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Blast Pressure Simulation of a Suicide Vest Attack

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ABSTRACT

Suicide bomb vests represent one of the most devastating and indiscriminate forms of violence, often employed by extremist groups to instill fear and terror within communities. Computational techniques can be used to simulate blast wave propagation to gain a better knowledge of pressure dynamics, threat of explosions on human health and life, and the effects of explosions on infrastructure. The current study utilizes a coupled Eulerian-lagrangian (CEL) approach in ABAQUS to numerically simulate blast wave propagation generated from a suicide bombing in free-air. A virtual scene of targeted area is proposed to assess the lethality of a fully vented burst. The peak-overpressure (P_{so}) in free-air is predicted and compared to empirical prediction by Kingery-Bulmash model. The CEL model prediction of peak-overpressure in free-air demonstrated good convergence with Kingery-Bulmash measurements. The CEL analysis results of incident peak-overpressure showed an excellent agreement with empirical model measurements with maximum difference of 9%. Furthermore, the reflected peak-overpressure value is double the incident peak-overpressure magnitude in front of the walls. However, blast walls attenuated blast wave energy and peak-overpressure dropped by 53% at a distance 1.5h behind the walls. The measurements clarified high risk zone around the explosion source due to severity of the detonation, and further studies are essential to suggest protection methods to mitigate blasts and minimize losses in areas at risk of explosion.

1. Introduction and Background

Numerous areas of the world have been suffering from suicide bombing attacks. These attacks have become a daily routine of the targeted spots [1]. According to Jackson Harry, spreading a fear of state within communities, inflicting casualties, and achieving political aims are the main elements of terrorism. The consequences of these attacks have impacted communities lifestyle and left psychological crises and economic hardships [2], [3]. The Chicago Project on Security and Terrorism website stated number of victims due to suicide attacks are much higher than other terrorist tactics [4]. The data showed an incredible increase in suicide bombings and casualties in the last 33 years as shown in Figure 1. The challenge of suicide bombings attributed to uncertainty factors and techniques, complexity in nature, and spatial conditions, and dynamism and non-discriminatory goals [2],[3]. Hence, understanding blast wave phenomena around targeted areas, and possibly mitigating their effects is urgent.

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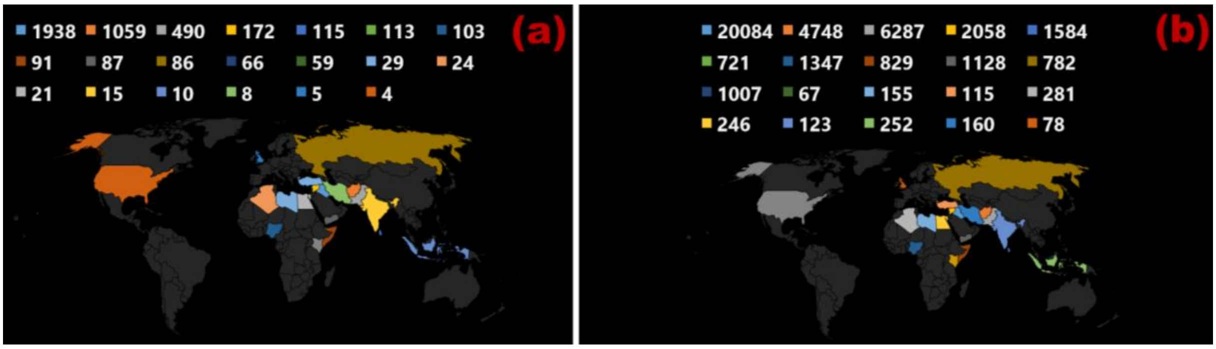


Figure 1. Worldwide suicide bombings in numbers from 1982-2015 a. number of suicide bombings b. number of casualties (Adopted and regenerated from cpost.uchicago.edu)[4]

The blast pressure intensity is initially controlled by the volume of released energy. The differentiation in blast pressure created forces act on the faces of nearby structures [7]. However, the blast shock wave may interact and reflect from surrounding objects and/or structures, Furthermore, ground-wave reflections are probable [8]. For instance, in an unconfined air burst, blast shock wave is reflected from the ground before reaching the targeted surface, and the reflected wave pressure is higher than the incident wave pressure. In a free-air burst there is no reflection as the shock wave moves towards the target [9]. In this study, fully vented burst is considered to simulate suicide vest explosion.

Blast design codes, technical manuals, documents, and handbooks have been published comprising the fundamentals of blast loads, design criteria, tables, charts, personal protection and safety measures [9], [10], [11]. Design approaches and technical information for cantilever blast walls, which have been used as blast barriers have been documented [12]. However, some of this information is limited in scope and not released to the public due to sensitivity information [11]. Blast wall function is to block the blast shock wave and keep detonation locations at a safe distance from occupied structures [12]. The characteristics of blast load impact and blast environment behind vertical walls are minimal in the literature. Beyer (1986) conducted a series of blast tests to estimate blast phenomena behind blast walls [12]. The study considered three blast wave parameters behind the wall in the design criteria of blast wall: peak-overpressure (P_{so}), total impulse (i_s) and blast duration (t). The study attempted to answer the following question: where should the blast wall be installed to provide optimal protection. The author stated that wall height (H)-meter, explosive mass (W)-kilogram, and standoff distance(R)-meter control the blast environment behind the wall. Moreover, adding a canopy at the top of wall can mitigate the blast wave intensity by reflecting the shock wave and preventing it from passing over the wall. Figure 2 shows the blast protection cantilever wall with and without a canopy, respectively, and the blast phenomena behind it [12].

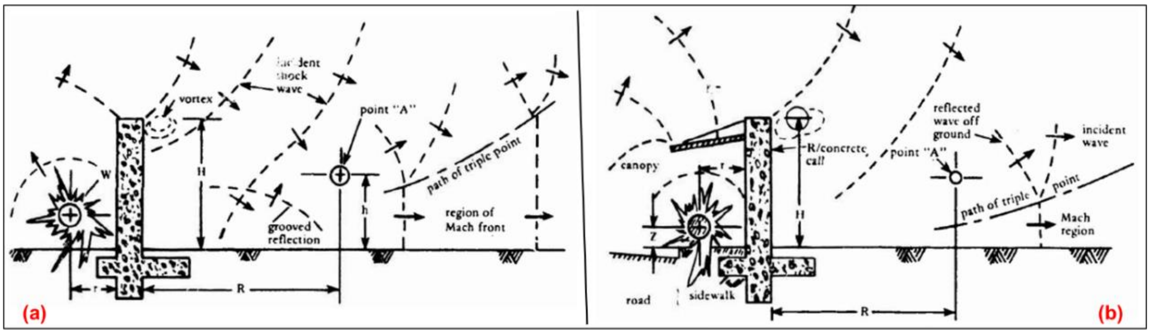


Figure 2. Blast phenomenon behind wall a. cantilever wall b. canopy wall [12]

Rose et al. (1995) conducted blast field tests to study the blast wave environment behind 1/10th scale of steel vertical blast walls [13]. The authors measured the blast peak-overpressure (*P_{so}*) and impulse (*i_s*) without wall and with wall at up to (*6h*), and up to (*3h*) above the ground level, where *h* is the wall height. The study outcomes presented a measurement matrix of blast peak-overpressure and impulse and compared to the measurement without wall. The authors concluded that the present wall attenuated the pressure by 60% to 80%. Thereafter, the authors examined blast loading parameters around concrete, wood, sand, and foam blast walls at different standoff distance and height of spherical TNT charge [14]. The authors stated simple blast barriers can mitigate blast intensity and provide a sufficient safety and protection based on the inertia of the wall. Moreover, the use of sand and geotextile had provided higher protection by employing both resistance and inertial, and adding water reduced generated debris [14].

Published literature have investigated the blast wave parameters of high explosive burst. Blast field tests, analytical and numerical analyses have been performed to estimate blast load parameters, peak-overpressure (*P_{so}*), time of arrival (*t_a*), positive duration (t_o^+), reflected peak-overpressure (*P_r*), and blast impulse (i_s).[15], [16], [17], [18], [19], [20], [21], [22]. Moreover, blast response of structural systems has been the focus of interest by researchers [2], [23], [24], [25], [26].

While there is a lack on the literature of blast pressure distribution of suicide of vest explosions, few research work have performed numerical simulation to identify improvised explosive devices (IEDs) of suicide bombings which can carry by suicide bombers [1], [27]. Usmami et al. (2010) developed a 3-D simulation of a proposed suicide bombing explosion. The study aims are to understand how geometry layout and presence of civilians can be arranged to attenuate losses of life and damage of property [1]. The study concluded that the zig-zag layout arrangement is the least effective in minimizing the causalities through suicide bombing attack. According to the simulation results, this formulation leads to a 30% probability of fatalities and a 45% probability of injuries. Row-wise formulation is the best effective in attenuate the impact of suicide bombing [1], [28], [29], [30]. Other studies had interested in detection technologies of IEDs [27], [31], [32]. However, the published work have interested in blast load characteristics and/or structural systems response of blast. Therefore, there is an urgent necessity for a comprehensive study to analyse the suicide bombings environment to guarantee there is an integrated knowledge of the level of potential risk of such threat. The outcomes of these study can help engineers, security agencies, and urban planners to have a clear view about structural response to explosions, evacuation plans, and risk assessment model. In conclusion, there is a research gap and lack of knowledge on nature and characteristics of suicide bombings attacks.

The present study utilized the coupled Eulerian-Lagrangian (CEL) approach in ABAQUS to numerically simulate blast wave propagation generated from a suicide bombing in free-air. The peak-overpressure (*P_{so}*) in free-air is predicted and verified with empirical prediction by Kingery-Bulmash model [20], and a virtual scene of targeted area is proposed to assess the lethality of a fully vented burst.

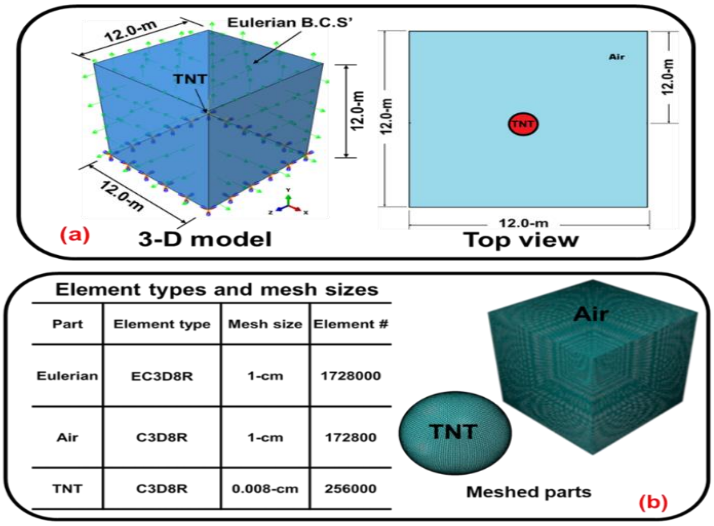
2. Study significant and contribution

Suicide bombings cause serious casualties and property damage to nearby structures due to the intensity of the explosion. The suicide vest detonation releases large amount of energy in a short time, generating intense blast waves that propagate outward. The literature on simulated suicide vest detonation is sparse studies, hence, the present study performs numerical simulation of blast wave expansion in open air for better understanding the mechanism of the suicide vest explosion, specifically the shock wave propagation. This knowledge is essential for developing effective mitigation strategies. The findings of this study can enhance engineers ability to adopt reliable design methods to introduce mitigating strategies to potentially preserve lives and property.

3. Geometry Details and Finite Element Model Overview

3.1 Free-air blast model

Three-dimensional (3-D) non-linear dynamic finite element (FE) model was performed using Coupled Eulerian-Lagrangian (CEL) technique in ABAQUS/Explicit software [33] . Figure 3 shows the model details and explosive location, and finite element model overview of the CEL analysis, respectively. The Eulerian domain dimensions are 12-m x 12-m x 6.0-m. The TNT equivalent mass is 9.0-kg, height of the explosive (HOE) is 6.0-m. The Eulerian is fixed in all directions from the bottom side of the modelled region, and surface conditions are non-reflecting. The total step time of the analysis is 10 milliseconds.



Element types and mesh sizes

Part	Element type	Mesh size	Element #
Eulerian	EC3D8R	1-cm	1728000
Air	C3D8R	1-cm	172800
TNT	C3D8R	0.008-cm	256000

Figure 3. Free-air blast model details a. Geometry details b. finite element model

3.2 Suicide vest detonation model

It is noticeable that suicidal terrorists most frequently cross security checks to reach a targeted area. Generally, statistics have clarified that most of these bombings have been implemented in publicly crowded spots, like malls, restaurants, shopping centers, and community carnivals. The scene and scenario of the explosions varies from attack to other, and sometimes a combination of two or more tactics is employed. Therefore, it is difficult to make a precise assumption to simulate blast due to these reasons. In this study, suicide bomber is assumed to have passed through all security precautions and reach the detonation point, and an explosion resulted from detonating of 9.0 kg of TNT in open space at the center point of a four IS 2062 E410 steel barriers as shown in Figure 4. The total step time of the analysis is 20 milliseconds to measure the pressure behind the walls.

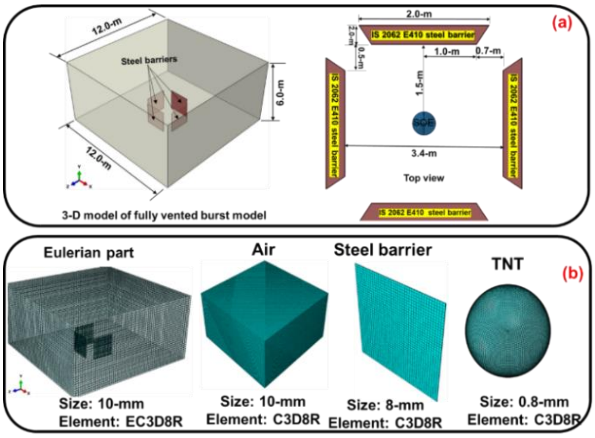


Figure 4. Suicide vest detonation model a. model details b. Meshed parts

3.3 Material models

- Explosive charge

The TNT explosive material is modelled using Jone-Wilkins-Lee (JWL) [34]. The JWL equation of state is utilized to simulate and compute detonation pressure of high explosive. Table 1 listed the JWL parameters of TNT material [35].

Table 1: JWL model parameters of TNT explosive material [35]

Parameters	Value
Density (kg/m^3)	1630
Detonation velocity (m/sec)	6930
A (GPa)	3.738
B (GPa)	3.747
R_1	4.15
R_2	0.9
ω	0.35
V	1.0
E (MPa)	6.0

Here, P is the total pressure, A, and B, are linear pressure parameters ω, R_1, R_2, are nonlinear pressure parameters, V is the relative volume, and E is internal energy/unit volume.

- Air

The ideal gas equation of state (EOS) is employed to model air in specified circumstances[33]. The equation of state model parameters of air is listed in Table 2 [36], [37]. Here, p is the density of air, (p_A) is the ambient pressure, R is the gas constant, C_P is the specific heat at constant pressure, η is the dynamic viscosity of air, and θ_Z is absolute zero on the temperature scale.

Table 2: EOS model parameters of air [37]

Parameters	Value
Density (kg/m^3)	1.297
P_A	101.325
R (J/kg. k)	287
Cp (J/kg. k)	717.6
H (kg/m.sec)	0.0000182
θ_Z	0

- Steel

The IS2062: 2006 GR- E410W steel is modelled using Johnson-Cook (J-C) material model to represent the dynamic behavior of steel material under high-strain rate load. Moreover, J-C damage model can estimate metal damage when subjected to blast [33]. Table 3 lists the IS 2062: 2006 GR E410W steel properties and J-C constitutive law parameters. Here A, B, C, n and m are material constants measured at or below the transition temperature, ε^*_0 is the critical strain rate, T_m, and T_R are the melting and room temperature, respectively. Table 4 shows the J-C damage model parameters.

Table 3: Material properties and J-C model parameters of E410W steel [38]

Parameters	Value
Density (kg/m^3)	7862
μ	0.3
E (GPa)	200
A(MPa)	220
B (MPa)	579
n	0.431
m	1.0
C	0.014
ε^*_0 (sec^{-1})	1.0
Tm (k)	1573
T_R (k)	298

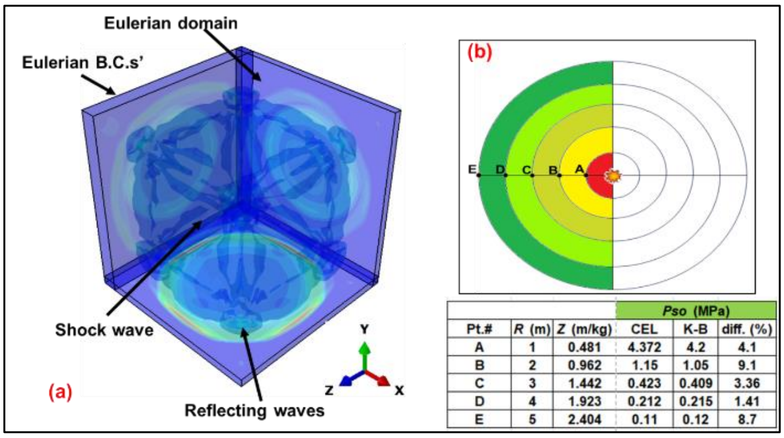
Table 4: J-C damage parameters of E410W steel [38]

Parameters	Value
D_1	0.25
$D2$	4.38
$D3$	2.68
$D4$	0
$D5$	0

4. Results and Discussion

4.1 Free-air blast measurements verification

The CEL model is applied to simulate blast shock wave propagation in free-air to estimate blast pressure-time curve and blast peak-overpressure (P_{so}) without walls. Figure 5a shows blast wave propagation through the Eulerian domain. It is noticeable that ground reflection waves have disrupted the initial shock wave. A two-dimensional contour plot is established to present peak-overpressure measurements at specified standoff distances (R) as shown in Figure 5b.



			Pso (MPa)		
Pt.#	*R* (m)	*Z* (m/kg)	CEL	K-B	diff. (%)
A	1	0.481	4.372	4.2	4.1
B	2	0.962	1.15	1.05	9.1
C	3	1.442	0.423	0.409	3.36
D	4	1.923	0.212	0.215	1.41
E	5	2.404	0.11	0.12	8.7

Figure 5. a. Point blast in un-walled domain b. Peak-overpressure of CEL and Kingery-Bulmash models

The results of the CEL model analysis are compared and validated with empirical prediction Kingery-Bulmash [20]. Figure 6a, and 6b shows the CEL prediction of blast-pressure-time history, and comparison between the CEL and Kingery-Bulmash measurements in terms of scaled distance, respectively. The results showed an excellent agreement with empirical model measurements with maximum of difference of 9% as shown in Figure 6b.

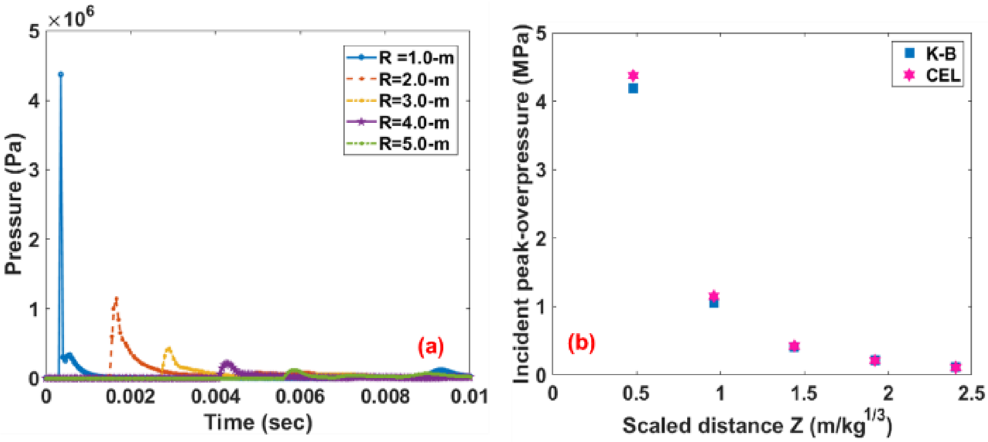


Figure 6. a. Pressure-time history of CEL model b. Comparison of incident peak overpressure of CEL model with Kingery-Bulmash model

4.2 Suicide vest detonation blast environment and pressure prediction

Following validation of CEL with empirical approach results [20] , the CEL model is applied to simulate suicide vest burst of equivalent TNT charge of 9.0-kilogram. The present study proposes a virtual attack scenario and scene as shown in Figure 4a. Four steel barriers are positioned around the source of explosion (SOE), the wall dimensions are 2.0-m by 2.0-m and thickness is 10-mm. The explosive charge is placed at 1.0-m above the ground inside the Eulerian domain (see Figure 4a). At the onset of the detonation, ground reflection waves are initiated intersecting the incident shock waves. As the shock wave propagates towards surrounding walls, rarefaction zone is generated behind the shock front. Blast shock wave reached and hit blast walls in 1.5-millisecond, incident shock waves diffracted, and blast wall deformed. After 2.0 millisecond, blast shock wave passed over the blast walls and travelled away. Figure 7 shows blast shock wave phenomena of suicide vest burst.

The blast effect on a human body and structures is function of maximum pressure, standoff distance, and duration of the event. The peak-overpressure measurements state high probability of fatality and severe damage of properties around the detonation source. For instance, threshold of lung damage can happen at 689.5 kPa, and chance of death happens at 896.3 kPa, while typical window glass can break at 1.03 kPa, and buildings collapse begins at 69 kPa. According to the U.S. Federal Emergency Agency (FEMA), the Safe evacuation indoor distance of suicide vest attack scenario is 34-meter, and 415- meter for outdoor [39].

Figure 8a, and b shows a comparison between CEL and K-B incident peak-overpressure measurements at point 1 to 5 in front of the walls, and the blast pressure distributions of suicide vest detonation, respectively. The CEL model estimates provided a good match with K-B measurements as shown in Figure 8a. Due to nature of the explosion and presence of blast walls, it is obvious there is a variation in the peak-overpressure values around the source of explosion. However, reflected peak-overpressure (P_r) is higher due to reflection phenomena.

The CEL analysis results of suicide vest detonation demonstrated a deadly impact due to high intensity of the blast. The reflected peak-overpressure around the steel barriers is higher due to reflection phenomena. The magnitude is twice the incident peak-overpressure in front of the wall. However, blast walls attenuated blast wave energy and incident peak-overpressure dropped by 53% at a distance 1.5h behind the walls. Therefore, conducting further investigations to analyse risk and fatal zone around explosion source is required to lessen losses.

In conclusion, the suicide vest detonation scenario is complicated due to unpredictability and extreme complexity of blast environment. This study suggests conducting further studies to propose mitigating methods of blast and minimize losses in areas at risk of explosion.

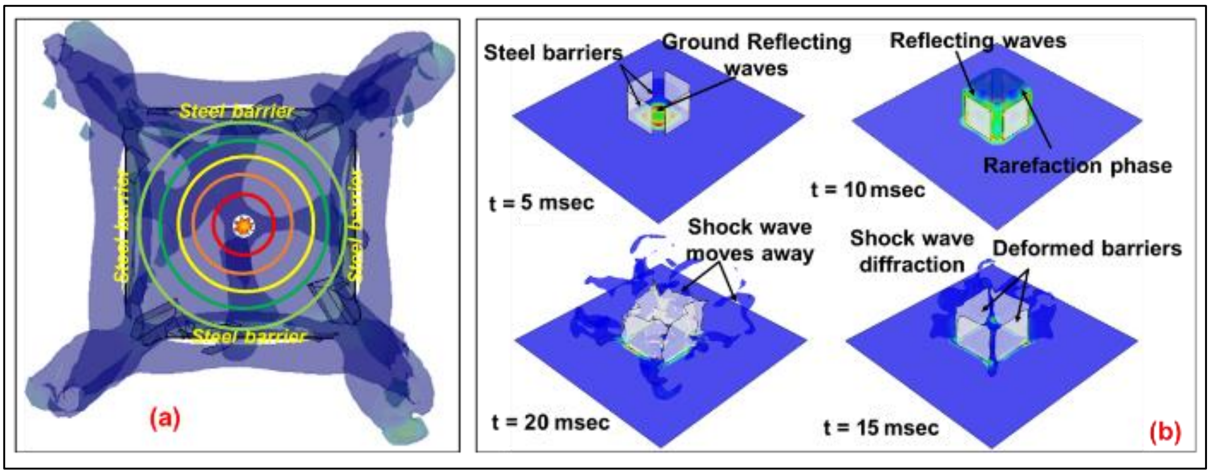
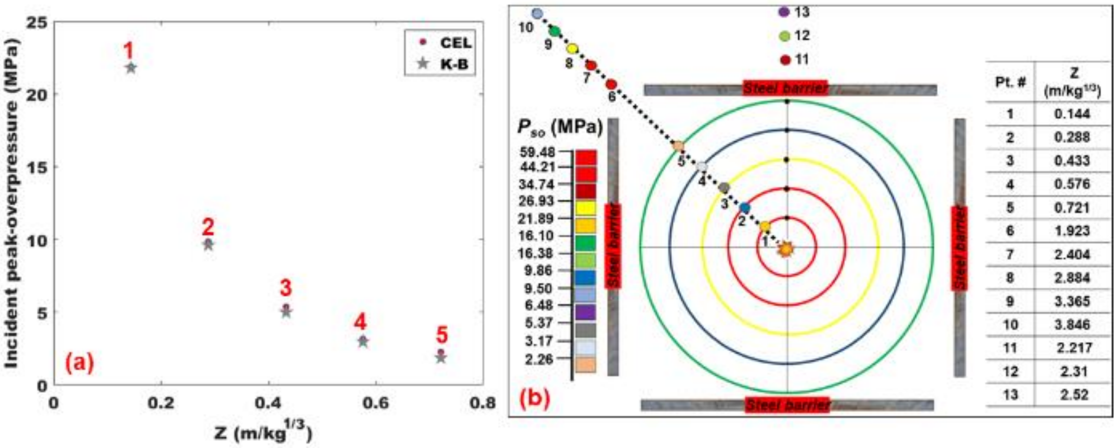


Figure 7. Blast shock wave phenomena of suicide vest burst a. top view b. 3-D view of suicide vest blast wave environment



Pt. #	Z (m/kg$^{1/3}$)
1	0.144
2	0.288
3	0.433
4	0.576
5	0.721
6	1.923
7	2.404
8	2.884
9	3.365
10	3.846
11	2.217
12	2.31
13	2.52

Figure 8. a. Incident peak-overpressure of CEL model without wall comparing to K-B measurements b. blast peak-overpressure distribution of suicide vest burst

5. Conclusions

This study presents simulation of a suicide vest detonation utilizing coupled Eulerian-Lagrangian analysis in ABAQUS. The current study framework includes free-air blast and suicide vest detonation models using CEL analysis. The CEL model is employed to simulate blast wave propagation in free-air (without walls) to measure the peak-overpressure (P_{so}). The free-air blast model has been validated and compared with empirical model measurements by Kingery-Bulmash. Then, the CEL model is applied to simulate blast wave phenomena with existing of steel walls. The following conclusions have been obtained from the results of this study:

- The CEL analysis results of incident peak-overpressure showed an excellent agreement with empirical model measurements with maximum difference of 9%.
- The results of the CEL model analysis showed deadly impact of suicide explosion due to high intensity of burst.
- The reflected peak-overpressure around the blast walls is higher due to reflection phenomena.
- The reflected peak-overpressure value is twice the incident peak-overpressure magnitude in front of the walls.
- The steel blast walls attenuated blast wave energy and peak-overpressure dropped by 53% at a distance 1.5h behind the walls.
- According to the proposed explosion scenario, and FEMA manuals specifications, the results of peak-overpressure showed deadly zone around the source of the explosion. Therefore, it is vital to conduct further investigations to analyse risk and fatal zone around explosion source is required to lessen losses.

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