VALIDITY OF BLAST PARAMETERS IN THE NEAR-FIELD

Karlos Vasilis, Solomos George, Larcher Martin
European Commission, Joint Research Centre, Directorate for Space, Security & Migration, Safety & Security of Buildings Unit
Ispra (VA), 21020 Italy
E-mail: vasileios.karlos@ec.europa.eu

1. ABSTRACT

Over the last decades improvised explosive devices (IEDs) have been used by terrorist groups that aim at producing infrastructure damage, victims and disruption in the community. The outcome of such attacks vary depending on a number of factors, such as the amount and type of the explosive, the distance of the detonation centre, the target etc. For the design of structural elements to resist blast-induced loads, the calculation of the blast parameters is essential and is commonly performed with the use of the Kingery-Bulmash technical manual. Even though the proposed parameters have proven adequate for medium and large scaled distances, there exist serious doubts concerning their validity for close-in explosions. As the supporting experimental data are scarce, numerical simulations will be employed, with the FE code EUROPLEXUS, for simulating the evolution of the spherical blast wave through the air. The analysis reveals that the widely utilized Friedlander equation cannot capture adequately the pressure-time history at small scaled distances due to the effect of the expanding detonation products. A new set of equations and corresponding diagrams in terms of scaled distance is proposed that update the Kingery-Bulmash relationships providing enhanced parameter accuracy for points located close to the detonation centre.

2. INTRODUCTION

The response of members under blast induced loads has gained considerable attention over the last years due to the worldwide rise of terrorist attacks, where commonly improvised explosive devices (IEDs) are used for causing damage, casualties and inflicting fear to the public. Examples of such types of attacks are the bombing incidents at the Brussels airport and metro in 2016, the bombing of a police bus in Istanbul in 2016, the London subway attacks in 2005, the train explosions in Madrid in 2004, the Oklahoma City bombing in 1995 etc. A common feature of all these incidents is the large number of victims, as the attacks were performed at places of mass congregation of people.

Looking at the mechanics of an explosion following a detonation, the produced gases expand through the available space forming a blast wave, which is characterized by a number of parameters (overpressure, impulse, arrival time, phase duration, shock wave speed, wavelength etc.). These parameters can be calculated either by relationships and diagrams included in various publically available blast design manuals, or by the use of finite element models. The current article focuses on numerical analyses of explosions by the use of the explicit finite element program EUROPLEXUS [1]. Special attention is given to the estimation of blast parameters at small scaled distances, near the interface between the explosive material and the surrounding air, as several researchers have raised doubts on the validity of the currently used values. A new set of equations is proposed that guarantee increased accuracy in the case of spherical bursts for both incident and reflected blast waves.

3. SIMULATION OF THE BLAST WAVE PROPAGATION BY THE USE OF EUROPLEXUS

3.1 Jones-Wilkins-Lee equation of state

EUROPLEXUS [1] is a finite element program that uses an explicit algorithm for the discretization in time, which makes it suitable for the simulation of explosions. If the examined problem is characterized by spherical symmetry, a re-mapping option is available for transferring the results of a 1D analysis into a finer 2D or 3D analysis [2].

When simulating the expansion of a blast wave through the air with the use of finite elements, an equation of state (EOS) is required to describe the relationship among the variables (pressure, volume, internal energy, temperature etc.). One of the most commonly used equations in case of a solid explosive, is that of Jones-Wilkins-Lee (JWL) [3]. It is expressed by the following equation,

$$P = \mathrm{A}\left(1-\frac{\omega}{R_1 V}\right)e^{-R_1 V} + B\left(1-\frac{\omega}{R_2 V}\right)e^{-R_2 V} + \omega\rho e_{\mathrm{int}} \tag{1}$$

where, P is the pressure [MPa], A, B, R_1, R_2, ω are material constants that can be obtained from experimental data, ρ is the current gas density [kg/m^3], V is the ratio ρ_{sol}/ρ, where ρ_{sol} is the density of the solid explosive, and e_{int} is the internal energy per unit mass.

From Eq. 1 we can conclude that for larger volume ratios V, the first two terms become very small and the equation degenerates into that of an ideal gas (third term). In the current study, the JWL model will be also utilized for modeling the surrounding air, to avoid the use of a multi-material finite element model that may cause numerical instability problems. In the EUROPLEXUS code a standard version of the JWL model has been incorporated, along with the JWLS which is used for modeling the solid TNT. The parameters for both the JWL and JWLS models used in the current study are included in [4].

3.2 Comparison studies

The accuracy of the EUROPLEXUS code and the utilized JWL equation of state was identified through a comparison with the work of Needham [5], who described the evolution of a blast wave in the air by a 1D analysis with a Lagrangian code. Needham utilized the Landau-Stanyukovich-Zeldovitch-Kompaneets [6] equation of state for the solid TNT detonation products and the Doan-Nickel [7] equation of state for the surrounding air. The explosive consisted of 18000kg of TNT with a radius of 1.37m, and the test was similar to a series of experiments that were performed at the Suffield Experimental Station in Alberta, Canada.

The results of Needham were compared with 1D finite element calculations performed in this study, in which frustum-shaped cells were used, whose radius increases linearly with their distance from the detonation centre. The following diagrams show at specific instants the relative overpressure space distribution, calculated by dividing the overpressure values with the ambient pressure at sea level (P_o=101.3kPa). Three different models with constant cell sizes were used (10mm, 5mm and 1mm) resulting in a total number of 4000, 8000 and 40000 elements for the first 40m from the detonation centre. Through these diagrams the creation and propagation of the rarefaction wave can be studied, which is created when the detonation front (still inside the charge) reaches the outer surface of the charge causing the surrounding air to expand and compress. Fig. 1 shows the overpressure distribution when the shock radius has exceeded the charge radius by 60% (1.37*1.6m=2.19m) and by 2500% (1.37*26m=35.62m). The overpressure distribution near the detonation centre (Fig. 1 left) shows that the rarefaction wave has just reached the charge centre, as can be derived from the absence of constant values. Fig.1 [right] shows that the rarefaction wave that moves in the opposite direction to that of the blast front, creates negative overpressures behind the front of the detonation products. The results from the three different finite element models are similar to the ones from Needham when the distance from the centre is over 1.0m, but for smaller distance values, the finer mesh models provide increased accuracy.

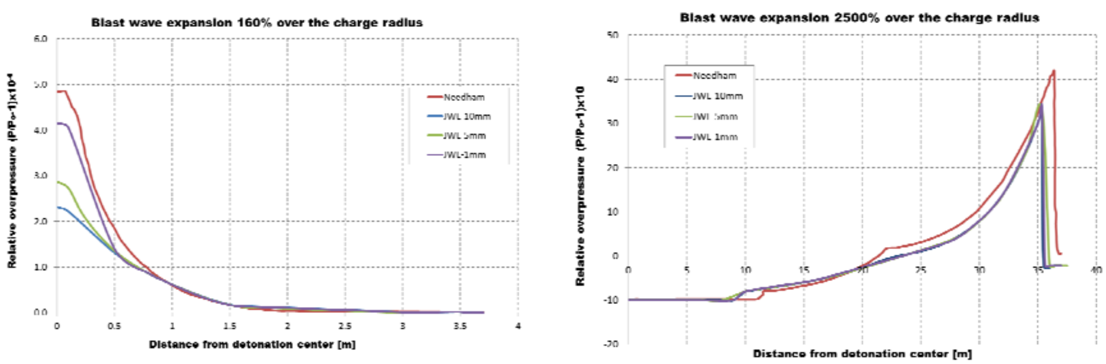

Fig. 1: Relative overpressure values at 0.58ms [left], and at 27.20ms after detonation [right]

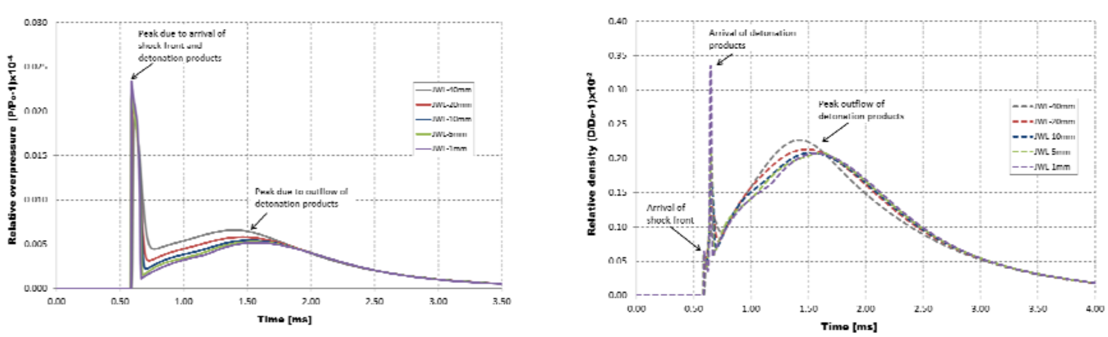

Fig. 2: Relative overpressure [left] and relative density [right] values at 3.56m from charge center for different cell sizes

Alternatively, the propagation of the blast wave though the air can also be displayed in relation to time. Fig. 2 shows the overpressure and density time histories at a point located 3.56m from the charge centre. Five different finite element models with various cell sizes have been used. At the density diagram, one can notice three peaks, which are associated with the arrival of the shock front (first and smallest peak), the arrival of the detonation products (second peak) and the outflow of the detonation products (third and more substantial peak). It is clear, that for small scaled distance values, the overpressure-time history is different from the ideal curve of the Friedlander equation. This is attributed to the expansion of the detonation products that affects the shape of the curve, while at larger distances their effect is less pronounced as they lose a considerable amount of speed and energy.

4. VERIFICATION OF KINGERY-BULMASH DIAGRAMS

4.1 Mesh sensitivity at close range

The behaviour of structural or non-structural elements under blast induced loads depends greatly on the pressure-time history. One of the most widely utilized manuals for the calculation of the main blast parameters is the technical report of Kingery-Bulmash [8], which includes polynomial equations for calculating the blast parameters of both incident and reflected blast waves from spherical and hemispherical bursts. They can be found in the form of diagrams in [9] and their metric version is included in [10].
Studies have shown that the blast parameters proposed in these manuals are sufficiently accurate for medium and large scaled distance values. Nevertheless, at small scaled distances there is noticeable difference between the peak overpressures calculated through the Chapman-Jouguet equations and those through the Kingery-Bulmash curves, as noted by Shin [11]. It should be underlined that for their manual [8], Kingery and Bulmash were based on an extensive database of explosion tests [12-13], the majority of which were performed at large scaled distances, whereas at small scaled distances ($Z<0.4m/kg^{1/3}$) a very limited number of tests were available.
At this section, a mesh sensitivity analysis is performed considering three TNT spherical charges (23kg, 960kg and 18000kg). If the TNT density is equal to $1630kg/m^3$, the radius of each charge is 0.149m, 0.52m and 1.37m, respectively. Fig. 3 shows the space distribution of overpressure at the moment the shock front reaches the face of the corresponding charge. 1D models have been used with element sizes of 0.05mm, 0.1mm, 1mm, 5mm, 10mm, 20mm and 40mm. According to Baker [14], the Chapman-Jouguet detonation pressure of TNT is equal to 21GPa for a packing density of $1630kg/m^3$. As expected, the smaller the cell size during the simulation, the closer the detonation pressure is to that reported by Baker. From the diagrams, it can be derived that the overpressure values practically coincide for scaled distance values greater than $0.07m/kg^{1/3}$ for both examined cases and the steepness of the shock front is also well reproduced.

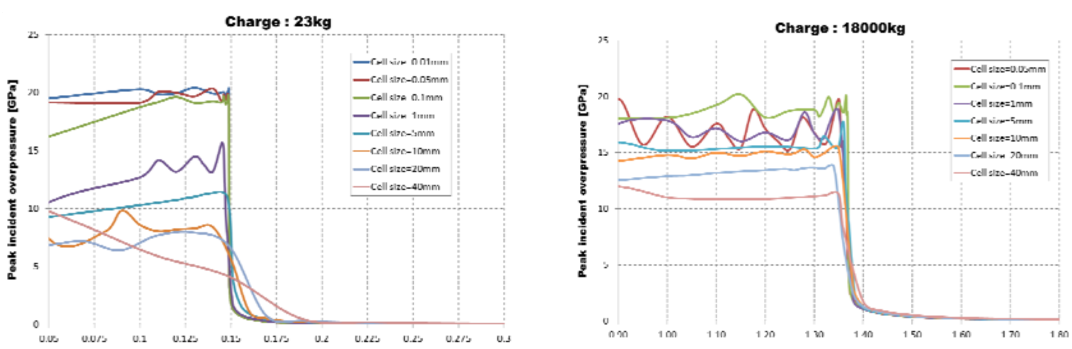

Fig. 3: Incident overpressure distribution when the shock front reaches the face of the 23kg [left] and 18000kg [right] charge

4.2 Comparison to Kingery-Bulmash diagrams

Various simulation studies and experiments [11,15] have shown that at small scaled distances the peak pressure and impulse values appear to be higher compared to those proposed in the Kingery-Bulmash technical report [8], due to complex phenomena, such as the afterburning and the violent outflow of the detonation gases. In this section the results from several 1D EUROPLEXUS simulations are compared with the diagrams included in [10], which are a graphic representation of the Kingery-Bulmash relationships. In particular the above three TNT charges of 23kg, 960kg and 18000kg are used. The results from all three of them coincide and show that for scaled distance values less than 0.25m/kg$^{1/3}$ the calculated peak overpressure and positive impulse values are much larger than the ones proposed in [10]. Fig. 4 shows the incident and reflected blast wave parameters of the positive phase of a spherical wave due to a free-air burst as included in [10], but with the addition of the new curves that were calculated through fitting of the EUROPLEXUS simulation results, denoted as "epx".

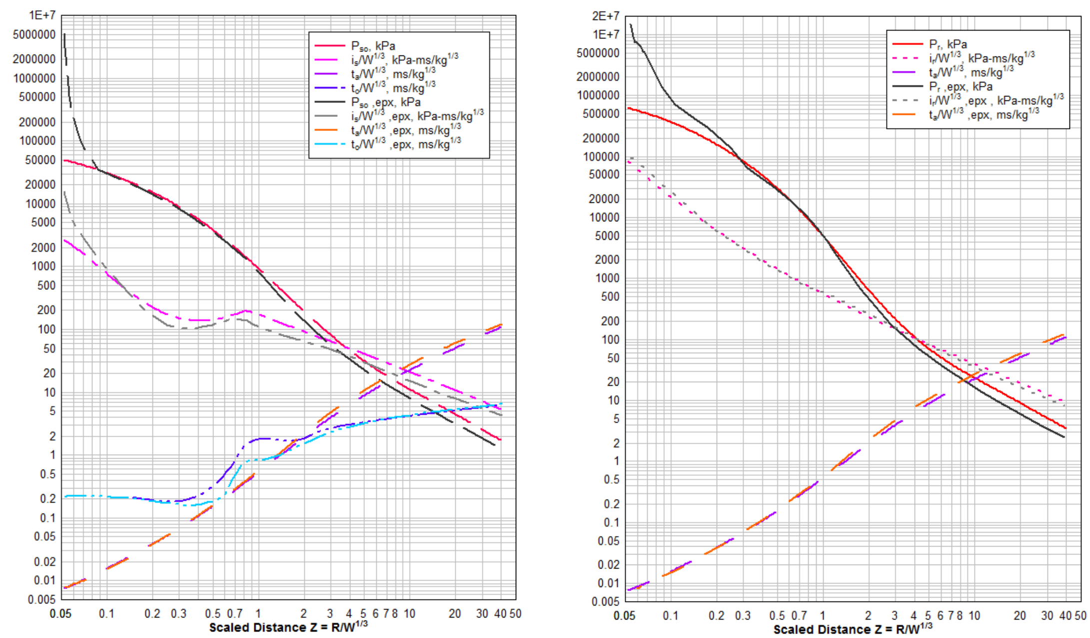

Fig. 4: Additional incident [left] and reflected [right] parameter curves of positive phase of shock spherical wave of TNT charges from free-air bursts

5. NUMERICAL APPLICATION

The response of a steel section subjected to an explosion will be examined by utilizing the blast parameters of Fig.4. The profile is a 2.4m long steel rectangular hollow section (400x200mm) with thickness equal to 16mm, simply supported at its extremities. The detonation point was considered in such a way so that the smaller side faced the blast load (bending about the strong axis). The charge consists of 300kg of TNT placed at a stand-off distance equal to 1.4m and a height of 1.2m (Z varies from 0.21m/kg$^{1/3}$ at the middle of the beam to 0.27m/kg$^{1/3}$ at its ends). Only the positive phase of the blast wave is taken into consideration and the side of the steel section is treated as an infinite surface during the application of the blast loads. The first natural period of the member corresponding to flexural vibration in the strong axis is equal to 5ms, which is close to the positive phase duration of the blast (1.35ms). This means that the response of the steel section will be governed by both the blast peak overpressure and impulse.

The response of the steel section was numerically simulated using EUROPLEXUS [1]. The rectangular hollow section was geometrically modelled employing three-dimensional shell elements of maxiumum size equal to 2cm. The Lagrangian description was used and the total analysis time was set to 15ms to evaluate the behaviour of the members over a relatively large period of time. The time step was kept equal to $10x10^{-7}$ms, as this provided good accuracy of the derived results. The effect of high strain rates on the material strength was taken into account by using the Johnson-Cook constitutive equation [16], which considers that the material flow stress is influenced independently by the temperature, the loading speed and the strain hardening. In the current analysis, the equation constants proposed by Jones [17] were utilized and the steel strength was taken equal to σ_y=355MPa.

Fig. 5 shows the deformed shape and the mid-span response of the steel member. The deflection at mid-span has been calculated both according to the Kingery-Bulmash relationships and the new equations that were graphically presented in Fig. 4. For the considered scaled distances (0.21-0.27m/kg$^{1/3}$) the reflected impulse is approximately the same in both approaches. However, the maximum blast pressure proposed herein is 35% higher than that proposed by the Kingery-Bulmash manual, which leads to mid-span displacements that are almost 10% higher, as seen in Fig. 5. In blast design, yielding is not excluded in order to avoid extremely large member sections, which means that for small scaled distances the parameters of the blast wave should always be treated with conservatism as they might be underestimated thus leading to imprecise results of the expected component behaviour.

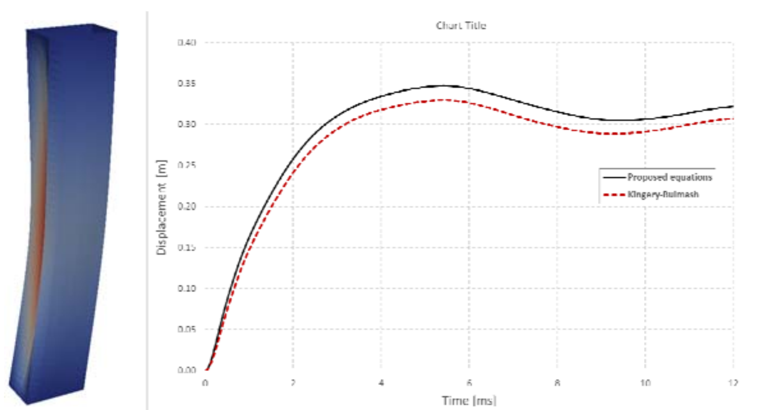

Fig. 5: Displacements at mid-span of beam section

6. CONCLUSIONS

This study aimed at investigating and confirming the blast parameter values at small scaled distances through the use of the explicit finite element code EUROPLEXUS. Comparisons with the simulation results showed that the incident and reflected spherical blast wave equations proposed by Kingery-Bulmash, give positive impulse and peak pressure values much smaller than the numerically derived ones if the scaled distance is smaller than 0.25m/kg$^{1/3}$. When the scaled distance is larger, the differences are much smaller. From the analysis results, a new set of equations was produced that is graphically presented in the form of diagrams similar to the ones presented in the Kingery-Bulmash manual. These results can be important in calculating with improved accuracy the blast parameters due to an explosion and quantitatively assessing the effects of the blast on a structure or structural element, as shown through the illustrative example. Nevertheless, it is reminded that the blast phenomenon is extremely complex and there exist many factors that could affect its characteristics, such as the explosive type, the afterburning effect, the environmental conditions etc.

7. REFERENCES

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1. ΠΕΡΙΛΗΨΗ

Τις τελευταίες δεκαετίες αυτοσχέδιοι εκρηκτικοί μηχανισμοί έχουν χρησιμοποιηθεί από τρομοκρατικές ομάδες που στοχεύουν στην πρόκληση καταστροφών στις κτιριακές υποδομές, τη δημιουργιά θυμάτων και την κοινωνική αναστάτωση. Το αποτέλεσμα αυτών των επιθέσεων εξαρτάται από διάφορους παράγοντες, όπως είναι ο τύπος και η ποσότητα των εκρηκτικών, η απόσταση από το σημείο της εκπυσοκρότησης, ο στόχος κλπ. Κατά το σχεδιασμό κατασκευαστικών στοιχείων υπό φορτία έκρηξης, ο υπολογισμός των παραμέτρων της έκρηξης είναι απαραίτητος και συνήθως πραγματοποιείται σύμφωνα με το τεχνικό εγχειρίδιο των Kingery-Bulmash. Παρά το γεγονός ότι οι προτεινόμενες παράμετροι της έκρηξης είναι επαρκείς για μεσαίες και μεγάλες σχετικές αποστάσεις, υπάρχουν αμφιβολίες σχετικά με την εγκυρότητά τους σε εκρήξεις κοντινού πεδίου. Καθώς τα πειραματικά αποτελέσματα από τα οποία έχουν προκύψει τα διαγράμματα των Kingery-Bulmash είναι λιγοστά, στο παρόν άρθρο πραγματοποιούνται αριθμητικές αναλύσεις το με πρόγραμμα EUROPLEXUS οι οποίες προσομοιώνουν την ανάπτυξη ενός σφαιρικού κύματος διαμέσου του αέρα. Η ανάλυση καταδεικνύει ότι η ευρέως χρησιμοποιούμενη εξίσωση του Friedlander δεν καταφέρνει να αποτυπώσει με ακρίβεια την χρονοιστορία των πιέσεων σε μικρές σχετικές αποστάσεις, εξαιτίας των διαστελλόμενων υλικών της εκπυσοκρότησης. Στο παρόν άρθρο προτείνονται νέες εξισώσεις, οι οποίες εξαρτώνται από την σχετική απόσταση και είναι παρόμοιες με τις εξισώσεις των Kingery-Bulmash, και οι οποίες εγκυώνται ενισχυμένη ακρίβεια για σημεία που βρίσκονται κοντά στο επίκεντρο της έκρηξης.