school administrators and designers to define and evaluate threats, consequences, and vulnerabilities for the purpose of integrating the security risks into an effective design strategy. Understanding the risks will help administrators prioritize their mitigation activities and allocate their resources accordingly, and will help architects, engineers, and security experts identify the most cost-beneficial protective measures to reduce the risk for a school's unique security needs.

Conflicts Of Interest:

None Declared.

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