Analysis of the Explosive Internal Impact on the Barriers of Building Structures

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Abstract. Work issues concern the safety of construction in relation to the hazards arising from explosion of the explosive charge located inside the building. The algorithms proposed in the paper for determining the parameters of the overpressure wave resulting from the detonation of clustered explosive charges, determine the basis for numerical simulation analyzes. Determination of the maximum value of peak pressure on the wave forehead of an internal explosion is presented on the basis of reflected wave analysis. Changeability in time of the internal explosion action describes the overpressure phase only. The analysis of the load caused by the internal explosive charge detonation was carried out under conditions of the undisturbed standard atmosphere. A load determination algorithm has been developed, taking into account the geometrical characteristics of the building barriers and the rooms as well as the parameters of environment in which the detonation occurs. The way of taking into account the influence of venting surfaces, i.e. windows, doors, ventilation ducts, on the overpressure wave parameters, was presented. Discloses a method to take into account the effect of the surface relief, i.e. windows, doors, air ducts, pressure wave parameters. Modification of the method for explosive overpressure determination presented by Cormie, Smith, Mays (2009), was proposed in the paper. This modification was developed on the basis of substitute impulse analysis for multiple overpressure pulses. In order to take into account the pressure distribution of explosive gases on the barrier surface, the method of modification the relationship for determination the changeability over time and space of the pressure of explosive gases, was presented. For this purpose, the changeability of the pressure wave angles of incidence to the barrier and the distance of the explosive charge to any point on the surface of the barrier, was taken into account. Based on the developed procedure, the overpressure changeability over time was determined for selected measurement points of the reference room. A comparative analysis of the determined loadings with experimental results and theoretical results of other authors, taken from the original work of Weerhiejm et al. (2012), was carried out.

1. Introduction

The paper presents the issues concerning the determination of pressure wave formed by the explosion of explosive charge situated on the inside of a building. The most common methods for determining internal explosive loads in the analytical way are the methods of Kinney (1985) [1], Włodarczyk (1994) [2], as well as the newer one of Cormie, Smith, Mays (2009) [3]. Another manner of loading calculation is to use software for determining the explosive load, e.g. SBEDS (Single-degree-of-freedom Blast Effects Design Spreadsheet), which was used among others in the paper of Zapata and Weggel (2008) [4]. Note, however, that this software uses a method of Single Degree of Freedom (SDoF), which is an analytical method. Similar software of this type are the calculating processors for explosive load
included in programs of finite element method LS-DYNA - which was used eq. by He, Chen and Guo (2011) [5] in the analysis of behaviour of subway station structure, and Abaqus - which was used eq. by Wu et al. (2015) [6] in the analysis of tunnel structure. In the literature, there is commonly known the analysis of the action of internal explosions in the tunnels constructions, in which are not taken into account the vented surfaces: Bulson (1997) [7], Feldgun al. (2008) [8], Tiwari et al. (2014) [9], Wu et al. (2015) [10]. There are also known the studies on the analysis of the impact of the internal explosion of gas - air mixtures on the buildings structures Chyży (2009) [11]. In the works of Siwiński and Stolarski (2015) [12] the analysis of the action of the internal explosion on the rigid building barriers, were presented. Some new numerical method of numerical analysis of the phenomenon of the air shock wave propagation was presented in the work of Lidner, Szczęśniak [13]. In this method the changes in energy due to heat transfer with conservation of linear heat transfer were considered. Values of impulse, pressure, and its duration were studied in details.

This paper presents the phenomenological approach of method for determining the load on the rigid barrier constructions from the explosion of explosive charges located outside and inside the structure. The aim of the work is to develop the algorithms for determining the characteristics of the action of internal explosion, generalized on the basis of procedures known in the literature as well as the analysis of the influence of variable explosion parameters on the function of load changes over time. The second aim is modification of the formula taken from paper of Cormie, Smith, Mays (2009) [3] and comparison of obtained results with the numerical simulation and the experimental data. The formulas in the analytical methods for determination of explosive loads were used in simulation of the building behaviour in paper of Siwiński and Stolarski (2016) [14]. The study includes the examples of calculating the load parameters from the detonation of TNT on internal barriers of the building structures, with taking into account the shape and proportions of the geometrical dimensions of the rooms and the occurrence of vented surfaces that reduce the overpressure. The examples of determining the explosive load on the barrier structures from the detonation of the explosive charge were developed taking into account the following simplifying assumptions consisting in: (1) the use of approximate formulas, (2) treating the building barrier as the separated object to be acted upon only the load from the explosive charge, (3) considering the influence of the loading waves reflected from the opposite or adjacent barriers in the room.

2. Parameters of internal explosion

2.1. General characteristics

Considerations on the effects of the impact of the explosion inside the building structures are closely related to the way to take into account the so-called vented surfaces. In case of the absence of vented surface the structure must take a greater load than in case of its presence. Considering that vented surface allows the pressure reduction, as a result of e.g. the breaking away the windows and doors, partition walls, the covers of the inlets of ventilation ducts, or the opening of special vented devices. The application of vented surfaces for pressure reduction in buildings may be advantageous to protect the structure from the accumulation of potentially harmful gas pressure after explosion. However, for the protection of personnel inside of the building, the use of vented surface is not always beneficial because the greatest losses will be first of all substantially associated only with the initial phase of the shock wave action, even before the opening of vented surface. Considerations concerning the action of the internal explosion is presented based on the analysis of the reflected waves. Detonation of condensed explosive materials in the inner rooms of building structures is carried out in two phases, Cormie, Smith and Mays (2009) [3]. The first phase determines the impact of the shock wave. In the second phase, the initial pressure wave is remapped by a few pulses due to repeated processes of waves reflection from the barriers located in the relatively small distances. The pressure variations usually occur by overlapping of the succeeding pressure amplitudes. The reflecting shock waves – i.e. Mach’s waves - cause an increase the pressure inside the structure. This phenomenon is called as the post-explosive gas pressure.
2.2. Variability of the reflected waves overpressure in time

Values of the initial pressure parameter of the shock wave are relatively easy to determine, Hetherington and Smith (1994) [15]. However, quantification of the parameters in case of wave re-reflection is generally more difficult, in particular if Mach’s waves are repeatedly generated. Basically, it is then necessary the approximate determination of the internal pressure as a function in time by idealizing the shock pulses as a series of the successive, diminishing, of jumping type pulses of pressure (i.e. without the phase of gradual growth of pressure), figure 1.

\[ p_{r2} = \frac{1}{2} p_{r1} , \quad p_{r3} = \frac{1}{2} p_{r2} = \frac{1}{4} p_{r1} , \quad p_{r4} = 0 . \]  \( (1) \)

The similar relationships for overpressure pulse of successive reflected waves are applicable:

\[ l_{r2} = \frac{1}{2} l_{r1} , \quad l_{r3} = \frac{1}{2} l_{r2} = \frac{1}{4} l_{r1} , \quad l_{r4} = 0 . \]  \( (2) \)

In equation 1, the value of pressure of the first reflected wave \( p_{r1} \) can be determined on the basis of an appropriate Sachs expression as equal:

\[ p_{r1} = \Delta p_{ref} , \]  \( (3) \)

where: \( \Delta p_{ref} \) – is the overpressure value on the forehead of the reflected wave according to the formula:

\[ \Delta p_{ref} = 2 \Delta p^+ + \frac{6 \Delta p^+^2}{\Delta p^+ + 7 p_0} . \]  \( (4) \)

In equation (4), the overpressure value \( \Delta p^+ \) on the pressure wave forehead can be determined on the basis of the second Sachs variable:

\[ \Delta p^+ = p_0 \cdot p_s , \]  \( (5) \)
where: \( p_0 \) – is the initial pressure equivalent to the atmospheric pressure, and \( p_s \) – is the dimensionless pressure.

Detailed descriptions of the dimensionless pressure \( p_s \) formulas are presented in the paper of Siwiński and Stolarski (2015) [17].

The assumptions defined by relationships (1) and (2) are not fully compatible with the experimental results of Baker and Cox (1983) [2] because in fact the next impulses will be weaker and the waves will propagate slower than the first one.

The time \( t_d \), defined in figure 4, is assumed as the substitute time duration of each overpressure impulse equal to:

\[
t_d = \tau^+, \quad (6)
\]

where: \( \tau^+ \) – is the time duration of the load depending on the zone in which the explosive load exists and its value can be determined on the basis of formulas presented in paper of Siwiński and Stolarski (2015) [19].

The reflection time \( t_r \), referred to as the time delay between each successive shock wave arriving at the surface of the structure, is assumed to be constant:

\[
t_r = 2t_a, \quad (7)
\]

where: \( t_a \) – is the arrival time of the first shock wave to the reflecting surface.

To determine the arrival time of the first shock wave to the reflecting surface, the following relationship is used:

\[
t_a = \frac{r}{D}, \quad (8)
\]

where: \( r \) – is the distance of the explosive charge load from the load point, \( D \) – is the speed on the forehead of the shock wave determined by the relationship of Krzewiński (1982) [18]:

\[
D = \sqrt{\alpha_0^2 + \frac{\Delta \rho (\alpha_0 + 1)}{2 \rho}}, \quad (9)
\]

where: \( \alpha_0 \) – is the coefficient depending on the heat of explosion \( Q \), which according to Krzewiński (1982) [18] should be taken within the range of <1.2, 1.4>, \( \rho \) – is the density of the medium in which the explosive charge detonates; for the air medium \( \rho = 1.227 \text{ kg/m}^3 \).

### 2.3. Pressure venting and variability of substitute pressure in time

The phenomenon of the formation of multiple reflected waves can be presented in the form of a substitute pressure pulse of post explosive gas. The parameters of this substitute pressure pulse depend on the size of the room, the size of all the venting surfaces in the room, and the properties of the explosive materials. A typical pressure distribution in time for the exemplary construction with the venting surfaces is shown in figure 5, Cormie, Mays and Smith (2009) [3].

In figure 2 can be seen a series of reflected waves (approximately the first three dominant), confirming the correctness of the interaction model of development the post explosive pressure described by idealization according to figure 1 and by relationships (1) or (2).
Figure 2. Overpressure of reflected waves over time

In case when the response time $t_f$ of the loaded structure is much longer than the total load duration $t_k$ determined by the relationship:

$$t_k = (5t_a + t_d),$$

then according to Baker's proposal, one can assume that all three pulses can be replaced by a single, substitute impulse:

$$i_{rT} = i_{r1} + i_{r2} + i_{r3} = 1.75i_{r1},$$

with the total peak pressure determined according to the Cormie, Smith and Mays (2009) [3] relationship:

$$p_{QS} = 1.75p_{r1}.$$  \(12\)

However, the more general form of Baker's proposal results from on the assumption that any number of $N_r$ reflected pulses can be replaced by a single, substitute impulse with the total peak pressure determined according to the relationship:

$$p_{QS} = 2(1 - 2^{-N_r})\frac{t_d}{2(N_r-1)t_a + t_d}p_{r1}.$$  \(13\)

Then one can obtain the peak pressure for different numbers of reflected pulses:

| $N_r$ | $p_{QS}$  |
|------|-----------|
| 1    | $p_{r1}$  |
| 3    | $1.75\frac{t_d}{4t_a + t_d}p_{r1}$ |
| 5    | $1.9375\frac{t_d}{8t_a + t_d}p_{r1}$ |

Baker and Cox (1983) [16] presented an approach that allows for quantification of the most important parameters of pressure over time diagram using the approximate formula of pressure description. The equation approximating the actual graph of pressure distribution over time describes the relation:

$$p(t) = (p_{QS} + p_0)e^{-2.13t}.$$  \(14\)
In this equation the most important role plays the parameter $\tau$ – as a dimensionless time modifier, defined by:

$$\tau = \frac{a_e A_s a_0}{V} t,$$

(15)

where in: $a_e = \frac{A_U}{A_P}$ is the ratio of all venting surfaces $A_U$ to the inner surface of the considered barrier in the room $A_P$, $A_S = \sum A_P$ – is the total surface of the barriers surrounding the room in which the explosion occurred, $V$ – is the cubage of the room where the explosion occurred, $a_0$ - is the speed of sound at ambient conditions, $t$ – is the time over the period duration of the substitute explosive action $< 0$, $t_k$ > in which the overpressure value is determined.

The experimental results conducted by Weibull (1968) [19] on the determination of overpressure peak value at the internal explosion, overpressure time duration, and total overpressure impulse, according to Cormie Smith and Mays (2009) [3], show a high convergence with the results obtained from the approximate formula (14).

3. Analysis of load from the detonation of internal charge

The analysis of the load caused by the internal explosive charge detonation was carried out under conditions of the undisturbed standard atmosphere (ISA). Figure 3 shows a scheme of the room as well as the location of the charge and the pressure sensors on the inner side of the building barriers.

![Figure 3. Scheme of the room, location of the charge and the pressure sensors](image)

Based on the developed procedure, the overpressure changeability over time was determined for selected measurement points P5 as well as P4 and P6 inside the reference room, taken from the original work of Weerheijm et al. [20]. Figure 4 shows the results for point P5. The result of the experimental studies [20] is marked in white colour, while in the red colour the result obtained according to the developed procedure for the mass of 6.9 kg TNT is described.

Figure 5 shows comparison of the author’s results obtained with the proposed formula (13) for $N_r = 3$ reflected pulses and of the Cormie, Mays, Smith results obtained with the formula (12), in the diagram of the pressure changeability over time at the P5 point. The pressure peak value of author’s results is slightly less than 3 times in relation to the Cormie, Mays, Smith results, and shows very good accordance with the experimental results [20].
Figure 4. Pressure changeability over time at the P5 point

Figure 5. Comparison author’s results (13) and Cormie, Mays, Smith results (12) for the pressure changeability over time at the P5 point

In turn, in figure 6 and figure 7 the results for the points P4 and P6 are shown in the analogous manner. We can also observe a large discrepancy between the author’s results (13) and Cormie, Mays, Smith results (12); now the pressure peak value of author’s results are slightly larger than 3 times in relation to the Cormie, Mays and Smith results, but also shows very good accordance with the experimental results [20].
4. Distribution of explosion pressure on the surface of barrier
In order to take into account the pressure distribution of the explosive gases on the surface of the barrier, the relationship for determination of pressure variability in space should be modified by taking into account the variable incidence angles of pressure wave at the barrier, Poneta, Stolarski et al. [21]:

![Figure 6. Pressure changeability over time at the P4 and P6 points](image)

![Figure 7. Comparison of author’s results (13) and Cormie, Mays, Smith results (12) for the pressure changeability over time at the P4 and P6 points](image)
\[ \Delta p_{ref}^{VH} = \Delta p_{ref} \cdot \cos^2 \alpha_V \cdot \cos^2 \alpha_H \]  \hspace{1cm} (14)

where: \( \Delta p_{ref}^{VH} \) – is the overpressure at the forehead of the reflected wave at the distance of \( x \) in the horizontal direction and in height of \( z \) in the vertical direction from the intersection of the normal axis with the partition according to figure 8, \( \Delta p_{ref} \) – is the basic value of overpressure on the forehead of the reflected wave front specified by the relationship (4), \( \alpha_V = \arctg \frac{x}{y} \), \( \alpha_H = \arctg \frac{z}{y} \) – are the corresponding wave incidence angles according to figure 6.

**Figure 8.** Scheme of the location of the explosive charge in relation to any point on the surface of the barrier

5. Conclusions

The paper presents a procedure that allows the simplified determination of explosive wave parameters as a result of the internal explosion. As a result of the analysis of determination method for pressure wave parameters, the modifications of the formula for peak pressure value developed in the work of Cormi, Mays and Smith, was proposed. This modification makes it possible to obtain a large convergence of the obtained results with the results of the experiment carried out by Weerheijm et al., [19].

References

[1] G. F. Kinney “Explosive shocks in air”, Springer Science + Business Media, New York, 1985.
[2] E. Włodarczyk, “Introduction to explosive mechanics”, PWN, Warsaw, 1994, (in Polish).
[3] D. Cormie, P. Smith and G. Mays, “Blast effect on buildings”, Cranfield University at the Defence Academy of the United Kingdom, London, 2009.
[4] B. Zapata, D. Weggel, “Collapse study of an unreinforced masonr y bearing wall building subjected to internal blast loading”, *Journal of performance of constructed facilities* vol. 22(2), pp. 92-100, 2008.
[5] W. He, J. Chen, J. Guo., “Dynamic analysis of subway station subjected to internal blast loading”, *Journal of Central South University Technology*, vol. 18, pp. 917-924, Springer, 2011.
[6] D. Wu, B. Guo, Y. Shen, J. Zhou., G. Chen, “Damage evolution of tunnel portal during the longitudinal propagation of Rayleigh waves”, 75, 2519-2543, Springer, Dordrecht, 2015.
[7] P. S. Bulson, “Explosive loading of engineering structures”, Taylor & Francis, London and New York, 1997.
[8] V. R. Feldgun, A. V. Kochetkov, Y. S. Karinski, D. Z. Yankelevsky, “Internal blast loading in a buried lined tunnel”, International Journal of Impact Engineering, Elsevier, vol. 35, pp. 172-183, 2008.
[9] R. Tiwari, T. Chakraborty, V. Matsagar, “Dynamic analysis of underground tunnels subjected to internal blast loading”. World Congress of computational Mechanics (WCCM XI), Barcelona, 2014.
[10] T. Chyży, ”Method of the residential buildings analysis with overpressure load in the zone of the internal gas explosion”, Białystok University of Technology Publisher, Białystok, 2009, (in Polish).
[11] J. Siwiński, A. Stolarski, “Analysis of the internal explosion affecting building barriers”. Bulletin of MUT, vol. LXIV, nr 2, pp. 197-211, Warsaw, 2015, (in Polish).
[12] M. Lidner, Z. Szczęśniak, ”Numerical Analysis of Blast Load from Explosive Materials Using Finite Volume Method”, Key Engineering Materials, vol. 723, pp. 789-794, 2017.
[13] J. Siwiński, A. Stolarski. Modeling of buildings behaviour under blast load, 341-351; in: Dynamical Systems: Modelling, Springer Proceedings in Mathematics & Statistics, vol. 181, DOI 10.1007/978-3-319-42402-6_27, J. Awrejcewicz (ed.), Springer International Publishing Switzerland 2016.
[14] P.D. Smith, J.D. Hetherington, ”Blast and ballistic loading of structures”, Butterworth-Heinemann, 1994.
[15] W. E. Baker, P. A. Cox, P. S. Weslina, J. J. Kulesz, R. A. Strehlow, ”Explosion Hazards and Evaluation”, Elsevier Scientific Publ. comp., Amsterdam - Oxford - New York, 1983.
[16] J. Siwiński, A. Stolarski, ”Analysis of the external explosion affecting building barriers”. Bulletin of MUT, vol. LXIV, nr 2, pp. 197-211, Warsaw, 2015, (in Polish).
[17] R. Krzewiński, ”Explosive dynamic, Part I – Method of the load determining. MUT, Warsaw, 1982, Part II – Action of explosion in the inertial environments, MUT, Warsaw, 1983, (in Polish).
[18] H. R. W. Weibull, ”Pressure recorded in partially closed chambers at explosion of TNT charges”. Annals of the New York Academy of Sciences. 152 (Article 1), pp. 357-361. New York, 1968.
[19] J. Weerheijm, A. Stolz, W. Riedel, J. Mediavilla Varas, ”Modelling loading and break-up of RC structure due to internal explosion of fragmenting shells”. Proceedings 22nd MABS - Military Aspects of Blast and Shock, Bourges, France, 4-9 November, Paper 76 (20 p.), 2012.
[20] P. Poneta, A. Giluń, J. Jurczuk, P. Świeżewski, A. Stolarski, G. Bąk, T. Błażejewicz, R. Krzewiński, S. Onopiuk, R. Rekucki, Z. Szczęśniak, Research of the reinforced concrete elements laminates strengthened under blast load. Part I: Description of the research program and study of the composit material, Bulletin of MUT, vol. LX, 4(664), pp. 41-77, 2011, (in Polish).