Code for Blast Analysis using the Finite Element Method

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Abstract **J Shock waves generated by explosions move at supersonic speeds with great pressure and temperature, and not only incapacitate military and civilians, but also damage buildings and nearby areas. In many cases, damage can lead to the total or partial collapse of the target building and other facilities close to it. There are several programs for blast analysis, however, obtaining such licenses is almost impossible in countries with limited research resources. Thus, the purpose of this article is to present a MatLab code developed for blast analysis using the Finite Element Method. The code was developed for numerical analysis of hemispherical surface burst using an equivalent quantity of TNT, based on the *Kingery-Bulmash* equations. Numerical results were compared with experimental data from others publications with great convergence.**

Keywords **J Shock Wave, Explosion, Blast Loads.**

I. INTRODUCTION

During World War II the study of explosions gained much importance and several advances were made from then on. Today, this area of study is also of great relevance, mainly because of the imminent terrorist attacks that many nations have been suffering (and may suffer). However, the theme is also investigated for commercial purposes, such as mining, constructions (demolitions, excavations, among others) and the petrochemical industry. Regardless of the circumstances that led to the explosion, the blast effects can be disastrous and, in some cases, can initiate the progressive collapse [1].

On the light of exploring this complicated physical problem generated by explosions, this paper aims to present a tool for estimating the blast effects of hemispherical surface bursts on buildings façades. The code was written in MatLab® and analysis were made using different charges of explosives.

The information presented in this article is part of a project developed in the Federal University of Technology – Paraná (UTFPR), whose purpose is to develop cumulative tools for blast analysis on buildings.

II. SHOCK WAVES AND BLAST LOADS ON BUILDINGS

One detonation releases a huge quantity of energy in a small volume and, in a non-confined gaseous surrounding such as the air, these energy interactions rapidly originate shock waves and pressure waves that expand in all directions [2,3]. In a set point away from the detonation, an almost instantaneous increase in the static pressure is followed by a period of rapid reduction of pressure. Depending on the conditions of the explosion, as well as on the distance to the source, the static pressure can eventually decrease and become lower than the atmospheric pressure. Finally, with enough time, the pressure gets balanced with the atmospheric pressure [4].

A typical graph of a shock wave due to an explosion is presented in Fig. 1, in which P_{S0} is the peak overpressure and P_0 is the ambient pressure (equal to 101,3 kPa). The terms overpressure and pressure must not be confused because peak overpressure is the difference between peak pressure and the ambient air pressure [5]. The subscript term *"so"* refers to *"side-on pressure"* or *"free-field"*, and is used when the blast wave sweeps over a wall parallel to its direction of travel [6].

The shock wave properties can be approximated by using the Rankine-Hugoniot relations [3], which is only applicable if the particle velocity ahead of the shock front is zero and if the air behaves as an ideal gas (with a specific heat ratio of 1,4) [7]. Typically, the duration of a negative pulse is superior to the duration of a positive pulse. However, its intensity is smaller.

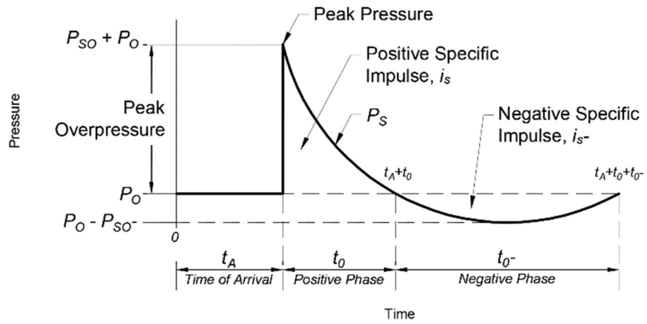

Fig. 1. Typical graphic for a Shock Wave in free-field, according to [8],[9].

The area under the positive pressure curve is called *"positive impulse"*. The area under the negative pressure curve is called *"negative impulse"*.

A. Hopkinson-Cranz Scaling Law

The quantification of the parameters of an explosion depends on the energy quantity released by the detonation, on the type of the explosion wave and on the distance to the explosion source. To describe the explosion effects in a universal and standardized way, it is possible to use a scaled distance Z, from (1), based on the approach derived from the *Hopkinson-Cranz Scaling Law* [7,10,11],

$$Z = \frac{R}{W^{1/3}}. \tag{1}$$

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In this equation, W is the charge of explosive in kg given as the equivalent mass of TNT (trinitrotoluene) and R is the distance from the source to target, in meters, also called Standoff Distance.

B. Blast Loads on Buildings

To calculate the blast loads on buildings it is necessary to determinate the charge mass of *TNT*, the distance to the explosion source and the type of explosion: air or surface burst. After it is possible to estimate the peak overpressure, P_{S0}. To do this several equations were proposed by many researchers, and some of these equations are shown in [12] for both detonations in the air (spherical bursts) and on the ground surface (hemispherical surface bursts).

When the wave reaches a wall or another object it is reflected, thus increasing the pressure applied to a surface. This reflected pressure is considerably larger than the incident pressure wave and according to [13], the shock wave may be reflected with an amplification factor of 13 times the original wave. For normal reflection, the reflected peak overpressure P_r can be estimated by (2) [3,14],

$$P_r = 2P_{so}\left(\frac{7P_o + 4P_{so}}{7P_o + P_{so}}\right). \quad (2)$$

The positive side-on specific impulse (or incident impulse) can be calculated by integrating the area under the pressure curve, for positive and negative phases (Fig. 1). Alternatively, the (3) can be used, i_{SO} in *Pa*s*,

$$i_{so} = 300\left(\frac{1}{Z}\sqrt[3]{W}\right). \quad (3)$$

The positive phase duration of a blast wave, in milliseconds, for surface and air bursts are expressed in (4) [15] and (5) [16], respectively,

$$t_0 = 10W^{1/3}, \quad (4)$$

$$\frac{t_0}{W^{1/3}} = \frac{980\left[1+\left(\frac{Z}{0,54}\right)^{10}\right]}{\left\{\left[1+\left(\frac{Z}{0,02}\right)^3\right]\left[1+\left(\frac{Z}{0,74}\right)^6\right]\left[1+\left(\frac{Z}{6,9}\right)^2\right]\right\}^{\frac{1}{2}}}. \quad (5)$$

During the positive phase the air particles get away from the explosion source, then getting closer during the negative period. This flow, created by the air particles, generates a pressure which is like the one caused by the wind and is referred to as dynamic pressure. It is smaller in magnitude than the shock waves and transmits a dragging load similar to wind loads and can be computed using (6),

$$q_s = \frac{5}{2}\frac{P_{so}^2}{\left(P_{so} + 7P_o\right)}. \quad (6)$$

To compute pressure $P_{(t)}$ at any instant *t*, it is possible to use the Friedlander's decay function, as shown in (7), where t_o is the duration of the positive pulse [msec], t_A the shock wave's arrival time [msec], *A* and α are the decay coefficients (nondimensional). This function is in the *ConWep* software, which is a collection of conventional calculations for effects of weapons, which are then derived from the equations and curves of [9] and used by many researchers to estimate the explosion parameters,

$$P(t) = P_{so}\left(1 - \frac{t - t_A}{t_0}\right)e^{\left[-\frac{(t-t_A)}{\alpha}\right]}. \quad (7)$$

This section above explained only the key basics to estimate pressures and impulses from explosion. For further readings, the readers are directed to [3], [14] and [17]. For near-field [18] presents predictive equations and scaled-distance charts for the incident and reflected overpressures and impulses, arrival time, and positive phase duration based on numerical studies of free-air detonations of spherical charges of TNT. Also, for a review of the current practices in blast-resistant analysis the readers can consulted the work published in [19].

III. Analysis Procedure in MatLab® code: B-Blast

For this research, pressures and impulses, which took place on the building, were calculated using a *MatLab®* code called *"B-Blast" (B of Bueno + Blast)*, which was developed to estimate the blast loads for hemispherical and free-air bursts [12,20], . The code follows the guidelines of some references, like the [8], [9] and [21]. The graphics in [4] were used to calculate the incident and reflected overpressures, impulse (incident and reflected), dynamic pressure, time of arrival and positive phase duration of the shock wave.

The *B-Blast* code allows one to calculate the parameters for positive and negative phases, but all analysis in this paper considered only the positive phase as it is the most significant one. This is also recommended by the manuals cited above.

To verify the *B-Blast* accuracy, the numerical results were compared with experimental data and with numerical results obtained with *ConWep* software.

A. Building Discretization in B-Blast Code

For the façade of the building a discretization similar for plate analysis was used, as shown in [22,23]. In addition, since the code is in development for finite element analysis, the quality of the results depends on the walls discretization. Thus, this procedure was utilized only to calculate the blast loads at the nodal points.

The incident loads were calculated using the Kingery-Bulmash equations documented in [4] (Fig. 2), which were transformed into data files to be used in *MatLab*® software. To find values between data points a linear interpolation was used.

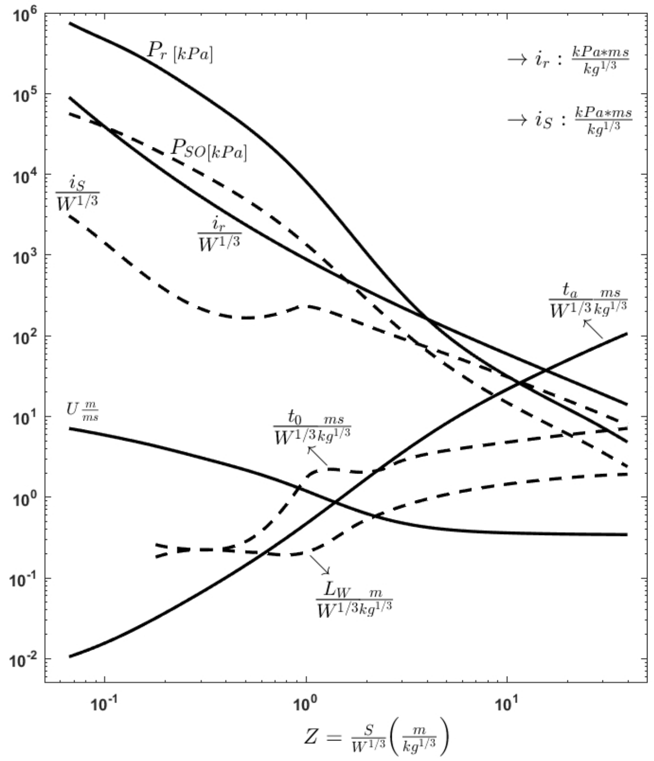


Fig. 2. Parameters for a positive phase of a shock wave for surface burst [4].

Direct reflection effects, where appropriate, are also calculated using the *Kingery-Bulmash* approach (Fig. 3). The angle of incidence is based on a line drawn directly from the bomb to the load point. No secondary reflection effects are included.

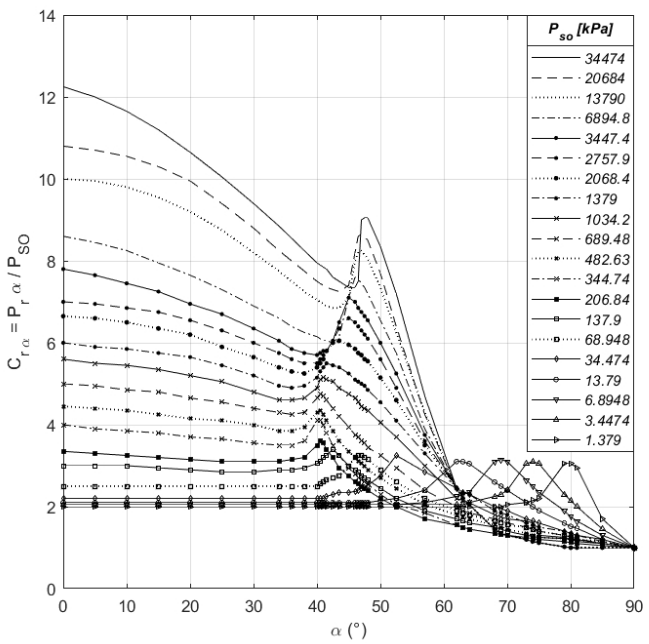


Fig. 3. Reflected pressure coefficient as a function of the incident angle [4].

The distance for each point in the mesh from the bomb is based on a ray-stretching approach similar to that discussed in [4], which is based on the additional distance required to travel over or around the building.

The cross-section model was idealized as rigid, which is valid according to the study shown in [24]. For the representation of the distribution of these loads, the MatLab command *"colormap('jet')"* was used.

B. Blast Load on Building Façade

When the shock wave strikes the front wall (façade), the pressure immediately rises from zero to the normal reflected overpressure P_r - see (2). After some time, this reflected overpressure will be relieved and the pressure acting on the façade will be the algebraic sum of the incident overpressure and the dynamic pressure. This time of relieving is known as *"Clearing Time"*. *B-Blast* considers these two phases.

C. Blast Load on Roof and Side Walls.

The blast pressure acting on the roof slab and side walls is equal to the incident overpressure at a given time at any specified point, reduced by a negative drag pressure. Thus, the *B-Blast* code allows two different forms for estimating the blast pressure on these regions. The first option considerate the clearing effects due to the dynamic pressure and the drag coefficient C_D, as shown in (8),

$$P_R = C_E P_{sof} + C_D q_{of} \,. \quad (8)$$

In this equation, P_{SOf} is the incident overpressure occurring at point f, C_E is the equivalent load factor (obtained in [4] as a function of the wavelength span ratio) and q_{of} is the dynamic pressure corresponding to $C_E P_{SOf}$. The drag coefficient C_D for the roof and side walls is a function of the peak dynamic pressure and recommended values are found in [4].

In the second option, *B-Blast* conservatively assumes that the drag coefficient is zero. As such, no load reduction is provided on these regions (as is fairly common for design). Like the roof and side walls, the blast loads acting on the rear wall are a function of the drag pressures in addition to the incident overpressure.

IV. Computational Results

A. Validation of B-Blast code with Experimental Results

For the validation the experimental results published in [25] were used. The blast trials were conducted for the authors in [25] at the University of Sheffield Blast & Impact Laboratory, Buxton, UK. In the experimental test, the explosive charge was placed on the ground and pressure and impulse sensors were positioned at different distances from the explosive. Further information on the tests may be obtained directly from the cited article.

Table 1 compares the average of the experimental results obtained by [25] with those obtained by the *B-Blast* code. "*W*" is the *TNT* equivalence charge of explosive.

With these results it is possible to verify that the *B-Blast* code was able to estimate the values of overpressures and impulses with accuracy since the maximum difference found was only 4%.

TABLE I. COMPARATIVE BETWEEN EXPERIMENTAL AND NUMERICAL RESULTS.

R	*W*	***Overpressure*** [kPa]			***Impulse*** [(kPa·msec)/$W^{1/3}$]		
[m]	*kg*	*B-Blast*	*Exp**	*Exp. (B-Blast)*	*B-Blast*	*Exp**	*Exp. (B-Blast)*
4	0,42	88,56	89,45	***1,01***	116,76	121,15	***1,04***
4	0,3	71,87	71,70	***1,00***	103,22	104,35	***1,01***
6	0,42	44,03	42,35	***0,96***	75,15	76,30	***1,02***
6	0,3	37,09	36,30	***0,98***	66,67	67,50	***1,01***
8	0,3	24,52	25,30	***1,03***	49,16	49,55	***1,01***
10	0,3	18,13	18,70	***1,03***	38,90	38,40	***0,99***

* Average of the experimental results obtained by [25].

Thus, it is shown that in a controlled trial, the experimental results will be very close to those estimated by the *B-Blast* code presented in this article.

B. Overpressure Distribution on Building Façade

In this topic, it is shown how the distribution of blast effects in the building façade takes place. The numerical model used a front wall with *6 m* in *x* and *z*. For the discretization, a mesh of 5x5 (cm) was created and the blast loads were calculated on each nodal point. The hemispherical burst was simulated with a charge of 30 kg of TNT, placed on the ground surface at 25 m from the façade (R), as can be seen in Fig. 4.

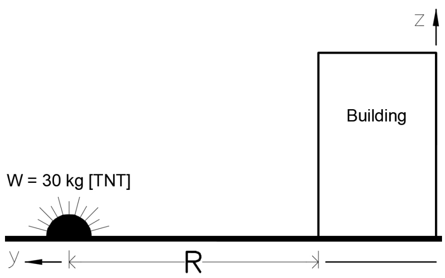


Fig. 4. Model in B-Blast code for blast analysis - Elevation view.

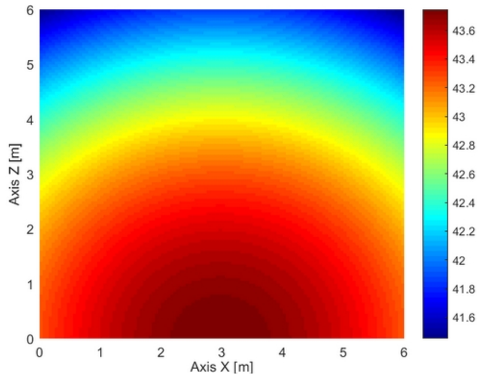
Fig. 5 and 6 shows the results of the distribution of blast loads on the building façade. These results are the principal for design purposes. With these, a finite element analysis can be performed and the stresses and displacements in the structure can be determined.

Table II presents a comparison between the results obtained by the *B-Blast* code and the *ConWep* software.

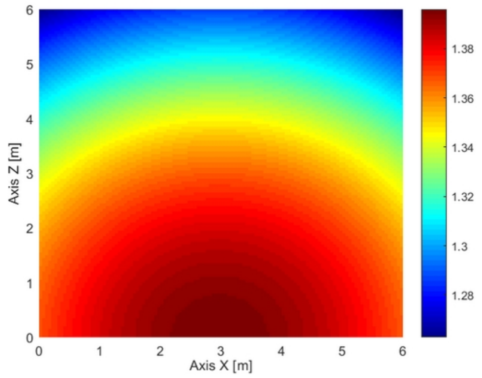
TABLE II. COMPARISON BETWEEN CODE AND SOFTWARE.

	B-Blast	ConWep	$1-\frac{B_B}{ConWep}$
P_r	43.74	43.72	-0.05%
q_O	1.4	1.4	0%
i_r	232.5	232.4	-0.04%
t_A	50.65	50.65	0%
t_O	13.86	13.87	0.07%

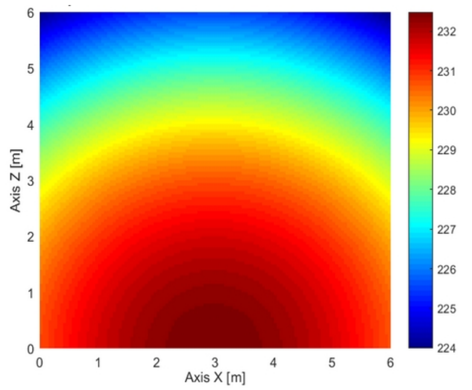
P_r - Normal reflected overpressure ..kPa
q_O - Peak dynamic pressure ……......kPa
i_r - Reflected impulse ……………...kPa*m
t_A - Time of arrival ………….……..msec
t_O - Positive phase duration ….……..msec



a) Overpressure distribution (kPa).

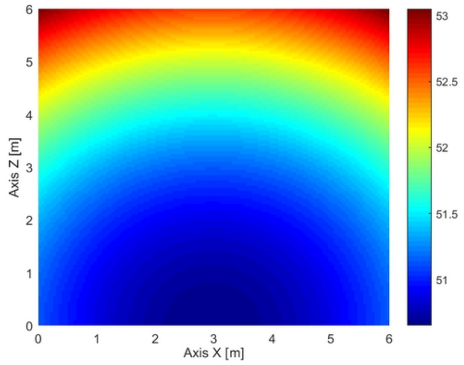


b) Dynamic pressure (kPa).

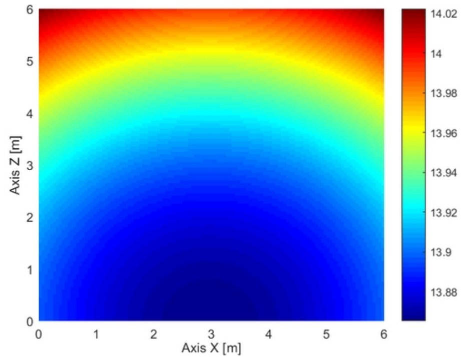


c) Reflected impulse (kPa-msec).

Fig. 5. Blast analysis results for the building façade.



a) Time of arrival (msec).



b) Positive phase duration (msec).

Fig. 6. Times on blast analysis.

The differences between results is very small, and this is due to the fact that the *ConWep* software also uses the *Kingery-Bulmash* equations.

In relation to structural integrity, the level of overpressure suffered by the structure can cause serious damage to steel framed buildings or severe damage to reinforced concrete structures. Still, a probable destruction of the building may occur.

V. Conclusion

In this research, a *MatLab* code named *B-Blast* was presented as a tool for estimating blast loads. This code was based on *Kingery-Bulmash* equations. To evaluate the validity of the results obtained by the code, this article compared the code results with experimental ones and with the *ConWep* software. In both evaluations, the *B-Blast* code presented a good agreement with the comparisons. To date, these results show that the *B-Blast* code can be used to assess explosion scenarios, at least in the academic world.

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