Risk analysis of an urban environment under explosive attacks in Tehran

Mohammad Hossein Lashkari[1] MD, Mehdi Navidbakhsh[2] PhD, Kambiz Kangarlou[3] PhD

[1]*Department of Surgery, AJA University of Medical Sciences, Tehran, Iran.*
[2]*School of Mechanical Engineering, Iran University of Science and Technology, Tehran, Iran.*
[3]*Postdoctoral Researcher, School of Mechanical Engineering, Iran University of Science and Technology, Tehran, Iran.*

ABSTRACT

Purpose: 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 geometrical type of a congested urban environment.
Materials and Methods: The first step in predicting blast effects on a target is to predict blast loads on it. In this study a computational fluid dynamics program and analytical methods developed by the Federal Emergency Management Agency (FEMA) were used to solve two and three dimensional air blast problems.
Results: Explosions in confined spaces (mines, buildings, large vehicles) which cause structural collapse are associated with greater morbidity and mortality. The reflected pressures for explosive detonations are two to thirteen times greater than peak incident pressures. A rough estimate of the total casualties following such events are the result of the composition and amount of involved materials, surrounding environment, delivery method, distance between the victim and the blast, crowd density and any intervening protective barriers or environmental hazards.
Conclusion: 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.

Keywords: blast wave; risk analysis; lethality assessment; urban environment; Ansys-cfx.

AMHSR 2014;12:151-158
www.journals.ajaums.ac.ir

INTRODUCTION

International economic pressures and unbalance of power caused by globalization has led to an increased number of terrorist activities, which primarily targets civil infrastructures such as strategically important buildings and public environment. Attacking strategically important buildings is not new, but the occurred events of the past decades show the importance of this topic today. In the ten years after September 11, 2001, there were 336 suicide attacks in Afghanistan and 303 in Pakistan, while there were 1,003 documented suicide attacks in Iraq between March 20, 2003, and December 31, 2010. A number of suicide attacks have also occurred in Russia as a result of the Chechen conflict, notably the Moscow theater hostage crisis in 2002 and the Beslan school hostage crisis in 2004. The 2010 Moscow Metro bombings are also believed to result from the Chechen conflict.[1]

Various attempts have been made to assess the impact of explosions on targets.[2-7] However, much work needs to be done to improve care and reduce the consequences of explosion-related injuries. There is no single method to map the blast overpressure to human injuries that is calibrated against the real-life victims' data. All of the existing estimates and pressure-lethality curves are based on experiments on pigs, sheep, plus data collected from stationary sensors without any consideration of blockage and 3D environment. Most of the models have also neglected the effects of the negative phase, reflection waves and blockage shields by living and non-living objects, crowd density, projectiles and debris.[8]

Suicide bombings seem to be terrorist acts. But contrary to other terrorist attacks, the suicide bombing is an operational method in which the very act of the attack depends on the death of the perpetrator. As a weapon, it is difficult to deny the benefits of the suicide bomb attacks. Few researchers such as Harrison[9] have also focused on the motivation and psychological profiles of suicide bombers, the economical and political gains behind the attacks, their role in destabilizing countries, and the role of bystanders in reducing the casualties of suicide bombing attacks.

Blast injuries are the result of four basic mechanisms

Figure 1. The four basic types of blast-related injury are described in relation to the mechanism by which they occur, (a) primary, (b) secondary, (c) tertiary and (d) quaternary or miscellaneous. **(a)** A 10-year-old boy, resident of Bahraich in India, was joining three commonly available pencil batteries in series and twisting the wire with his teeth when one of the batteries exploded causing severe injuries to his midface and mandibular region. (Source: Kumar V, Singh AK, Kumar P. Blast injury face: An exemplified review of management. Natl J Maxillofac Surg. 2013;4(1): 33–39. Doi: 10.4103/0975-5950.117878). **(b)** Injuries resulting when a person is struck by particles impelled with violent force from an explosion. (Source:http://upload.wikimedia.org/wikipedia/commons/f/f5/Blast_injury-lower_extremities.PNG). **(c)** The Alfred P. Murrah Federal Building, Oklahoma City, Oklahoma, U.S, in the wake of the terrorist bombing on April 19, 1995. (Source:http://www.britannica.com/EBchecked/media/70968/The-Alfred-P-Murrah-Federal-Building-Oklahoma-City-Oklahoma-US). **(d)** Flash burn victims from Hiroshima showing pattern burns. The dark colored material pattern on the victims clothing preferentially absorbed the thermal energy and burned the skin. (Source:http://aksynelek.wordpress.com/2011/01/23/radiation-effects-part-i).

termed as primary, secondary, tertiary and quaternary (miscellaneous). Victims may have complex injury patterns involving multiple organ systems as a result of a combination of some or all of these blast injury mechanisms. Primary injuries caused by the direct result of pressure wave travel through the body. This includes rupture of tympanic membranes, pulmonary damage and rupture of hollow viscera. Secondary blast-related injuries include penetrating trauma due to projectiles and flying debris. Tertiary injuries are the result of physical displacement of the victim, with rapid acceleration and deceleration, resulting in blunt force trauma. Lastly, miscellaneous blast injuries are caused by flame and chemicals that includes burns, asphyxia, and exposure to toxic inhalants **(Figure 1)**.[10]

In this study only primary and direct injuries were considered. The physical environment in which an explosion occurs plays a significant role in the type and degree of injury that may result. Blasts that occur in an enclosed space (e.g. a closed room) can intensify the effect of the blast wave, resulting in more severe injury patterns than those that occur in open air (e.g. plaza, open market or train platform). Thus, this paper describes a numerical method for assessing the interaction of high explosive air blast within the complex geometrical type of a congested urban environment in Tehran.

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 2**. Generally, explosion reactions are completed within a few micro seconds. 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 is expressed as W and R, respectively. Mays and Smith[11] expressed the peak overpressure as a function of $Z=R/W^{1/3}$ (m/kg$^{1/3}$), which is designated as the blast load scaled distance by the following formula:

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

The duration of the blast impulse, t_d, can be determined

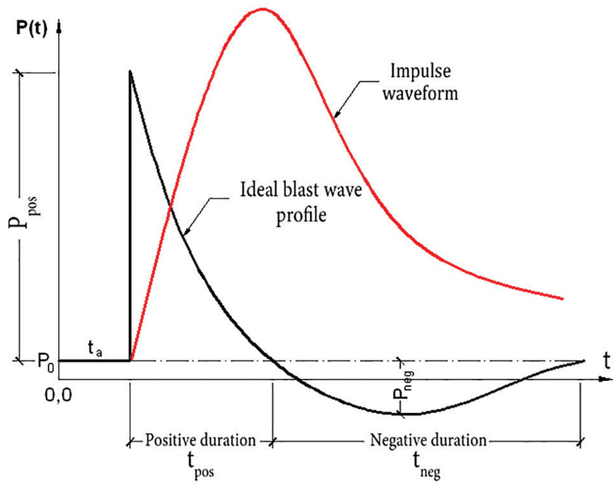


Figure 2. A typical pressure-time profile of an explosion in a free field.

as a function of W and R, given by Lam and colleagues:[12]

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

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[13] have noted that the following relationship is used for calculating the peak reflected overpressure (P_r) :

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

In this formula 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 $\gamma=1.4 \rightarrow P_r=2P_s\ (7P_0+4P_s) / (7P_0+4P_s)$).

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. **Table 1**, based on Department of Defense data from Glasstone and Dolan[14] and Sartori[15], summarizes the effects of increasing blast pressure on various structures and the human body. This data originates from weapons tests and blast studies to assess the effect of blast overpressure on structures and people. This data provides some guidance on the possible effects of mine explosions on miners.

Table 1. Effect of various long duration blast overpressures and the associated maximum wind speed on various structures and the human body.[14,15]

Peak Overpressure	Maximum Wind Speed	Effect on Structures	Effect on the Human Body
1 psi (lbf/in^2)	38 mph	Window glass shatters	Light injuries from fragments occur
2 psi (lbf/in^2)	70 mph	Moderate damage to houses (windows and doors blown out and severe damage to roofs)	People injured by flying glass and debris
3 psi (lbf/in^2)	102 mph	Residential structures collapse	Serious injuries are common, fatalities may occur
5 psi (lbf/in^2)	163 mph	Most buildings collapse	Injuries are universal, fatalities are widespread
10 psi (lbf/in^2)	294 mph	Reinforced concrete buildings are severely damaged or demolished	Most people are killed
20 psi (lbf/in^2)	502 mph	Heavily built concrete buildings are severely damaged or demolished	Fatalities approach 100%

Keys: psi, pound-force per square inch; mph, miles per hour.

Numerical analysis

For complex structures requiring refined estimates of blast load, blast consultants may use sophisticated methods such as computational fluid dynamics programs to predict blast loads. In this study a series numerical analyses were performed using Ansys-cfx. In all of the analyses TNT (Trinitrotoluene) charge was modelled using published Jones-Wilkins-Lee (JWL) data,[16] 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

Figures 3 and **4** show blast effects predictions for the Tehran Friday Prayer based on a typical car bomb and a typical large truck bomb detonated in the 16thAzar St. in Tehran, respectively. A computer-based geographic information system (GIS) was used to analyze the building's vehicular access and circulation pattern to determine a reasonable detonation point for a vehicle bomb.

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, since 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 5)**, 3D finite element modeling was done using the Ansys-cfx software. The results are shown in **Figures 6** and **7**. The duration of a blast wave must

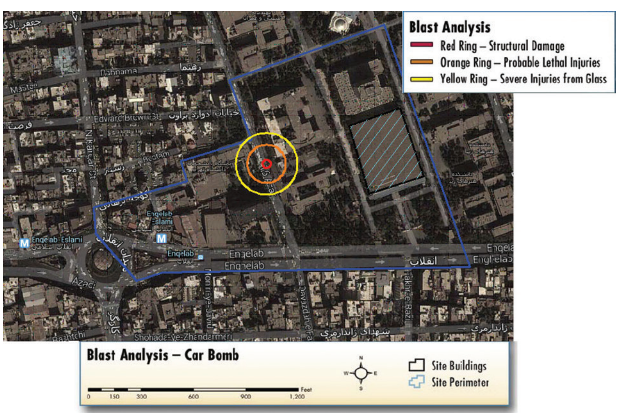


Figure 3. Blast analysis of the Tehran Friday Prayer for a typical car bomb detonated in the 16thAzar St.

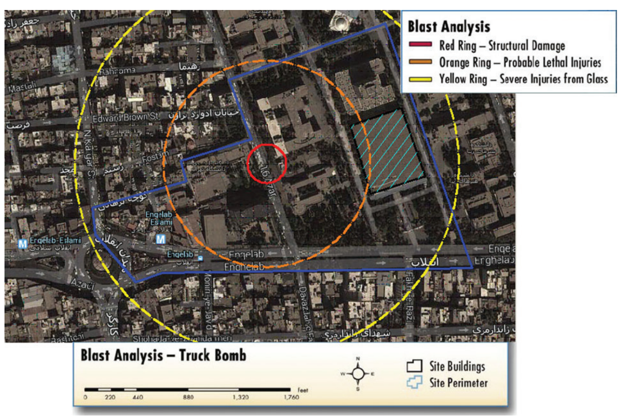


Figure 4. Blast analysis of the Tehran Friday Prayer for a typical truck bomb detonated in the 16thAzar St.

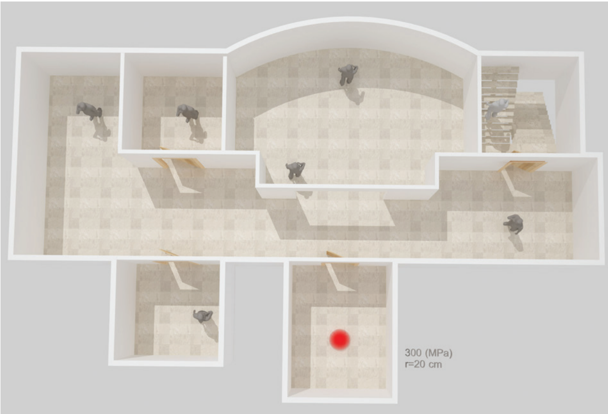


Figure 5. The plan of the building used in finite element modeling.

be considered because the magnitude of injury depends in part on how long the damaging forces are applied. In order to tie together the influence of peak overpressure and duration to injury and fatality probability, a series of theoretical and computational methods were utilized. **Figure 8** summarizes the findings of fatality risk curves predicted for a 70kg man applicable to free-steam situations.

DISCUSSION

This study was an attempt to give developers basic knowledge about expansion of high explosive blast waves in urban environment. This knowledge can help in developing models for risk assessments, and to mitigate blast effects when designing or assessing features (enhanced structural loading capability, helmets, body armor, etc.).

Risk is the potential for a loss of or damage to an asset. It is determined based upon the level of potential consequences related to the given threat and the level of vulnerability of the targeted assets to that threat. Risk is based on the likelihood or probability of the attack or hazard event occurring and the probability that a successful attack or event will cause the maximum potential losses. For example, the exact explosive mass used in suicide attacks is hard to determine. However, it is possible to give

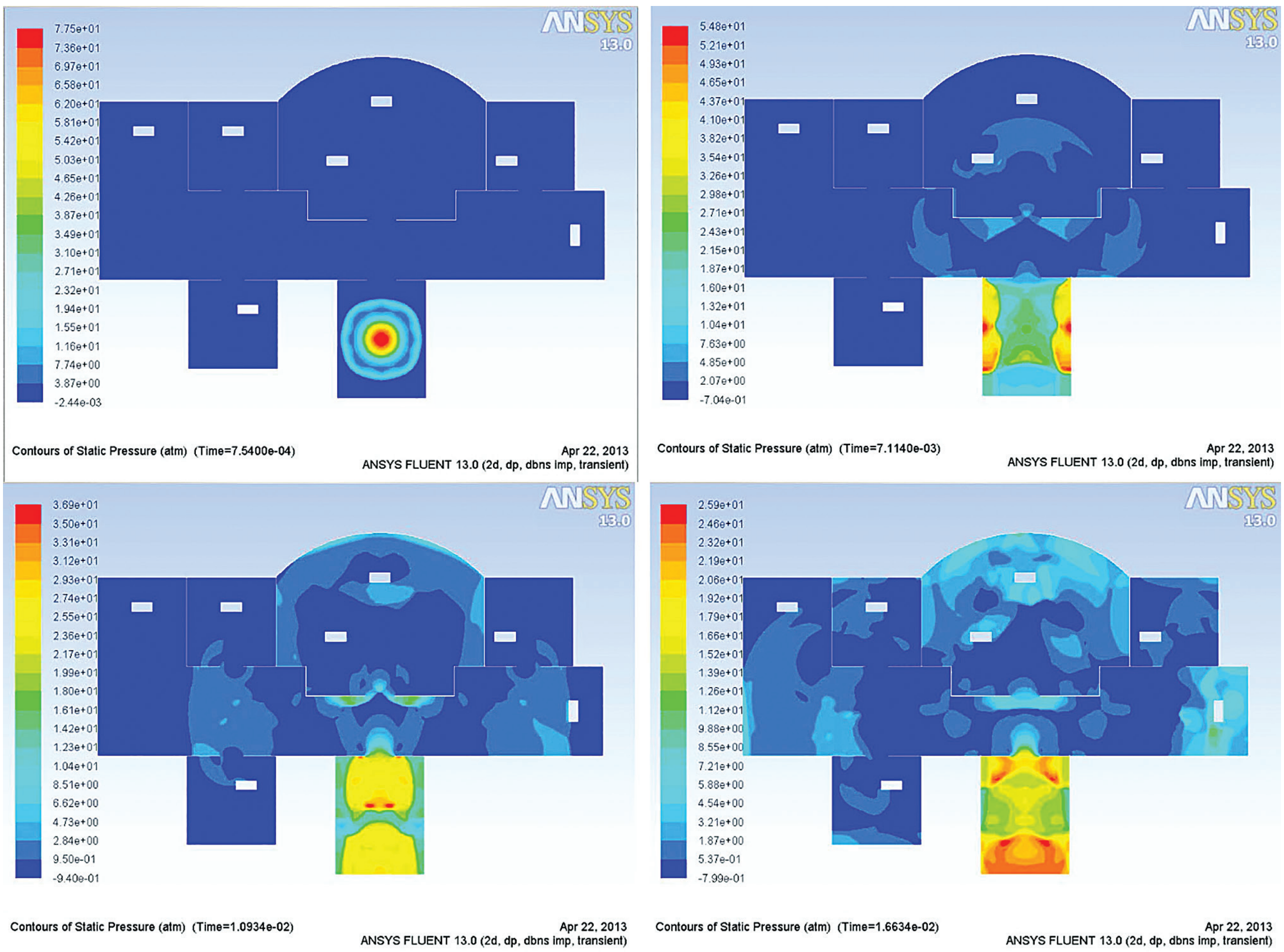


Figure 6. Static pressure contours at various time points.

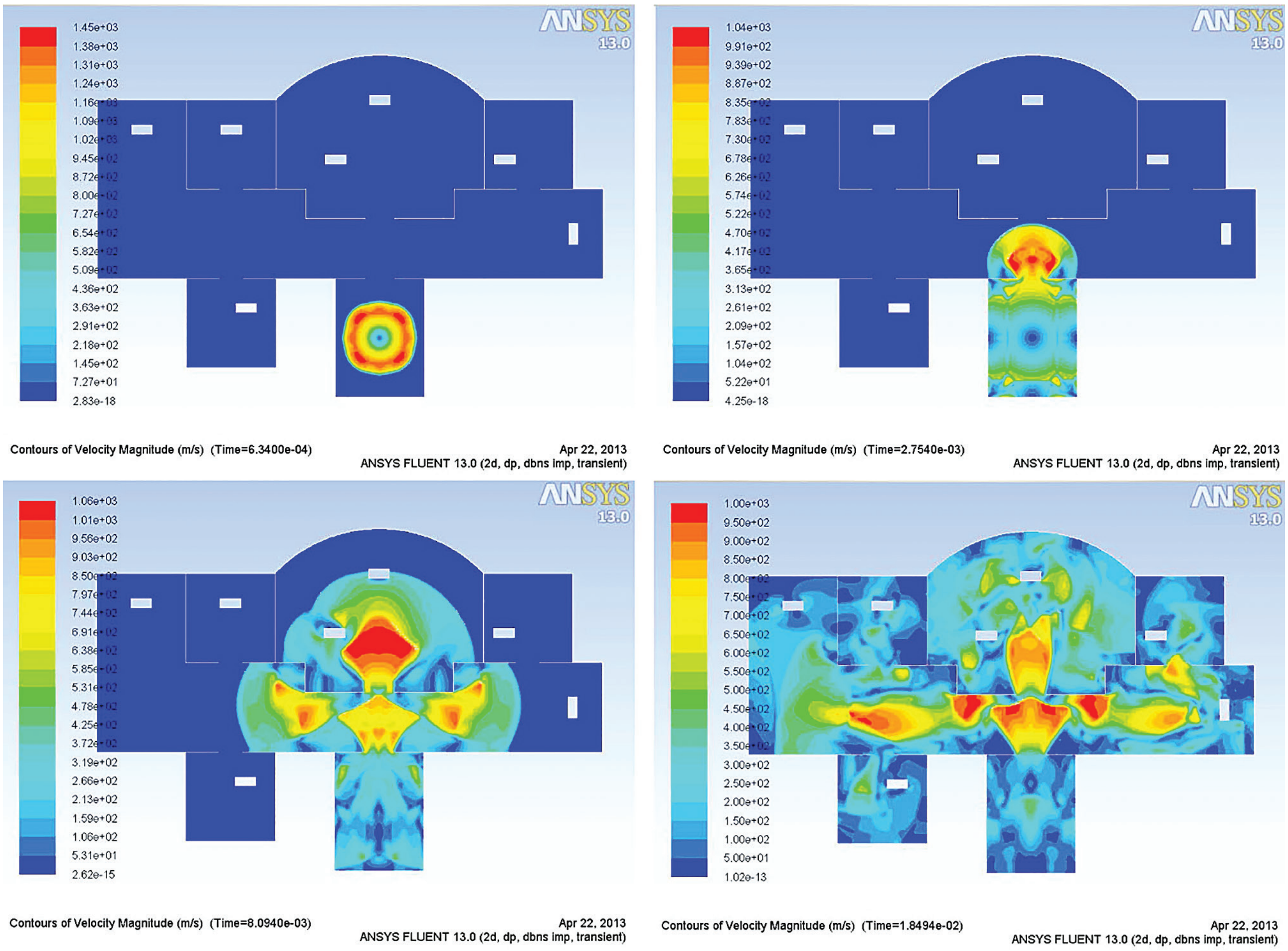


Figure 7. The velocity contours at various time points.

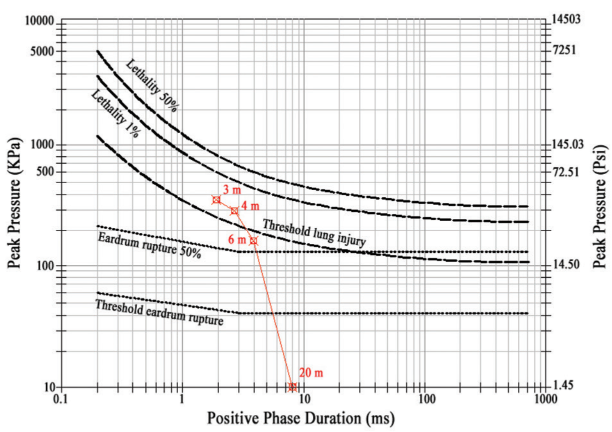


Figure 8. Fatality curves predicted for a 70-kg man applicable to free-steam situations where the long axis of the body is perpendicular to the direction of blast wave propagation. The red line is associated with 10kg TNT (Trinitrotoluene) at 3 to 20 meters distance from point of detonation.

some general indications of the overall level of injuries to be expected based on the size of an explosion, the number of participants and crowd formation. **Table 2** lists the weapons yield of various explosive threats as a function of the type of packaging or means of delivery. This chart assumes each sized package or vehicle is fully packed with explosives and the magnitudes, therefore, correspond to the maximum credible threat.

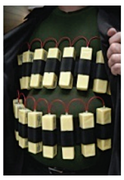
Risk assessment analyzes the potential for occurrence of each applicable threat/hazard for each asset. Numerous methodologies and techniques exist for conducting a risk assessment. One approach is to assemble the results of the threat assessment, consequences assessment, and vulnerability assessment, and to determine a numeric value of risk for each asset and threat/hazard pair in accordance with the following formula:[17]

$$\text{Risk} = \text{Threat Rating} \times \text{Consequences Rating} \times \text{Vulnerability Rating}$$

The effects of an explosion are contingent upon various factors, such as:[18]

1. Explosive type (i.e. TNT, RDX, C4, etc.),

Table 2. The maximum amount of TNT that could reasonably fit into a container or vehicle.[18]

Threat description	Maximum explosives mass (TNT equivalent)	Threat description	Maximum explosives mass (TNT equivalent)
	Pipe Bomb 5 lbs (2.3 kg)		Sedan 1,000 lbs (454 kg)
	Suicide Belt 10 lbs (4.5 kg)		Small Moving Van/ Delivery Truck 10,000 lbs (4,536 kg)
	Suicide Vest 20 lbs (9 kg)		Moving Van/ Water Truck 30,000 lbs (13,608 kg)
	Briefcase/ Suitcase Bomb 50 lbs (23 kg)		Semi-trailer 60,000 lbs (27,216 kg)

Key: TNT, Trinitrotoluene.

2. Explosive weight (pounds) and results overpressure (pressure-per square inch PSI),
3. Ignition source and criteria,
4. Crowd density (number of people per square meter),
5. Crowd demographics (i.e. age, sex, weight, height),
6. Pulse duration (milliseconds),
7. Blockage ratios (percentage),
8. Reflection waves,
9. Size, shape, and location of obstacles,
10. Number of obstacles,
11. Projectiles, debris, and fragments,
12. Shape of the explosive carrier.

A suicide bombing model and simulation should consider all of the aforementioned factors. Blockage or shields present in a crowd can play an important role in the event of an explosion. Even a person providing a blockage in the line-of-sight between another person and an explosion can actually save the later person's life by absorbing most of the shrapnel or by consuming part of the blast wave overpressure. Results indicated that the worst crowd formation is Zig-Zag (e.g. street) where 30% of the crowd can be dead and 45% can be injured in a typical explosive carrying capacity of a single suicide bomber. Row wise crowd formation was found to be the best for reducing the effectiveness of an attack with 18% crowd in lethal zone and 38% in injury zones.[8] Impulse is also an important aspect of the damage-causing ability of the blast, and may become a controlling factor for short duration, small yield explosives. Kinney and Grahm[5]have given the following formula in this regard:

$$I_{pos} = \frac{0.067\sqrt{1+\left(\frac{Z}{0.23}\right)^4}}{Z^2\sqrt[3]{1+\left(\frac{Z}{1.55}\right)^3}}(bar - ms) \quad (4)$$

The selection and implementation of protective measures to achieve an acceptable level of protection at an acceptable cost is perhaps the most important component of the risk management process. Because protection against the entire range of possible threats is cost prohibitive, developing a realistic prioritization of risk reduction objectives and measures that respond to these objectives is important. When evaluating protective measures, consider the following factors:[18]

1. The results of the risk assessment, including consequences and vulnerabilities;
2. The costs of the protective measures;
3. The value (in terms of life safety and protection) of risk reduction for a place and community as a whole;
4. The deterrence or preventive value of the protective measures;
5. The expected lifespan of the protective measures.

All these factors should be considered when calculating the value of protective measures, and weighing their value against their cost.

Prioritization is an integral component of all analyses. Intelligence agents in extreme conditions can an attempt to use agent-based simulation to save lives, and predict the outcome of catastrophic events like suicide bombing. Explosion modeling is a complicated task that requires the knowledge of physical properties of explosions, projectiles and debris, chemical properties of explosive materials and their reactions, fluid dynamics, and the overall impact of explosions on humans and structures supported by experimental and theoretical studies. Furthermore, a good explosive simulation should be easy to use, contain appropriate physics, should be able to work with different scenarios, blockage ratios, injury matrices, and different ambient conditions without special time-consuming tuning of constants.

CONCLUSION

Suicide bombers, unlike any other device or means of destruction, can think and therefore detonate the charge at an optimal location with perfect timing to cause maximum carnage and destruction. Suicide bombers are adaptive and can quickly change targets if forced by security risk or the availability of better targets. Suicide attacks are relatively inexpensive to fund and technologically primitive, as improvised explosive devices (IEDs) can be readily constructed.

This paper has suggested 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.

CONFLICTS OF INTEREST

None declared.

REFERENCES

1. Wikipedia. Suicide attack. Available at: http://en.wikipedia.org/wiki/Suicide_attack. Accessed February 2014.
2. Teich M, Gebbeken N. The influence of the under pressure phase on the dynamic response of structures subjected to blast loads. *Int J Prot Str*. 2010;1:219-34.
3. Larcher M, Herrmann N, Stempniewski L. Explosions simulation leichterHallenhüllkonstruktionen. *Bauingenieur*. 2006;81:271-7.
4. SadovskiyMA.*Selected works:Geophysics and physics of explosion*. Moscow: Nauka Press; 2004.
5. Kinney GF, Grahm KJ. *Explosive shocks in air*. Berlin: Springer; 1985.
6. Henrych J. *The dynamics of explosion and its use*. Amsterdam: Elsevier; 1979.
7. Brode HL. Numerical solutions of spherical blast waves. *J App Phys*. 1955;26:766-75.
8. Usmani Z, Alghamdi F, Kirk D. Intelligent agents in extreme conditions – modeling and simulation of suicide bombing for risk assessment. In: Usmani Z, ed. *Web Intelligence and Intelligent Agents*. Vukovar, Croatia: InTech;2010.
9. Harrison M. Bombers and bystanders in suicide attacks in Israel, 2000 to 2003. *StudConfl Terror*. 2006;29:187-206.
10. Elsayed NM, James Atkins JL. *Explosion and blast-related injuries: effects of explosion and blast from military operations and acts of terrorism*. San Diego, USA: Elsevier Academic Press;2008.
11. Mays GC, Smith PD. *Blast effects on buildings: Design of buildings to optimize resistance to blast loading.* New York, NY: Thomas Telford;1995.
12. Lam N, Mendis P, Ngo T. Response spectrum solutions for blast loading. *Elec J Str Eng.* 2004;4:28-44.
13. Kingery CN, Bulmash G. *Air blast parameters from TNT spherical air burst and hemispherical surface burst*. Maryland, USA:US Army Armament Research and Development Center, Ballistics Research Laboratory, Technical Report ARBRLTR-02555;April 1984.
14. Glasstone S, Dolan PJ, eds. *The effects of nuclear weapons*. 3rd Edition. Washington DC: US Department of Defense and the Energy Research and Development Administration; 1977.
15. Sartori L. The effects of nuclear weapons. *Phys Today*. 1983;36:32-41.
16. Dobratz BM, Crawford PC. *LLNL explosives handbook: Properties of chemical explosives and explosive stimulants*. University of California, Lawrence Livermore National Laboratory, Technical Report UCRL-5299, Revision2;1985.
17. Usmani Z, Daniel K. Modeling and simulation of explosion effectiveness as a function of blast and crowd characteristics. *J Def Model Simul.* 2009;6:79-95.
18. Federal Emergency Management Agency. *Building and Infrastructure Protection Series: Primer to Design Safe School Projects in Case of Terrorist Attacks and School Shootings*.2nd Edition. Washington DC:US Department of Homeland Security;2012.

Corresponding Author:
Kambiz Kangarlou, PhD
Address: No 2, 6th St., Iranzamin St., ShahrakGharb District, Tehran, Iran.
P.O. Box: 14656-93493
Tell: +98 21 88363337
Fax: +98 21 88363337
Cell Phone: +98 9122132379
E-mail: kangarloo_kambiz@yahoo.com

Received June 2014
Accepted August 2014