Estimation of building safety under explosion

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Explosions generate pressure waves that first load and then damage structural elements. There are dangerous for construction and first of all for personnel safety. Usually, this phenomenon is caused by terrorist scenario or unintentional detonation of condensed charge or gas mixture. This work undertakes a study of pressure propagation inside office area after an explosion in the plant room. The main results are marked on the section plan and show public safety zones in agreement with U.S. standards [1]. The calculations are carried out in the environment of finite element code Abaqus/Explicit.

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Introduction

The history of research concerning explosions dates back to the 10th century. This event deals with the military purpose of a gunpowder chemical explosive in China. Moreover, the first explosion used for industrial application was recorded about six hundred years later, that is in XVII century where the explosives were used for rock blasting in Hungary ore mines. The use of more powered charges as the nuclear one, was transferred really faster from the military to industrial field, than for chemical explosives. In a half century after first nuclear explosion in Hiroshima and Nagasaki in 1945, there
exist about five hundred nuclear power plants on the world. Nowadays, the explosive energy is widely used for all industrial fields, like rock blasting, sheet-metal forming, fast coupling of composite phases or producing electricity. For each of the used examples the safety of structures under explosion must be widely concerned.

Current design style is improved by some government agencies which deal with missing parts (i.e. columns, walls etc.) of the structure scenario. In particular, this approach makes really sense for buildings subjected to the impact and blast loadings. The headquarters like embassies, banks, skyscrapers, hotels and others are very concerned about the possibility of this kind of loading. Nowadays, the fundamental threat is connected with terrorism and it may involve a combination of thermal, impact and explosive loads. There exist much well-known examples of terrorist activity. The one spectacular of September 11 in 2001 has served to highlight the vulnerability of existing structures to terrorist attack in the United States. The politicians also aware of the consequences of an effective attack on government facilities and other related targets. Many of these buildings are historical, with ornate meaning, constructed using traditional techniques with masonry elevations like an attacked in 2008 on of the Bombay hotels. Nevertheless, the crucial goal for designers is the willingness to obtain a reliable structure safety for public. For this purpose, the paper concerns only the problem of public safety inside some engineering structure.

The area of office rooms is taken into account. This area covers 30 by 60 meters of one floor. The sketch of the floor section is presented in Fig.1. Assume that the explosion can take place in the plant room p1. This room is 8 by 6 meters, and is 3.5 meters high. The explosive risk is propane detonation, with properties according real parameters. There is assumed that before detonation the propane concentration in the air equals 56/44 in the plant room. The model of the geometry is prepared according to Fig.1. The full 3D model includes the boundary conditions, for which the velocity components are fixed specially for each wall disregarding the windows. Because of the authors will to find the most risk scenario, it is assumed that the walls remain rigid. The detonation point is located in the centre of the room p1. The initial conditions have a crucial role for the analysis of this phenomenon, and include among others a specific energy and an ambient pressure. The model has in total 4.8e6 finite elements, and for each element the pressure value as a function of time is obtained.

As a result, the maps which show the pressure distribution in the neighbouring rooms are presented in the next sections.

The numerical model which describes the blast model in a gas medium is formulated in Euler description, for better understanding see Eq.1 for two dimensional space [3].
\[
\begin{bmatrix}
\rho \\
\rho u \\
\rho v \\
\rho (e + \frac{u^2}{2}) \\
\rho u \\
\rho v \\
\rho (e + \frac{u^2}{2}) + p \\
\rho u \\
\rho v \\
\rho (e + \frac{u^2}{2}) + p \\
\rho u \\
\rho v \\
\rho (e + \frac{u^2}{2}) + p
\end{bmatrix}
+ \begin{bmatrix}
\rho u \\
\rho v \\
\rho (e + \frac{u^2}{2}) + p \\
\rho u \\
\rho v \\
\rho (e + \frac{u^2}{2}) + p \\
\rho u \\
\rho v \\
\rho (e + \frac{u^2}{2}) + p \\
\rho u \\
\rho v \\
\rho (e + \frac{u^2}{2}) + p
\end{bmatrix}
+ \frac{1}{r} \begin{bmatrix}
\rho u \\
\rho v \\
\rho (e + \frac{u^2}{2}) + p \\
\rho u \\
\rho v \\
\rho (e + \frac{u^2}{2}) + p \\
\rho u \\
\rho v \\
\rho (e + \frac{u^2}{2}) + p \\
\rho u \\
\rho v \\
\rho (e + \frac{u^2}{2}) + p
\end{bmatrix}
= \begin{bmatrix}
0 \\
0 \\
0 \\
0 \\
0 \\
0 \\
0 \\
0 \\
0 \\
0 \\
0 \\
0
\end{bmatrix}
\]

Where, the first two rows represent the mathematical formulation of mass and momentum conservation laws. The third part is responsible for adiabatic conditions, and the last one for the density distribution in disturb medium. The equation system is transparently derived e.g. by Krzewiński [4]. Moreover, \( p \) means the pressure in the air, \( \rho \) is the air density; \( u \) and \( v \) are two components of particle velocity. The term with specific energy \( e \) is responsible for the start of the process and it depends on a type of charge. The full three dimensional system with additional velocity component \( w \) is solved by Henrych in [3].

**Safety criteria**

This section elucidates different technical manuals for blast resistant design purpose. The most of them are connected with high speed impact and military area, where much higher strain rates are taken into account. The most popular is TM5-1300/UFC3-340-02 [1]. This paper is widely used in publications. The manual includes detailed processes for designing structures, equipment and specially personnel area to prevent of explosion effect. After presentation of pressure values for different combinations of surrounded area i.e. free field, ground reflection, obstacles etc., there are also presented the principals on dynamic analysis and steel, masonry and concrete tolerances. Nearly two thousand pages mean a guideline for windows and doors in addition. There exist also UFC3-340-01 [12] version, but there is viewable only for government agencies and contractors. The another one DOE/TIC-11268 [8] manual provides designer guidance for the prediction of the air blast, ground shock and fragment loadings on structures as a result of accidental explosions in or near those structures. The next one manual ESL-87-57 [9] presents the full structures protection methods especially for non-nuclear weapon effects. The paper demands the basic engineering knowledge of explosion and structural dynamics. The information about material hardened are also included. The paper TM5-855-1 [10] shows the information for protective buildings in general. The Design and Analysis of Hardened Structures to Conventional Weapons Effects [12] is written by more than two hundred experts, and it includes the same design area like [1]. The report Structural Design for Physical Security [7] is prepared especially for civilian architects, who try to obtain the most safety urbanised arrangement. The specification for any building under terrorist threats is presented in [11]. Where, the tables show many restrictions for minimum building distances in example, and damage levels for different structures. The proper design process for predicting the explosion effect demands the using of the above principles.

<table>
<thead>
<tr>
<th>Software</th>
<th>Analysis Type</th>
<th>Author</th>
</tr>
</thead>
<tbody>
<tr>
<td>AIR3D</td>
<td>blast prediction, CFD</td>
<td>Royal Military of Science College</td>
</tr>
<tr>
<td>ALE3D</td>
<td>couple analysis</td>
<td>Lawrence Livermore National Laboratory</td>
</tr>
<tr>
<td>AUTODYN</td>
<td>structural response, CFD</td>
<td>Century Dynamics</td>
</tr>
<tr>
<td>BLASTX</td>
<td>blast prediction, CFD</td>
<td>SAIC</td>
</tr>
<tr>
<td>CONWEP</td>
<td>blast prediction, empirical</td>
<td>US Army Waterways Experiment Solutions</td>
</tr>
<tr>
<td>CTH</td>
<td>blast prediction, CFD</td>
<td>Sandia National Laboratories</td>
</tr>
<tr>
<td>DYNAP</td>
<td>structural response, CFD</td>
<td>Lawrence Livermore National Laboratory</td>
</tr>
<tr>
<td>EME</td>
<td>blast prediction, CFD</td>
<td>SAIC</td>
</tr>
<tr>
<td>FOIL</td>
<td>blast prediction, CFD</td>
<td>Applied Research Associates</td>
</tr>
<tr>
<td>PROSAIR</td>
<td>blast prediction, CFD</td>
<td>Cranfield University</td>
</tr>
<tr>
<td>SHARC</td>
<td>blast prediction, CFD</td>
<td>Applied Research Associates</td>
</tr>
</tbody>
</table>
These codes propagate simple methods of single degree of freedom (SDIF) and multi degree of freedom (MDOF). Nevertheless, for many cases the solutions are really under- or over-estimated. Because of the failure of structure is crucial part for each structural calculation, there are prepared many computer codes, which base in general on finite elements method, and make the calculation easier. There are, no only, so sophisticated codes like commercial Abaqus Explicit, Autodyn or LS-Dyna but also much simpler. There are collected in Fig.2. The most of them use a computational fluid dynamics (CFD) approach and are really useful in prediction of blast effects. For real analysis of any structural element or personnel safety, the design codes suggest to prepare pressure-impulse (P-I) curves. The typical ideology for P-I curves is presented in Fig.3 where the regions with different sensitivity are signed. This approach typically uses for each blast resistant element, like doors or windows. One graph is an easy way to relate mathematically a simplified damage level to a combination of blast and impulse values. Base on many real or numerical tests the different kinds of damages are presented in diagram. There are two separate regions. The first one with the minor damage is located below the curve and the second one, where the damage is much higher, is above. The one of interesting example, in agreement with [1,12] is presented in Fig.4, where the people resistance under blast wave action is presented in SI unit system. These values are obtained base on many laboratory tests, and there are prepared for a lung part of human body. The vertical axis represents a pressure increase, above ambient pressure, in Pa units, and the horizontal axis is a pressure impulse. For Fig.4 the values on impulse axis are divided by cube root of human body weight $W^{1/3}$. Moreover, short description of different damage levels for new and existing buildings is collected in Tab.1 in agreement with UFC code [11]. The pressure change values, which are presented in left column in Pa, are taken from Federal Emergency Management Agency (FEMA). The values for very low level of protection mean total minimum for inhabited buildings. To better understand the general aspect and view another restrictions e.g. for temporary structures, please see [10,11] in details.

Table 1. Levels of protection for buildings
As we assumed before, the main goal of the paper is to obtain public safety areas for the analysed floor. Human tolerance to the explosion is relatively high. However, the orientation of a person, like standing, sitting, prone relative to the blast front, is a significant factor in determining the amount of injuries. Shock tube and explosive experiments have indicated that human blast tolerance in function of peak pressure as well as the shock duration. The pressure tolerance for short-duration blast loads is significantly higher than that for long-duration blast loads, the same relation proceeds for construction materials like steel, concrete, masonry etc. There exist two different criteria for personal safety, there are prepared separately for lungs and cardrums.

Moreover, human vulnerability under blast was elaborated originally in [1,2] in details, and it is transferred to SI units in Fig.2, where the survive curves for lung damage as a function of peak pressure and impulse duration are derived.

<table>
<thead>
<tr>
<th>Level of Protection</th>
<th>Potential Damage</th>
<th>Potential Door and Glazing Hazards</th>
<th>Potential Injury</th>
</tr>
</thead>
<tbody>
<tr>
<td>Below AT standards</td>
<td>Severe damage. Progressive collapse likely. Space in and around damaged area will be unusable.</td>
<td>Doors and windows will fail catastrophically and result in lethal hazards. (High hazard rating).</td>
<td>Majority of personnel in collapse region suffer fatalities. Potential fatalities in areas outside of collapsed area likely.</td>
</tr>
<tr>
<td>Very Low $\Delta p=25\text{e3}$</td>
<td>Heavy damage - Onset of structural collapse, but progressive collapse is unlikely. Space in and around damaged area will be unusable.</td>
<td>Glazing will fracture, come out of the frame, and is likely to be propelled into the building, with the potential to cause serious injuries. (Low hazard rating) Doors may be propelled into rooms, presenting serious hazards.</td>
<td>Majority of personnel in damaged area suffer serious injuries with a potential for fatalities. Personnel in areas outside damaged area will experience minor to moderate injuries.</td>
</tr>
<tr>
<td>Low $\Delta p=16\text{e3}$</td>
<td>Moderate damage – Building damage will not be economically repairable. Progressive collapse will not occur. Space in and around damaged area will be unusable.</td>
<td>Glazing will fracture, potentially come out of the frame, but at a reduced velocity, does not present a significant injury hazard. (Very low hazard rating) Doors may fail, but they will rebound out of their frames, presenting minimal hazards.</td>
<td>Majority of personnel in damaged area suffer minor to moderate injuries with the potential for a few serious injuries, but fatalities are unlikely. Personnel in areas outside damaged areas will potentially experience a minor to moderate injuries.</td>
</tr>
<tr>
<td>Medium $\Delta p=12\text{e3}$</td>
<td>Minor damage – Building damage will be economically repairable. Space in and around damaged area can be used and will be fully functional after cleanup and repairs.</td>
<td>Glazing will fracture, remain in the frame and results in a minimal hazard consisting of glass dust and slivers. (Minimal hazard rating) Doors will stay in frames, but will not be reusable.</td>
<td>Personnel in damaged area potentially suffer minor to moderate injuries, but fatalities are unlikely. Personnel in areas outside damaged areas will potentially experience superficial injuries.</td>
</tr>
<tr>
<td>High $\Delta p=8\text{e3}$</td>
<td>Minimal damage. No permanent deformations. The facility will be immediately operable.</td>
<td>Glazing will not break. (No hazard rating) Doors will be reusable.</td>
<td>Only superficial injuries are likely.</td>
</tr>
</tbody>
</table>

As we assumed before, the main goal of the paper is to obtain public safety areas for the analysed floor. Human tolerance to the explosion is relatively high. However, the orientation of a person, like standing, sitting, prone relative to the blast front, is a significant factor in determining the amount of injuries. Shock tube and explosive experiments have indicated that human blast tolerance in function of peak pressure as well as the shock duration. The pressure tolerance for short-duration blast loads is significantly higher than that for long-duration blast loads, the same relation proceeds for construction materials like steel, concrete, masonry etc. There exist two different criteria for personal safety, there are prepared separately for lungs and cardrums.
Figure 3. Ideology scheme of P-I curve

Figure 4. Survival curves for personal safety
The above picture shows the curves which represent different probability of survive for personnel. The vertical axis means the pressure values and horizontal a scaled impulse, in function of self mass. For the purpose of the analysis the default mass has been fixed and equals to 60kg. Basing on the average results of peak pressure and impulse for each room the safety zones are derived. The further analyses consist only of the three different areas of public safety. The red one, where the human survive probability is zero; the blue one for probability of 50%, and the green one, for probability more than 90%.

Theoretical background

The credible performing of numerical modeling of any structure’s failure demands the proper definition of loading conditions. This research is focused only on the external loading which comes from the blast. The perforation of structure and following internal explosion are not included in details. Nevertheless, in order to provide the further research for masonry failure and damage evolution imposed by stress wave action inside the brick structure, the introduction to explosion phenomenon and blast wave propagation in the surrounding air is particularly required. The study of these effects allow to obtain the replacing loading schemes, which comes from the blast [6]. The general aspects of explosion including general equations are discussed, but the theory of ignition and detonation phases were not taken into consideration. In order to provide further consideration connected with structure safety under blast wave action, there is a need to understand the basic concept. The Explosion or Burst describe a rapid phenomenon of physical, chemical or nuclear conversation. Where the change of potential energy to mechanical work is inseparable. This work is carried out by expanded gases, which before were in compressed state, or were formed during the phenomenon.

Moreover, the explosion can be described as a sudden release of large amounts of energy within a limited space of the charge during a detonation process. Where the detonation means a kind of reaction for any explosive which produces a high intensity shock wave, where the velocity of the process lies between $10^3 - 10^7$ meters per second. The good example of physical conversion is a fast disruption of tank in field with gas. There exist also the chemical phenomenon which is caused by microsecond, exothermic reaction in charges, that initially were in solid, liquid state or were initiated in gas mixture. The last one, there are the nuclear conversion. Here, there is high influence of thermal radiation with wide range of the electromagnetic spectrum, including infrared, visible and ultraviolet light and in nuclear radiation including as initial ionizing and further residual radiations consisting chiefly of neutrons and gamma rays emitted within the first minute after detonation addition. Noteworthy, the power of nuclear explosion is a few order higher than for conventional explosive charges. The reaction is measured in nanoseconds and there is also obtained a large amount of energy. This view is permanent since 1938, where the first nuclear fission was performed by Hahn and Strassmann [13].

The short draft shows the instruction scheme for all the processes:

\[
\text{Condensed explosive + Heat source = Energy + Detonation products.}
\]

Where, the heat source is delivered typically to condense or liquid explosives and is starting the process of transmutation or conversion. The right hand site of the draft is the product of detonation, there is a important part for obstacle loading. The authors neglect any kind of nuclear loading in further consideration and are focused only on conventional phenomenon. The conventional charge term, means thermodynamically metastable configuration in which there are proceed rapidly self-sustaining processes. There are initiated by heat, electrical or mechanical influences. The high-condensed gases or vapours are connected directly with the process and are capable to perform a mechanical work. They are so-called detonation products. These products are highly compressed at initial moment. There is rapidly pressure change (10GPa) during explosion, on the medium boundaries (charge-surrounding). The detonation products are called high-pressure carriers base on Włodarczyk [14]. The important property of each explosive is it’s exothermic. This feature responses for self-sustaining independently of external factors, like e.g. atmospheric conditions. The general parameter connected with exothermic is specific heat or capacity. This term means directly the amount of energy
formed during explosion of 1kg of any explosive. The term rapidly deals with the time of conversion is fundamental for quality of the explosion. The conventional charges property of specific heat equals to 10GJ/kg. The values for separate charges are known obviously and are presented by many authors in tables, see [2,3,4,6,14]. Because of the reason that primary aim at this article deals with the structural engineering part and safety analysis the charge considerations are reduced only to one explosive, the propane-air mixture. The properties of any other compounds could be recalculated if necessary, base on TNT equivalence [2,6]. This term is usually stated in kilotons or megatons for nuclear explosions in particular. The basis of the equivalence is that the explosion of one ton of TNT is assumed to release $4.2 \times 10^9$ Joules of energy. For any other material the properties will be translated including specific heats ratio. The energy released in the detonation of the explosion, expressed in terms of the mass of trinitrotoluene which would release the same amount of energy when exploded. In general, there are few processes which accompany in the first milliseconds of explosion. The first one is visual fireball, it’s expansion rapidly compresses the surrounding air and following produces a powerful blast waves. The second one are high temperature changes which are transmitted on the front of the pressure wave. The worth mention is also the density on the shock wave front, which can reach the values more than 2500kg/m$^3$ with the properties like a solid body [3,14]. Where, a Shock Wave means continuously propagated pressure wave in the surrounding medium which may be air, water or earth and it can be initiated by the expansion of hot gases produced by e.g. a nuclear explosion. The most important shock wave parameters were published in 1870 by Rankine and Hugoniot [15]. For loading purpose of any structural obstacle there is important to consider a pressure evolution in space and time. The typical scheme for some point in the free space is presented in Fig.5. This point is in the distance from the charge centre and it’s called stand-off distance.

![Figure 5. Typical pressure-time history of an airblast in free air space](image)

The blast pressure consists of two significantly different phases. There are so-called: positive and negative phases. When the process starts, following the explosion at the time of arrival $t_A$, pressure suddenly increases to a peak value $P_{SO}$ which is over the ambient pressure equals to $P_0$. The pressure then decays to $P_0$ at time $t_0$ and next through under pressure $P_{SO}^-$ before eventually it be again on barometric value, at time $t_0^-$. The sum of over and under pressures time is named time of duration $T$. The quantity of $P_{SO}$ is usually referred to as the peak side-on overpressure or incident peak.
overpressure and accords with the rules [1]. Where, overpressure is a transient pressure, usually expressed in stress units, exceeding the ambient pressure, manifested in the shock wave from an explosion. The peak overpressure is the maximum value of the overpressure at a given location and is generally experienced at the instant when the shock wave reaches that location. The integral form of positive pressure is named positive impulse $i_s$ and $i_s^-$ is a negative impulse. There are important both for further failure analysis of any obstacle. The experimental tests which allow to measure the real pressure in the certain distance from the ignition point are relatively rare and very costly. Usually, they end with the damage of the gauges and can not be repeated under the same conditions. Nevertheless, many authors based on hundred’s of experiments [8] elaborated some simplifications for predicting of pressure value, which is crucial for blast loading process. These simplifications are collected in further part of this work. The most important for the shock wave, there are: blast front velocity, air density and the maximum overpressure. The values of parameters used in computations can be obtained from empirical equations and in consequence used for the analyses. The times of separate phases are also useful and can be evaluated analytically [3,4]. The history of pressure increase in time is often presented by exponential functions such as well known Freidlander equation [2].

$$p_{FR}(t) = p_c \left(1 - \frac{t}{t_0}\right) \exp\left(-\frac{k(p_c)^{-1}t}{t_0}\right)$$ (2)

In this equation $p_c$ is the peak of overpressure and $t_0$ positive phase duration [1,2]. These parameters are crucial to obtain real pressure time relation. Fig.6, presented below shows the evolution of pressure, for exampled explosion, in time and distance function.

Figure 6. Typical scheme of pressure evolution in time and distance from the ignition point

The reliable numerical simulation of any charge explosion requires the Arbitrary Lagrangian-Eulerian (ALE) formulation. ALE formulation assumes the mesh motion dependent on the material motion at free boundaries and in other cases the material and mesh are independent.
The real constitutive behavior of explosive material and the air are used in simulation. The properties of explosive material as TNT are modeled by Jones-Wilkins-Lee (JWL) equation. The pressure produced by chemical energy of explosion is described by:

\[
p(\rho, E_{m0}) = A \left(1 - \frac{\rho \rho_0}{\rho_0}\right) \exp \left(-R_1 \frac{\rho \rho_0}{\rho_0}\right) + B \left(1 - \frac{\rho \rho_0}{\rho_0}\right) \exp \left(-R_2 \frac{\rho \rho_0}{\rho_0}\right) + \frac{\rho \rho_0}{\rho_0} E_{m0}
\]

where \(A, B, R_1, R_2, \omega\) are material constants, \(E_{m0}\) is internal energy per unit mass, \(\rho_0\) is initial density of explosive material and \(\rho\) is current density of detonation product. The values of material constants are presented in Tab.2. The air is also modeled by equation of the state. This equation can be used as for ideal gas. The ideal gas assumption for the air is valid only for shock pressure less than 10 atmospheres.

\[
p + p_x = \rho R (T - T^Z)
\]

where \(p_A\) is the ambient pressure, \(\rho\) is initial density of air, \(R\) is gas constant, \(T^Z\) and \(T\) are expressed in Kelvin. \(T^Z\) corresponds to -273.15 Celsius degrees. \(T\) is temperature on scale. An important material parameter of the air is a specific energy; which depends only on temperature and can be calculated as the following integral:

\[
E_m = E_{m0} + \int_{T_0}^{T} c_V(T) dT
\]

In above \(E_{m}\) denotes the initial specific energy at initial temperature \(T_0\) and \(c_V\) is the specific heat at constant volume, which depends only on the temperature (ideal gas).

**Numerical model**

The model of geometry bases on a real CAD blueprints, Fig.7 and consists only of a one floor of the building. The full openings are modelled, what means omitting of blast doors. There exists also a possibility of escaping of blast wave through the windows and elevator shaft. To fulfil this condition the outflow boundary condition is used, see [5,6].

![Figure 7. Spatial numerical model of structure](image)

The all outside faces are fixed while the windows and elevator area remains free and the outflow boundary are used. As a loading we assumed the ideal spherical blast of 330kg propane-air mixture. The properties of charge are presented in Tab.1. The equivalent charge expressed in TNT is presented for pictorial purpose.
Table 2. Properties of the propane charge

<table>
<thead>
<tr>
<th>Type of Charge</th>
<th>Propane-Air Mixture</th>
<th>Equivalent TNT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass [kg]</td>
<td>330</td>
<td>1923.5</td>
</tr>
<tr>
<td>Volume [m³]</td>
<td>172.8</td>
<td>1.18</td>
</tr>
<tr>
<td>Specific Energy [J/kg]</td>
<td>2.73e7</td>
<td>4.68e6</td>
</tr>
<tr>
<td>Density [kg/m³]</td>
<td>626 liquid 1.9 mixture</td>
<td>1630</td>
</tr>
<tr>
<td>Detonation speed [m/s]</td>
<td>1680</td>
<td>6940</td>
</tr>
</tbody>
</table>

The secondary objective is the willingness to reveal the difference between the same energy of gas and condensed charge explosives. The authors show the comparison of two pressure charges in exampled point (4m stand-off distance), see Fig.8. The dashed curve represents the pressure evolution that acts on the exit door in plant room, 4m from the ignition point, the continuous curve corresponds to them with equivalent TNT charge. The pressures and impulses are relatively different. The peak pressure for propane and TNT charges equal 1.4e9 Pa and 2.8e7 Pa, respectively.

![Figure 8. Pressure evolution for different charge type](image)

During the analysis, the obstacle reflection is also taken into consideration, when using verified results of increasing of front pressure. The pressure wave after reflection from the obstacle increases several times. The FE results which represent the reflection form the rigid walls are presented below. To be sure that we are in comparable area of the pressure increasing, in Fig.9 we present the results of pressure distribution for different angles of incidence. The coefficient of reflected pressure is in a good agreement with unified facility criteria [1,16], see Fig.10.
The above simulation of pressure evolution can be performed with the use of different modeling techniques. One of them is Coupled Eulerian Langrangian approach (CEL). There is also possible to simulate the detonation using Jones Wilkins Lee equation of the state or with CONWEP procedure, where the loading pressure is subjected the front surface of an obstacle. Both of them give comparable results, but using CEL we can not focus only on the obstacle without analysing the surrounding area and/or charge detonation in particular [6].

In Fig.10 the dashed line presents the reflection coefficient which is in agreement with code [1], and the continuous one is performed by the authors using of the FE model in Abaqus code environment. In the case under consideration the numerical model consists of 4.8e6 linear 8-node elements, and the calculation time lasts more than 36e3 seconds.

**Results**

The general results include evolution of pressure for each finite element. The authors transfer these values for average pressure for each room or corridor. Moreover, the average impulse is obtained. The
knowledge on the public safety, in agreement with Fig. 2, is very useful to obtain real zone where the personnel remain safe under explosion. The pressure maps presented below show cross sections, in a half height of floor. The grey colour means that the lung damage criterion has been reached.

Figure 11. Pressure evolution for different time moment without windows for a) 0.0006s, b) 0.008s, c) 0.02s, and d) 0.05s

Basing of these results the safety zones are obtained. The red one means that the possibilities of personnel survive is below 1%.

Figure 12. Safety zone for lung damage without windows

Nevertheless, existing openings must be taken into account to perform full analysis of safety. Because the pressure comes out through windows during explosion, the pressure peaks decrease rapidly. The windows are 1.2 meter high, and there are spaced on north, south and east direction on the building. The pressure maps for the same time instant as before are presented below.
Figure 13. Pressure evolution for different time moment with windows for a) 0.0006s, b) 0.008s, c) 0.02s, and d) 0.05s

When the windows boundaries are used what allows for outflow of pressure, the safe zone is really wider than before.

Figure 14. Safety zone for lung damage with full window openings

**Conclusions**

The analysis of complex floor and blast wave propagation inside the building are presented. The paper shows that the explosion of some gas-air mixtures is quantitatively and significantly different from that for condensed charge. The authors show also that using of rigid walls, in the sense of blast wave reflection effect, stays well with world standards. The public safety zones are obtained, and this knowledge is fundamental for future planning or retrofitting of existing structures possibly loaded by blasts. Nevertheless, the comparison of taking into account window openings is really necessary. Moreover, the results open the way for future analysis of structure and structural elements.

We wanted to demonstrate also computational aspects: first the complexity of this formulation as well as possibility of real using the numerical models for supporting the design decisions in cases which can be in focus.
References

3. J. Henrych, “The Dynamics of Explosion and Its Use”, Prague, Academia 1979
5. Abaqus Documentation v6.9
13. O. Hahn and F. Strassmann, “On the detection and characteristics of the alkaline earth metals formed by irradiation of uranium with neutrons”, Naturwissenschaften Volume 27, Number 1, 11–15 (1939)