Study on the Design of Metallic Doors Used for Underground Shelters

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***Abstract*—Ensuring the interior spaces and access routes of underground shelters subjected to extreme loading is a particularly important requirement in order to protect the personnel in any situation. Solid metal doors are currently used for such constructions, but they are not usually designed accurately according to the requirements imposed by the actual norms regarding the explosion action in closed space. The way of manifestation and the effects of an open field explosion differ considerably from the situation of detonation in a closed tunnel, specific to access routes of underground shelters. The present paper aims to determine, for different scenarios, the levels of pressure at the entrance of a shelter in order to determine the input data for an efficient further design of the metallic doors.**

***Index Terms*—access route, detonation, shock wave, standoff distance, scenario.**

I. Introduction

Armed conflicts of last decades mainly represent asymmetric warfare, with many terrorist attacks all over the world. Changing the warfare tactics determines radical modification of counter-attack approaches, which include finding and adopting proper safety measures for civilian, governmental and military buildings. A commonly protection solution is the underground positioning of valuable facilities in well-guarded area. The Achilles' heel of this kind of constructions remains the access routes, so it is intended to improve the doors system to become as safe as the rest of the building.

Recent research in the domain of doors resistant to explosion has led to important results. The tests are developed at reduced-scale [1] or full scale [2], validating numerical analyzes. Interesting outcomes were discovered and gradually improved; among these, the sandwich structure of the door leaf represents an efficient solution [3] and [4]. All these analyze and tests refer to the explosion in open field, with different effects as for the explosion in a closed gallery.

This paper aims to determine the correct level of pressure on the door surface when an explosive charge is detonated at certain distances in the underground access route.

The starting point of the analysis is the standardized protection levels for explosion-proof doors according to the side-on pressure, as well as the mass and standoff distance to obtain this pressure, [5] and [6], as shown in Table I. The highest protection level, EXR5, referring to detonation of 20 kilo TNT equivalent explosive, is the level used in the analysis.

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TABLE I. Classification of Protective Doors, Input and Output Parameters [5]

Class	Mass (kilo)	Distance (m)	Pressure P_{so}(bar)	Impulse i_{so} (bar*ms)
EXR1	3	5	0.75	1.05
EXR2	3	3	2.30	1.65
EXR3	12	5.5	1.70	2.25
EXR4	12	4	3.60	3.00
EXR5	20	4	6.30	4.20

II. Analysis Scenarios

The hypothetical configuration of the access route chosen for the analysis is complex, with a Z-shape succession of rooms, as for real underground shelters (Fig. 1). The walls are usually made of reinforced concrete, thick and resistant.

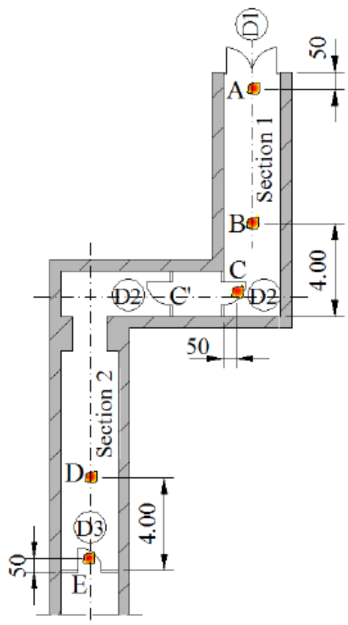

Figure 1. Route access configuration

In order to determine the highest levels of pressure on all the doors of the shelter, five scenarios are considered:

- Scenario 1 – determining the level of pressure on the metallic door D2 (point C) when the explosive is detonated at the entrance of Section 1 (point A);
- Scenario 2 – determining the level of pressure on the metallic door D2 (point C) when the explosive is detonated at a 4 m standoff distance from the end of Section 1 (point B);

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- Scenario 3 – determining the level of pressure on the metallic door D2 (point C) when the explosive is detonated at a 0.5 m stand-off distance from the door D2 (point C);
- Scenario 4 – determining the level of pressure on the metallic door D3 when the explosive is detonated at a 4 m stand-off distance from the door D3 (point D), and the D2 door (point C') is in turn opened and closed;
- Scenario 5 – determining the level of pressure on the metallic door D3 when the explosive is detonated at a 0.5 m stand-off distance from the door D3 (point D), and the D2 door (point C') is in turn opened and closed.

III. Simplifying Assumptions

To determine the loads and effects produced by the detonation of the explosive charge on metal doors, the finite element method was used. Given the dimensions of the space to be modeled, the amount of explosive detonated and the site conditions, the following simplifications were used:

- Reinforced concrete walls have been considered as rigid surfaces, as the shock or decomposition waves are perfectly reflected by these surfaces. In the real cases, at the top of the tunnels there are many pipes, cables and other objects that can change the direction of reflection and can deform with the effect of losing energy in the front of the shock waves. However, the results obtained from the simulations correspond to the worst case where there is no energy loss due to deformations and the loads on the metal doors are maximum.
- The dimensions of the mesh network were so chosen that the running time, on the non-performing, low-cost computing means available, be as small as possible and the errors induced in obtaining the results should be less than 10%.

IV. Geometrical Modeling

The geometric models of Section 1 and 2 are shown in Fig. 2 and Fig. 3.

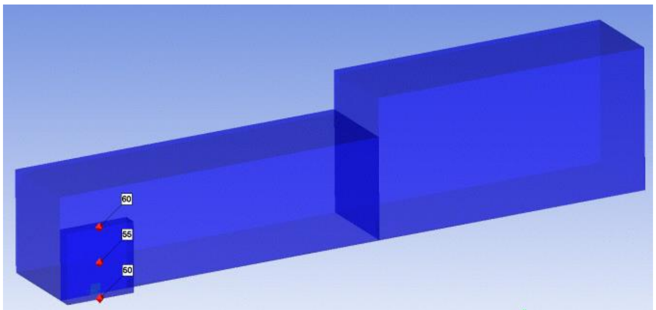


Figure 2.The model of Section 1 (with the transducers 50, 55, 60 on the door D2)

Also, for each section, the positions of the virtual transducers used to measure the pressure acting on the D2 metallic door (Section 1) and D2 and D3 (Section 2) are materialized.

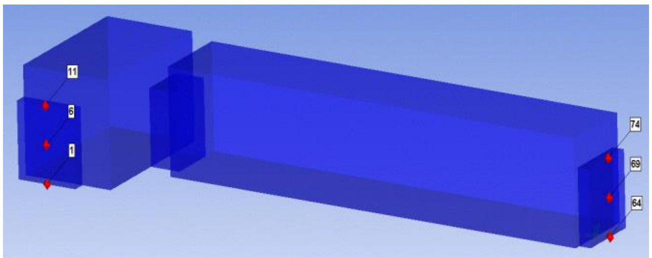


Figure 3. The model of Section 2(with the transducers 1, 6, 11 on D2 and 64, 69, 74 on D3)

Though hypothetical, the configuration and dimensions of the tunnel rooms were chosen according to common real situations.

V. Obtained Results

A. Scenario 1

In this scenario, it was assumed that the metallic door D1from the entrance to Section 1 did not resist to the pressure resulted from explosive detonation and was not taken into account. The explosive charge was detonated at 0.5 m inside the tunnel and the load on the D2 metal door (point C) was measured using virtual transducers. The variation of pressure for the three transducers is shown in Fig. 4.

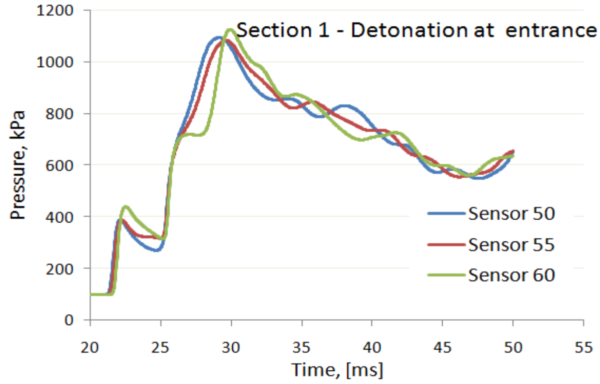


Figure 4. Pressure time-history for door D2 produced by the detonation of the explosive charges placed at the end of Section 1

Maximum values of overpressure at different distances from explosive charge at a height of 0.4 m and 1.5 m from the floor is shown in the Table II.

TABLE II. Maximum Overpressure Values for Different Standoff Distance (*10^2 kPa)

Standoff distance, m		0.5	2.5	5.5	7.5	8.5	10.5	11.5	13.5	14.5	15.5	16.5
Distance from the floor, m	0.4	187	8.55	6.12	5.86	5.61	5.87	6.08	7.56	9.23	9.79	11.3
	1.5	14.8	8.16	5.84	6.31	4.76	4.26	6.86	8.33	8.77	10.5	10.2

B. Scenario 2

In this scenario, the pressure on the door D2 (point C) resulted from the detonation of the explosive charge placed at a standoff distance of 4 m from the end of Section 1 (point B). The pressure time - variation on the door D2 is shown in Fig. 5.

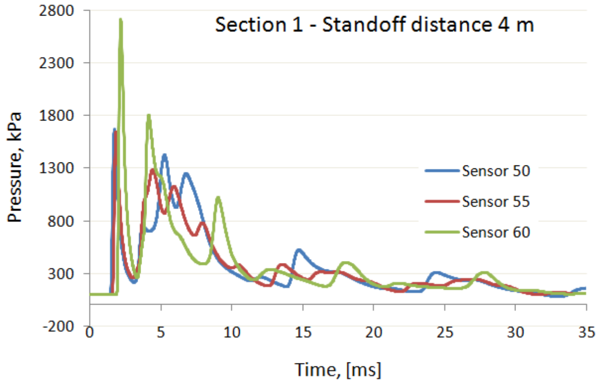


Figure 5. Pressure time-history for door D2 produced by the detonation of the explosive charges placed at a standoff distance of 4 m from the end of Section 1

C. Scenario 3

In this scenario, the pressure acting on the door D2was determined from the detonation of the explosive charge placed at a standoff distance of 0.5 m from D2 (point C). The variation of the pressure on the door D2 is shown in Fig. 6.

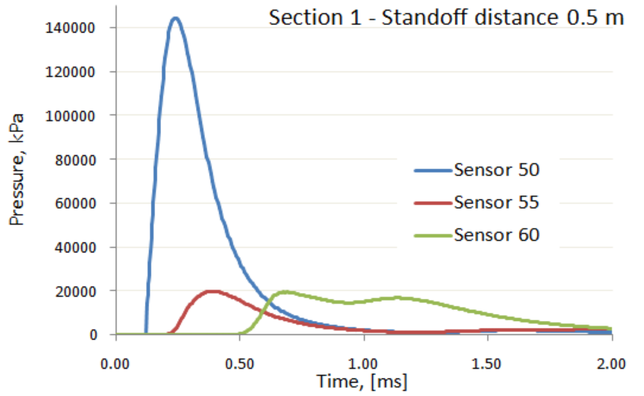


Figure 6. Pressure time-history for door D2 produced by the detonation of the explosive charges placed at a standoff distance of 0.5 m from door D2

D. Scenario 4

For this scenario, the explosive charge was placed at a standoff distance of 4 m from the door D3, in Section 2. The door pressure was determined for two cases: when the door D2, located at the other end of section 2 (point C') is closed and when it is opened. The time variation of the pressure determined in three points corresponding to the transducers, Fig. 7, insignificantly changes if the door D2 is closed or opened.

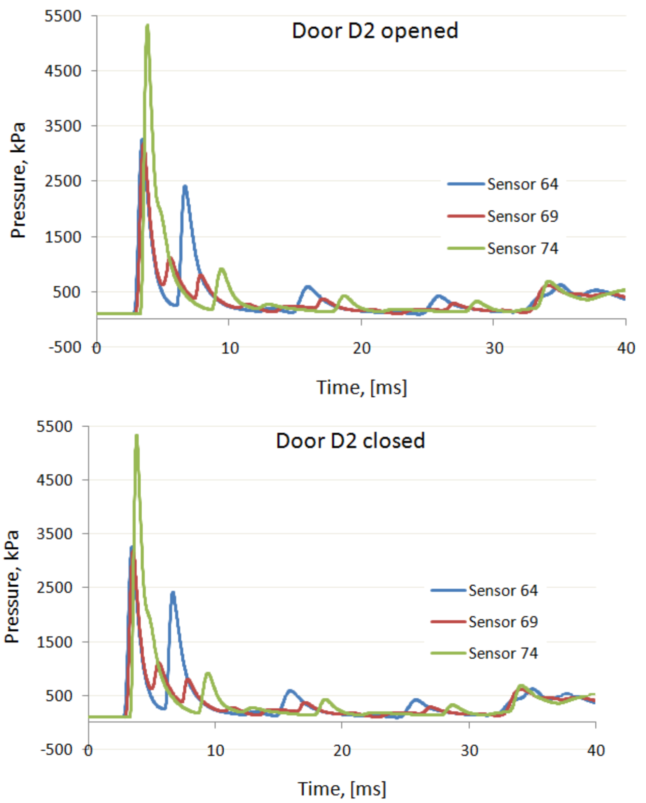


Figure 7. Pressure time-history for door D3produced by the detonation of the explosive charges placed at a standoff distance of 4 m from door D3, when the door D2 (point C') is opened (above) or closed (below)

However, the pressure on the door D2 significantly changes according to the closed or open position of the door D2 (Fig. 8).

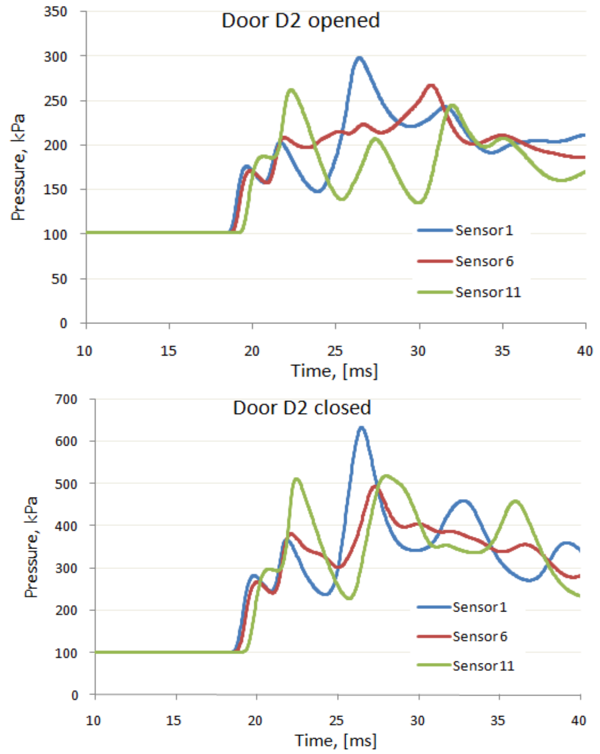


Figure 8. Pressure time-history for door D2 produced by the detonation of the explosive charges placed at a standoff distance of 4 m from door D3, when the door D2 (point C') is opened (above) or closed (below)

E. Scenario 5

The explosive charge was placed at a standoff distance of 0.5 m from the door D3, in Section 2. The door pressure was determined in two cases: when the door D2, located at the other end of the Section 2 (point C'), is closed and when it is opened. It was found that the time pressure variation in the three points (Fig. 9) changes insignificantly if the door D2 is closed or opened.

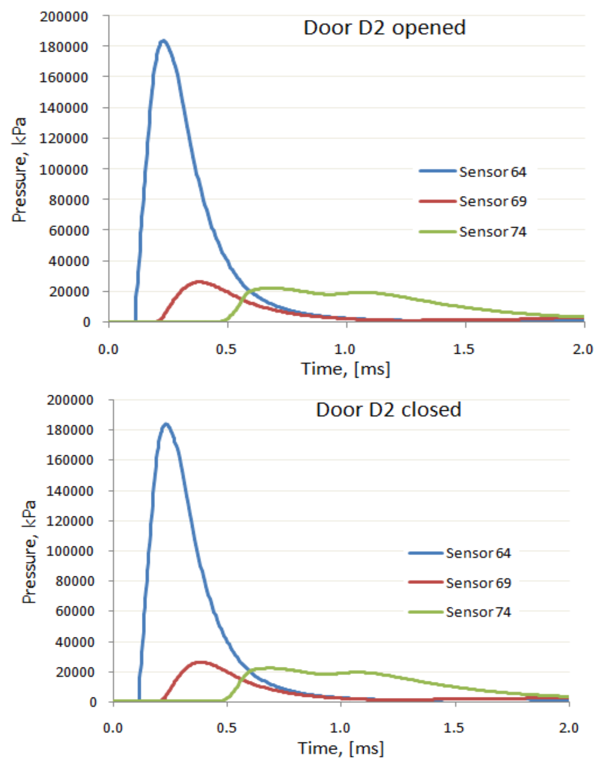


Figure 9. Pressure time-history for door D3 produced by the detonation of the explosive charges placed at a standoff distance of 0.5 m from door D3, when the door D2 (point C') is opened (above) or closed (below)

On the other hand, the pressure on door D2 significantly changes, depending on the closed or opened position of the door (Fig. 10).

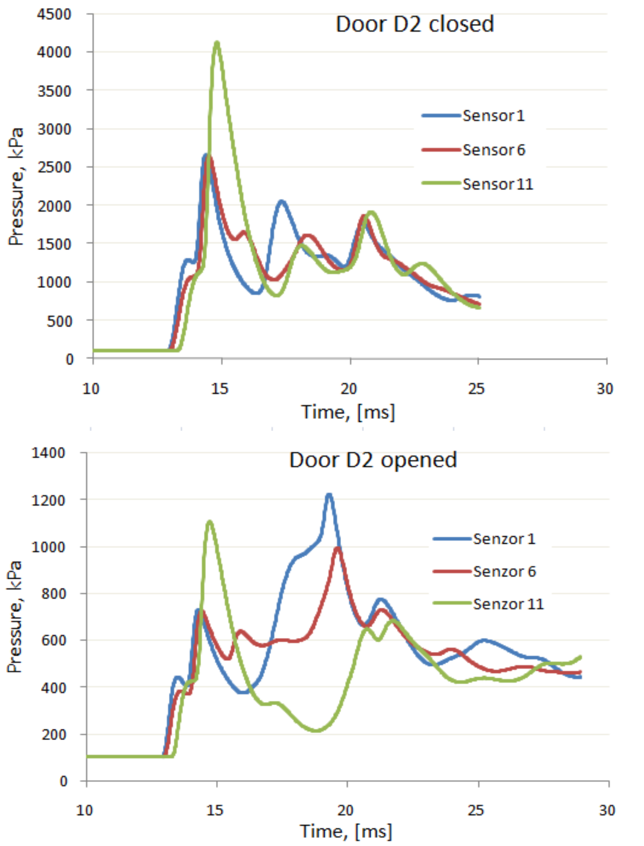


Figure 10. Pressure time-history for door D3 produced by the detonation of the explosive charges placed at a standoff distance of 0.5 m from door D3, when the door D2 (point C') is opened (above) or closed (below)

VI. Discussion

As a result of the simulations, the following maximum pressure values were obtained to the door D2 (Section 1) and D2 and D3 (Section 2), Table III.

Table III. Maximum Pressure Values on Metallic Door (kPa)

Standoff distance (m)	Section 1	Section 2	
	Door D2	Door D2	Door D3
0.5	140000	2610	182000
4	1630	624	3260

Maximum pressure values in Table III for doors in Section 2, the door D3 (distance between explosive charge and door - 4 m, Fig. 7) and the door D2 (distance between explosive charge and door - 0.5 m, Fig. 10), corresponds to the position of transducers at the base and at the center of the door. The transducers placed on the top of the doors measured very high values for the pressure because of the arrangement of the doors in the simulations performed (transducers 11 and 74). These values can be avoided by placing the door on the side of the wall where the Section cross-section is reduced.

Following the results of Table III, it can be noticed that the pressure values differ considerably for each door, due to the position of the explosive charge against the door. Thus, the highest values are obtained on the door D3 of Section 2, where the radius of the direct shock wave is perpendicular to the plane of the door leaf. The lowest values are determined on the door D2 of Section 2 because it is positioned around the corner, the pressure being generated by the shock waves reflected on the walls, floor and ceiling of the gallery. For door D2 in Section 1, the door leaf plane is parallel to the direct shock wave radius, so the pressure values lie between the other two values.

The fact that the detonation takes place into a closed space causes higher values of pressure compared to values obtained from a detonation in free field. This is due to the repeated reflections effect of the exposed elements of the underground facility: walls, floor, ceiling and other doors.

To make an eloquent comparison between the pressure on a door surface when the detonation takes place in a closed gallery and the pressure obtained from the open field explosion, the results of test on a real scale door fixed to a metallic frame are presented below.

The dimensions of the door leaf are 98×210 cm^2, and its internal configuration is a sandwich type (between two sheets of 2 mm steel sheets is placed a honeycomb structure, made of 0.2 mm thick corrugate sheets), Fig. 12.

Figure 11. Test set-up for the real-scale door

The test method was in accordance with the requirements of the standard [6], corresponding to the level EXR 5: a 20 kg equivalent TNT load was placed at a distance of 4 m from the door leaf fixed in the frame. The explosive charge was made of TNT explosive, cast in a spherical shape.

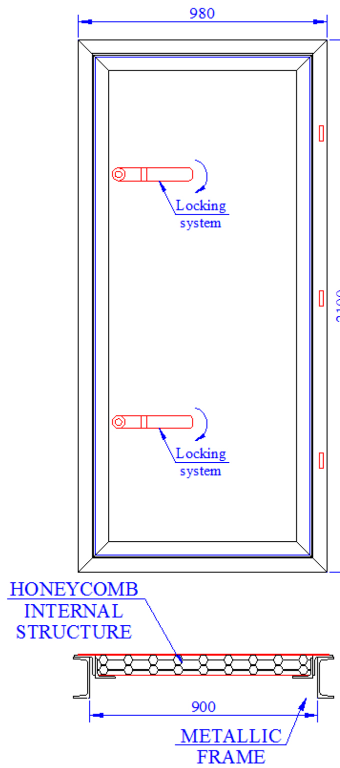
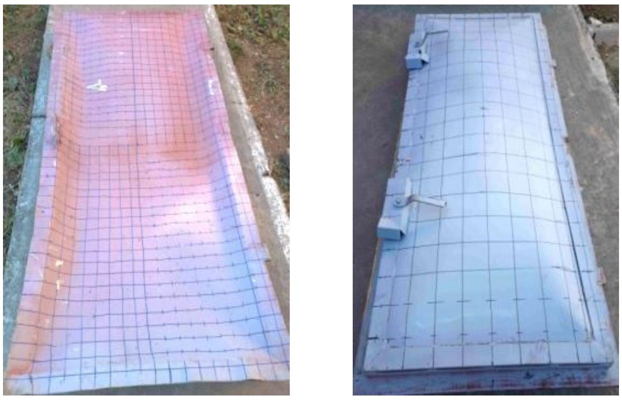


Figure 12. Configuration of tested door

To determine the pressure values, two PCB transducers are placed at 4 m distance from explosive charge: the first one measures the incident pressure and the second one – the reflected pressure (Fig. 11).

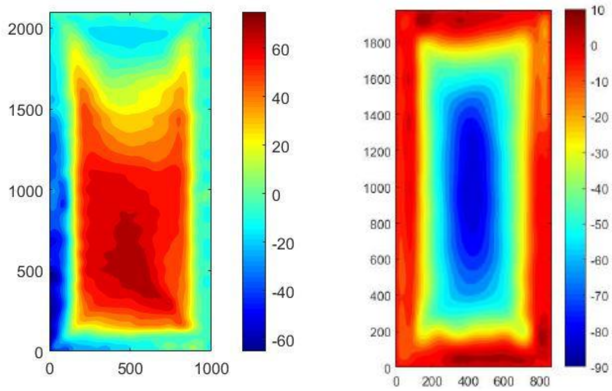
After the detonation of the explosive charge, the door leaf was heavily deformed, but maintained its position on the metal frame. The deformation of the door leaf can be observed in Fig. 13.



Exposed surface Posterior surface

Figure 13. Deformations of metallic door

Numerical analysis led to values of deflections very close to those measured on the real door, thus validating the model. The deformation of the front door leaf shows that the maximum deformation is at the bottom, in the load location area. It is also found that the deformation of the rear sheet is more even (with vertical / horizontal axis symmetry) than the deformation of the sheet exposed directly to the explosion (Fig. 14).



Exposed surface Posterior surface

Figure 14. Post-processing results on door leaf deformations

The comparison between the values recommended in the standards [6], those calculated using the Kingery-Bulmash relationships and those determined experimentally are shown in Table IV.

TABLE IV. PRESSURE VALUES ON REAL-SCALE METALLIC DOOR (KPA)

Pressure values / Methode	Incident Pressure P_{s0}, kPa	Reflected Pressure P_r, kPa
EN 13124-2:2004	630	-
Kingery-Bulmash	573	2668
Experimental	687	2726

The incidence pressure resulting from the experiment is higher than those recommended by standard [6], which means that the load on the door complies with the requirements for the EXR5 level.

The values of the pressure measured in the free-field test (incident pressure – 627 kPa and reflected pressure - 2726 kPa) listed in Table IV, are compared with the value of the pressure, 3260 kPa, obtained on the door where the radius of the direct shock wave is perpendicular to the plane of the door leaf (door D3 of Section 2) - from Table III. As expected, the value of the pressure generated by the shock waves reflected on the walls, floor and ceiling of the gallery is bigger than the values of pressure measured in the free-field test.

VII. CONCLUSION

The purpose of this study was to determine the pressures resulting from the detonation of an explosive charge of 20 kilos TNT equivalent on the metallic doors placed on the route access of an underground shelter. The studied structure was divided into two Sections and five different scenarios were considered, each related to the distance between the explosive charge and the metallic doors: 3 scenarios for Section 1 and 2 scenarios for Section 2.

The distances between the explosive loads and the doors were 0.5 m and 4 m, as there are mentioned in the standard regulations. Finite element method (FEM) was used to determine the pressure values.

The simulations performed correspond to the detonation of an explosive charge of 20 kilo TNT equivalent, the explosion being considered a chemical one. To simulate the detonation effects of an explosive charge other than classical load (e.g. nuclear), additional information is needed regarding the maximum value of overpressure at the front of the shock wave and its variation in time and distance.

In order to demonstrate the difference between the effects resulted after a detonation in closed space and the effects of an open-air explosion, the values of pressure obtained using FEM simulation are compared with the pressures measured in a test on real-scale multilayer door.

Using the maximum pressure values presented in Table III, the loads that occur on the metallic doors can be easily calculated and the correct design of a metallic door for an underground facility is now available, taking into consideration proper protection measures.

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