SIMULATION AND EXPERIMENTAL TESTS OF DOOR BREACHING USING MULTIFUNCTIONAL PROPULSION DEVICES

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In case of civil protection emergencies (landslides, fire, earthquake collapses, etc.) or in case of terrorist attacks, intervention teams need a quick method to enter the enclosed spaces inside buildings. The employment of special explosive devices to create door breaching is currently an efficient approach to gaining immediate access. Analyzing available door models, common features that influence the door behavior under explosive loads were identified in terms of leaf structure and locking systems.

The paper presents comparative results between simulations and full-scale experimental tests. The experiments are developed on various types of door structure components, employing both market-produced entrance doors and different specimens of manufactured door leaves.

Keywords: door breaching, explosive multifunctional propulsion device, door leaf, infill material, locking system

1. Introduction

The behavior of access elements in various types of constructions to the action of the explosion is a current topic and can be viewed from two perspectives: on the one hand, research is being carried out to develop doors that can withstand the explosion as well as possible [1-4], and on the other hand, research is being done to ensure access as quickly as possible through such elements of a construction, i.e. the creation of gaps in doors [5-9].

The use of explosive devices to create door breaching is related to the necessity to achieve very quick access to certain enclosed spaces in civil emergencies (fire, earthquake, hurricanes, etc.) or in cases of intervention by special forces. The analysis of the data from the specialized literature [9] shows that there

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are three main types of such devices/explosive charges: cutting charges; pushing/fluid impulse charges; blast charges, each with its own advantages and disadvantages. Fluid-propelled explosive devices consist of introducing a quantity of explosive (e.g. detonating cord), distributed in the form of a profiled curtain, between two layers of liquid. The two layers of liquid have different purposes: the first one produces the water jet required to deform/destroy the door leaf, and the second one has the role of stemming the explosive charge. Depending on the type of target, the amount of explosive and the quantity of propelled liquid to the target can be varied to produce the optimum effect. More details on this type of explosive device for creating door breaching can be found in [9].

Concerning this type of solution to create door breaching, among scientific documents and papers at the international level, Alford [10] remains as a reference. The analysis of the existing solutions shows that an important emphasis in the process of creating breaches in doors must be placed on the characteristics of the door and the place of placement of the load. In this paper, the results obtained by using a multifunctional explosive liquid propulsion device for creating door breaching are presented, taking into account the characteristics of the door leaf: the thickness of the metal sheets, the type of sound and thermal insulation material and the type of locking system.

Door systems may have various designs, both regarding resistance characteristics and facets. Following the analysis of the doors available on the market, the most common resistance, locking, and fixing system characteristics of apartment entrance doors have been assessed. Furthermore, the structure of the door leaf and the locking systems were identified as technical specifications of interest to analyze the effectiveness of the explosive devices.

The structure of the door leaf varies by the thickness of the metal sheet, the type of sound/thermal insulation, the existence and type of reinforcements, and the material used for the facets. Of these, the facets material (MDF, PVC boards) has a lower influence compared to the other elements in case of an explosion.Moreover, a door category encompassing embossed steel sheets does not contain facet materials.In this article, the analysis is applied to this type of doors.

Regarding closing systems, there can be monobloc locks (generally with two locks, multisystem), multi-point with multi-directional closure, and hook systems.Multi-point with multi-directional closuresystems are standard for embossed and luxury doors. The latter offer higher resistance classes and are intended primarily for premises protected against burglary in banks, shops, and financial-banking institutions. They are the most expensive versions of the companies that produce such doors. Therefore, they will be rarely found as apartment entrance doors. Thus, only the model with embossed sheet metal was considered representative of the multi-point with multi-directional closing system.

Commonly, embossed sheet metal doors have simpler structures. Both sides are made of sheet metal, the insulation material is made of honeycomb cardboard or polystyrene sheets, and the closing system has a multi-point with multi-directional lock.Considering this, the effectiveness of exploding systems was analyzed through numerical simulation and experimental testing on physical models of door leaves and an embossed door from the market.

All door models were tested using explosive devices with PETN detonating cord with 20 g per meter. The device has a sandwich configuration, with detonating cord between two layers of water: the one closed to the door having the role of propulsion, with a volume of 0.5 liters and the other one having the role of stemming material, with a volume of 1.5 liters. The length of detonating cord varied from 60 to 105 cm and was placed on a plane panel, with 2 to 4 chords of detonating cord. The explosive devices were positioned at the level of the central lock, under the doorknob (Table 4 and Fig. 11).

2. Numerical simulation

In this study, the Autodyn program was used to simulate the behavior of metallicdoors under the action of the water jet. The simplified model of the door leaf, Fig. 1, consists of two metal sheets on each side, the sound and thermal insulation as core material and the metal rod supporting the locking cylinders. The protective metal boxfor locking system was also considered to determine its influence on the deformation of the sheet metal and the metal rod.Specialized literature [7] founds that the water jet can cut the metal sheet of the door and therefore the deformation of the rod is reduced and consequently the gap is not created. To overcome this deficiency, a Kevlar fabric is placed between the explosive charge and the door, reducing the cutting effect by distributing the loads produced by the water jet.

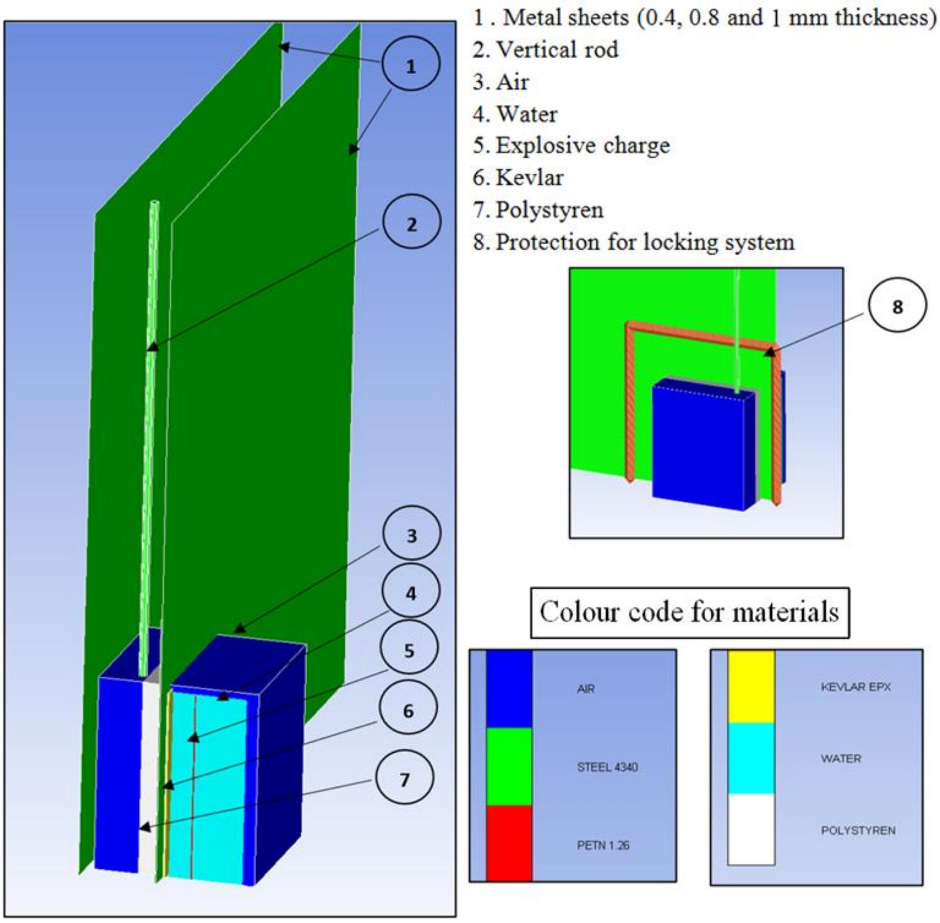


Fig. 1. The simplified model of the door

For modeling, it was considered that the load is placed in the middle of the door, therefore the simplified door wasonly half modeled, Fig. 1. The Euler 3D Multimaterial solver was used to model the detonation of the explosive charge and the formation of the water jet, while the Lagrange solver was applied for the door leaves, for the core materials and for the protection box oflocking system. For both solvers the discretization grid was set to 1 mm in order to ensure the transmission of the shock wave, the formation and the action of the water jet to the door surface. The material models used were picked from the Autodyn Library and a summary of their main characteristics is presented in the Tables 1 and 2.

The efficiency of the special explosive device is studied by varying the material characteristics that compose the door leaf. In total, 20 simulations are performed. The main variable is the thickness of the door sheet: four simulations are made for a door composed from a 1 mm sheet, eight simulations for 0.8 mm sheet and eight simulations for 0.4 mm door leaves respectively. Also, the influence of the presence of the thermal insulation material (often polystyrene) is studied, as well as the way in which Kevlar can make it more efficient by distributing the produced effects.

Table 1

Material properties for Autodyn simulations

Nr.	Components	Material	Density [g/cm^3]	EOS	Strength Model	Growth Model
1.	Energetic material	PETN	1.26	JWL	None	None
2.	Force dispensing part	Kevlar EPX	1.29	Puff	None	None
3.	Door leaf	Steel 4340	7.83	Linear	Johnson Cook	None
4.	Door rod	Steel 4340	7.83	Linear	Johnson Cook	None
5.	Jet	Water	0.998	Shock	None	None

Table 2

Material properties for PETN (energetic material)

Parameters of JWL EOS	PETN	Unit
Density	1.26	g/cm^3
Parameter A	$5.73 \cdot 10^8$	kPa
Parameter B	$2.016 \cdot 10^7$	Kpa
Parameter R1	6	None
Parameter R2	1.8	None
Parameter ω	0.28	None
C-J Detonation velocity, D	$6.540001 \cdot 10^3$	m/s
C-J energy per unit volume E	$7.190001 \cdot 10^6$	kJ/m^3
C-J pressure	$1.4 \cdot 10^7$	kPa

Among the models analyzed in this paper, the most interesting results are presented below.

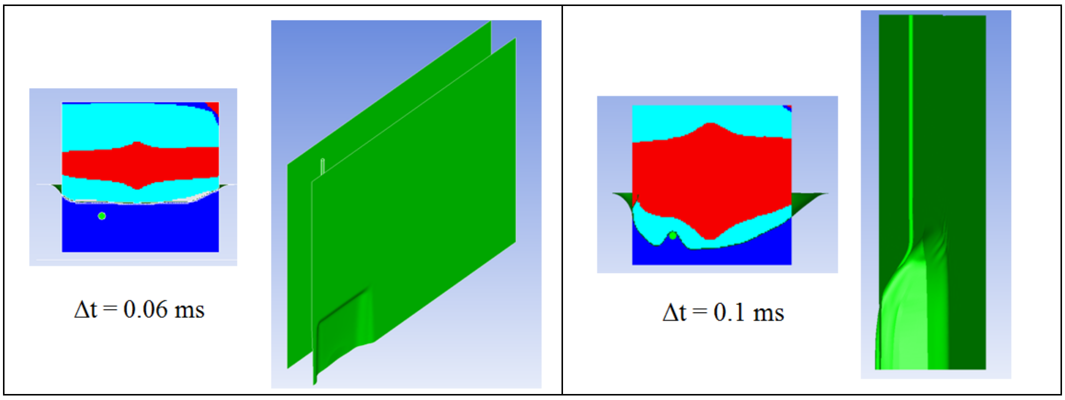


Fig. 2. Cross sections and 3D views – Door model with 1 mm thickness of exposed metal sheet, without Kevlar fabric

For the model of the door with sheet thickness of 1 mm, with protection of the locking system, but without Kevlar fabric, (Fig. 2) the deformations of the door leaf increase very quickly under the action of the water jet propelled by the explosion. It can be seen that the core material (extruded polystyrene) influences the dynamic response of the door leaf: it attenuates the velocity induced in the rod and smoothes the variation of speed in time; the velocity of the rod gradually increases before the door face with the rod is in direct, intimate contact (Fig. 3). After the exposed metal sheet reaches the rod, the latter also quickly deforms being pushed by that sheet.

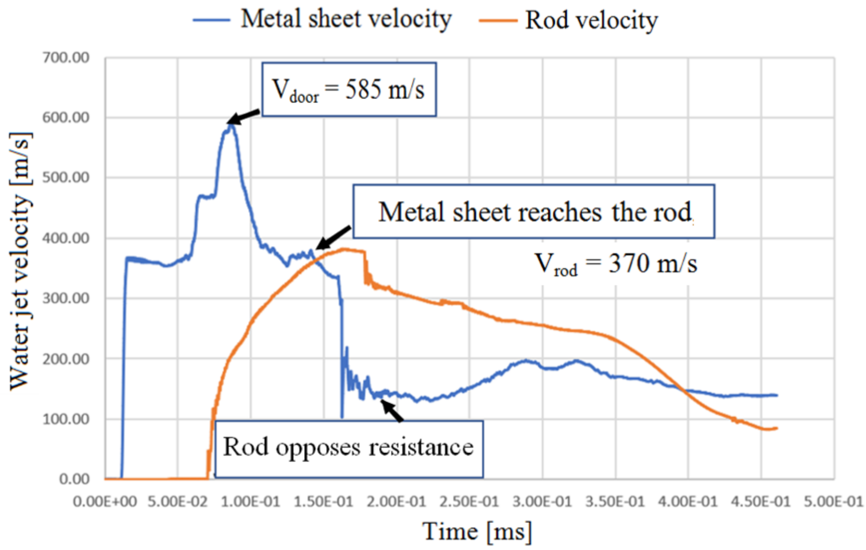


Fig. 3. Velocity-time graphs recorded at the base of the door face, respectively at the base of the rod(for the model without Kevlar fabric)

Keeping the same input data for the above door model, but adding Kevlar fabric this time (Fig. 4), different results are obtained.

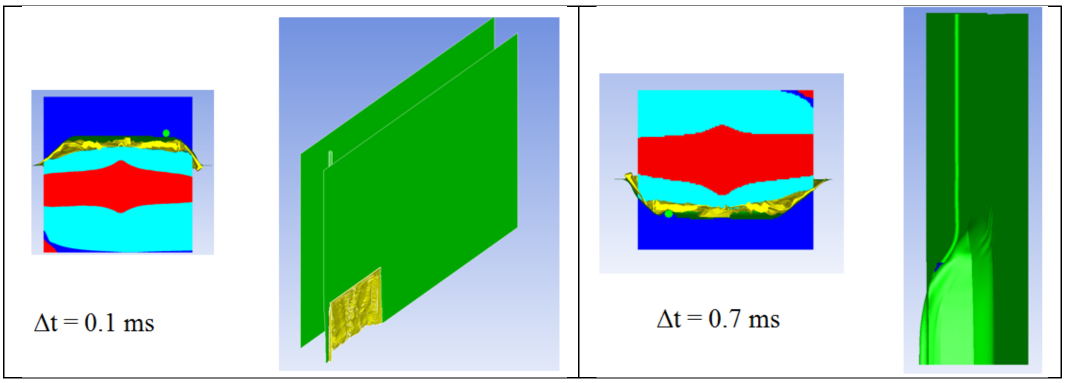


Fig. 4. Velocity-time graphs recorded at the base of the door face, respectively at the base of the rod (for the model with Kevlar fabric)

An advantageous redistribution of the water jet on the door leaf can be distinguished, considerably reducing the risk of the sheet metal cutting effect. Also, the strain rate values are significantly influenced by the presence of Kevlar fabric placed between the explosive charge and door (Fig. 5).

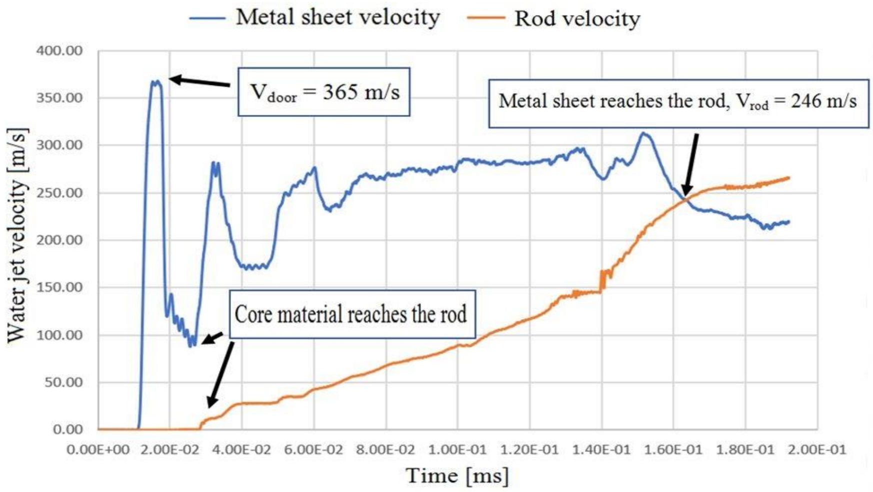


Figure 5. Velocity-time graphs recorded at the base of the door face, respectively at the base of the rod (for the model with Kevlar fabric)

Table 3 includes the deformations recorded after 2ms in the horizontal direction of the water jet on the elements of door models chosen for the comparative study.The purpose of the numerical simulations was to determine the influence of the different parameters of the door leaf (sheet thickness, sound and thermal insulation material etc.) so that a very large number of elements (over 1 million) were used. Under the conditions of the recorded deformations, they correspond to an analysis time of only 2 ms and do not correspond to the final deformation of the door leaf, which could be obtained after a second-order time, which implies a very long analysis time.

Table 3

Deformations after 2ms for door components

Model number	Thickness of the metal sheets [mm]	Protection for locking system	Kevlar	Deformations [mm]	
				Exposed metal sheet	Rod
1.	1		✓	26.8	1.5
2.	0.8		✓	28.4	3.3
3.	0.8	✓	✓	27.6	2.3
4.	0.4		✓	31.1	5.9
5	0.4	✓	✓	29.2	4

3. Testing setup

In order to validate the results obtained through the numerical approach, an experimental test was set up, which includes the testing of several commercial or manufactured doors, when they are subjected to loads generated by a controlled explosion.

All doors are fixed on a testing metallic frame, made of steel L profiles. According to [11], "the frame shall be plumb, square and rigid". Starting from these requirements, in the design phase of the frame, it was considered a firm ground anchor system and a high rigidity of the frame components facilitate, so that the test results not to be influenced. Thus, practically the same conditions are met as in the case of mounting the doors in a real masonry or reinforced concrete wall. On the other hand, the frame has the capacity to allow mounting of both market-produced entrance doors (with leaf and frame) and manufactured door leaves, in various configurations. To ease the transportation, the testing frame is made of parts, which can be swiftly assembled/disassembled by a three man team (Fig. 6).

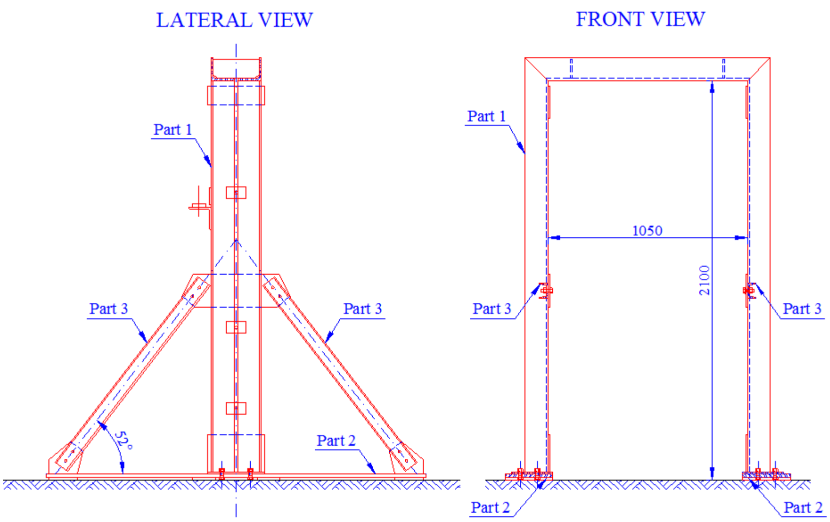


Fig. 6. Testing frame

The frame itself (Part 1 in Fig. 6) was made by arranging two L120 profiles face to face, with a gap of 20 mm. The continuous space left between those two profiles allows the door frame or the door leaf to be fixed at any point and thus allows the testing of any door, regardless of its geometric configuration. The two soles (Part 2 in Fig. 6), made of 250x15 mm steel plate are fixed with Conexpand M12 screws in the plain or reinforced concrete support flooring. The braces (Part 3 in Fig. 6) made of UPN80 profiles are positioned on both sides of each column, having the role of increasing the rigidity of the whole structure.

The doors are mounted on the testing frame using special fixing systems and wooden pieces, positioned in the place where the real doors are fixed on masonry or concrete walls. The market-produced entrance door is fully locked before the test.

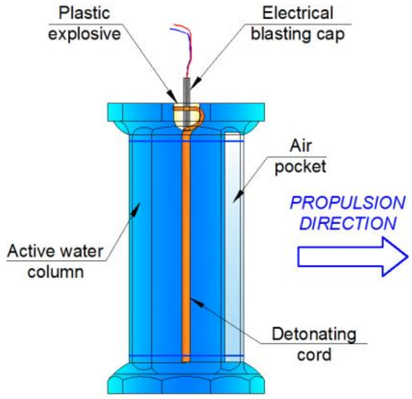


Fig. 7. Multifunctional propulsion device

The multifunctional propulsion device is design to be capable to open almost every conventional entrance door, using a small quantity of explosive (few grams of plastic explosive, an electrical blasting cap and detonating cord) and 2 liters of water as propulsion material (Fig. 7). A Kevlar fabric is placed between the door and the propulsion device, as damping material. The mass of the explosive was 12 to 16 grams for the manufactured models of door leaves depending on sheet thickness, and 21 grams for the embossed sheet door.

The multifunctional propulsion devices were positioned at the level of the central lock, under the doorknob (Table 4).

A high-speed video camera was mounted to capture the moment of explosive charge initiation and the failure of the door (Fig. 8).

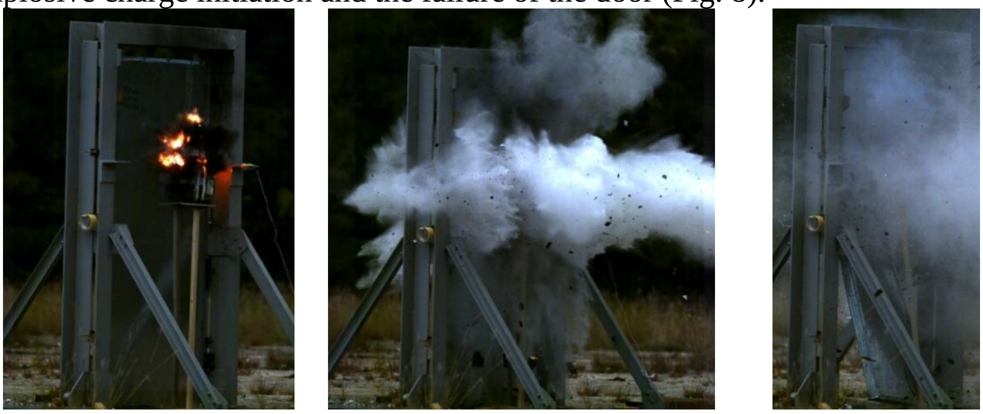


Fig.8. High-speed camera footage of explosive charge initiation and door leaf failure

4. Testing the embossed sheet door

Embossed sheet doors are made of galvanized sheets with thicknesses between 0.3-0.8 mm. They are made by cold rolling, and the joints between the two sheets and the metallic frame are made by welding. As insulation materials, they usually contain polystyrene sheets or honeycomb cardboard. They are equipped with multi-point, multi-directional locks that close in three or four directions with 7 – 15 steel bolts. The tested door has two steel sheets of 0.5 mm with honeycomb stabilizer cardboard. The closing system encompasses a multi-point, three-directional lock with 11 horizontal and vertical closing points of 20 mm steel bolts. The central lock is protected with a tin box.

The door was mounted on the metal test support by attaching the frame at the mounting points specific to the model. The multi-functional propulsion device was positioned at the level of the central lock under the doorknob. The mass of the explosive used for this door was 21 g.

Table 4

Door characteristics and charge position

Door type	Embossed sheet doors
Dimensions [cm]	202x88x10
Leaf door structure	Dimensions [cm]: 195 x 78 x 5 Steel thickness sheet: 0.5 mm Insulation material: cardboard stabilizer honeycomb
Closing system	Multi-point three-directional lock with key-centralized closing, 11 horizontal and vertical closing points with 20 mm steel bolts
Special features	Tin boxes for the lock protection

As a general response, the door opened - the leaf folded around the horizontal axis of the blast. The metal sheet broke locally in the lock area, where the charge was positioned. The local rupture was produced due to the interaction between the leaf sheet and the tin box, the perpendicular sides of the box acting as a blade.

The general folding produced the deformation of the locker rod and the tilting of all the locking bolts. Consequently, the bolts came out of their locking slots. The maximum deformation of the door leaf is 248 mm.

a) General response b) Leaf response c) Detail

Fig. 9. Explosion response of embossed door

The door frame also underwent deformations, more significantly on the opposite side of the explosion (on the side of the hinges). The frame deformations were small on the locking system side, where the closing slots are located.

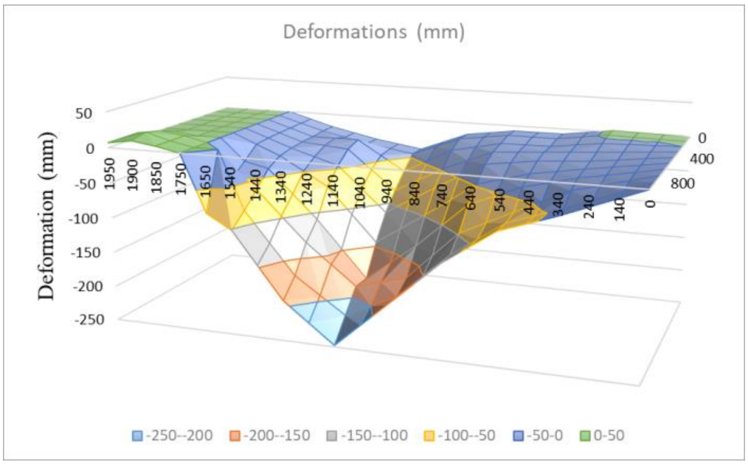


Fig. 10. Deformations of exterior embossed sheet

4. Testing the manufactured doors

The initial experiment plan involved determining the response under explosion loads for the widest possible set of doors on the market, with various geometric configurations and various component material variants. In order to limit costs, but especially to be able to have control over the dimensions of the elements and the quality of the materials, it was decided to manufacture door leaves in our own workshop, to be tested alongside the doors from the market.

Five door leaves were manufactured with standard dimensions 900x2000 mm, using two metal sheets (with a thickness between 0.4 and 2 mm for the exposed one, and 0.4 mm for the rear one). These metal sheets were fixed on a perimeter frame made of CD6 plasterboard profile, the same type of profile being used for the transverse stiffeners. The infill material, placed on the whole surface between metal sheets, is expanded polystyrene, generally used for thermal insulation.

Table 5

Types of manufactured door leaves and maximum deformations

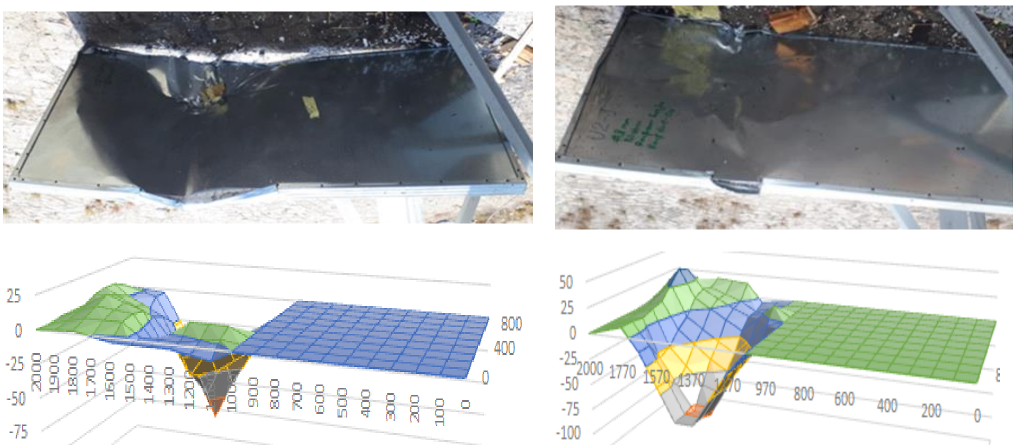
Door type	Metal sheet thickness [mm]		Quantity of explosive charge [g]	Deformations on exposed face [mm]
	Exposed face	Rear face		
U 1-1	0,4	0,4	12	110
U 2-1	0,8	0,4	12	97
U 3-1	1,0	0,4	12	80
U 4-1	1,5	0,4	16	108
U 5-1	2,0	0,4	12	45

Multifunctional propulsion devices were placed on the door leaves using a simple support-fixation system consisting of a wooden support and adhesive tape. To prevent the propagation of dangerous shrapnel, the assembly of the wooden support elements was made with plastic collars. Propulsion devices were mounted in the area corresponding to the position of the locking system on the real doors (Fig. 11).

Experimental tests demonstrated that the explosive charge was sufficient to cause failure of all door leaves (they left the test frame in a general translational and rotational motion). Different deformations resulted on the tested doors (Table 5), their values decreasing as the thickness of the exposed metal sheet increased. The only exception is provided by door type U4-1, where maximum deformation is larger than the trend; this is due to the use of a 30% higher amount of explosive than in the other 4 cases.

Fig. 11. Multifunctional propulsion device on the door leaf

Since the sheet of the exposed face had a reduced thickness (0.4 mm), at the door type U1-1, breaks of this sheet were found, over a length of approximately 25 cm.

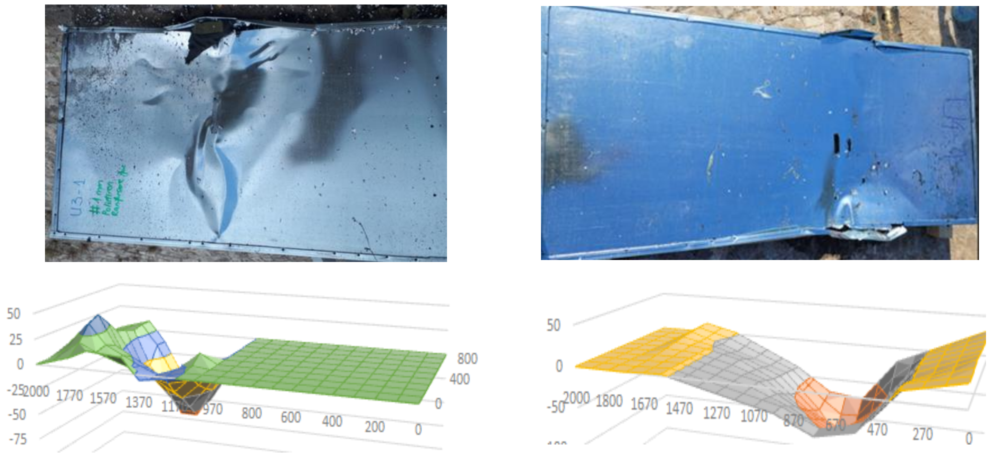


U1-1
[110 mm]

U2-1
[97 mm]

Fig. 12. Deformation of door leaves for specimens U1-1 and U2-1

For all doors, the CD6 profiles, used to form the perimeter frame of every leaf, are strongly deformed in the area of the explosive charge, and in some cases they are locally broken.

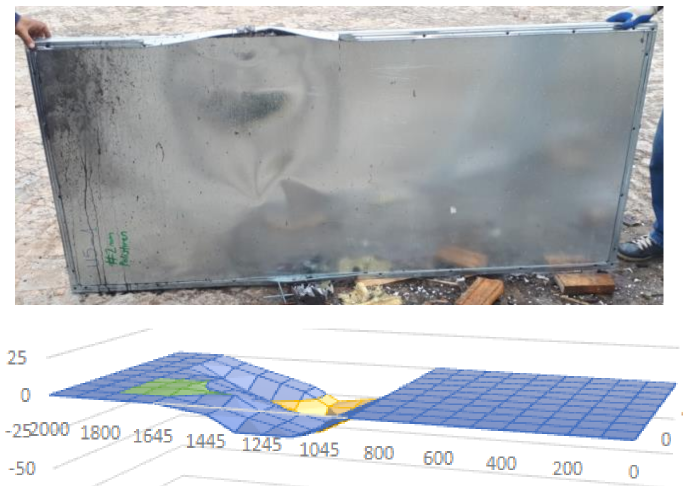


U3-1
[80 mm]

U4-1
[108 mm]

Fig. 13. Deformation of door leaves for specimens U3-1 and U4-1

The smallest deformations are determined on the manufactured door leaf - type U5.1 that has the thickest exposed metal sheet (2 mm).



U5-1
[45 mm]

Fig. 14. Deformation of door leaves for specimen U5-1

5. Conclusions

The collected output data from both numerical approach and experimental testing proved helpful in creating an efficient explosive multifunctional propulsion device that can be generally used for successful door breach. An interesting series of conclusions are drawn from observations on proprieties of materials and characteristics of constituent door elements.

All doors breached during the experimental test; large deformations determine the extraction of the bolt out of their locking slots. Numerical simulation offers a first impression on door response under explosive charges.

The thickness of the metal sheets decisively influences the results in terms of deformations: the thicker the exposed sheet, the less the deflections. Increasing the thickness of the door sheet also leads to an attenuation of the velocity induced in the locking rod.

The presence of confinement material, placed firmly between two metal sheets, also reduces (with 15 to 30 percent) the maximum deformations of the door under explosive charge. The core material attenuates the velocity induced in the locking rod and smoothes the velocity variation over time.

Both the simulations and the experiments have shown that the positioning of the Kevlar fabric between explosive charge and door considerably reduces the effect of cutting the metal sheet and redistributes more evenly the propulsion of the water jet on the door leaf.

On the other hand, the testing procedure developed for this experiment stage, with a firm demountable steel frame and a secure fixing system for any type of door, can be homologate in order to remain as a general approved method in testing doors (even special ones used for bunkers or shelters) subjected to explosive loads.

Acknowledgment

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R E F E R E N C E S

[1] *** - Composite sandwich structures when subject to air-blast loading, The International Journal of Multiphysics, vol. 6 (3): pp. 199-217, 2012

[2] *Chen W., Hao H.,* Experimental investigations and numerical simulations ofmulti-arch double-layered panels under uniform impulsive loadings, International Journal of Impact Engineering 63:140–157, 2014

[3] *Chen W.,* Experimantal and numerical studies of novel panels against blast and impact loadings, Doctoral Thesis, University of Western, Australia, 2013.

[4] *Lupoae M., Baciu C., Constantin D.,* Aspects regarding the blast loads on protective doors, MTA Review, **vol. XXVII**, No 1, pp. 19-24, 2017.

[5] *Jiang F., Han F., Wang J., Xu Y.*, Experimental study of overpressure caused by counter-terrorist door breaching explosive, Transaction of Beijing Institute of Technology 32(7):665-668, 2012.
[6] *Jiang F., Han F., Wang J.*, Numerical simulation of non-contact explosion by door breaching explosive, Journal of Beijing Institute of Technology 22(1):1-5, 2013.
[7] *Lupoae M., Goga D., Constantin D., Baciu C., Moldovan M.*, Aspects regarding the water jet propulsion using explosive energy for door breaching, Lecture Notes in Engineering and Computer Science, World Congress on Engineering, London, 3(2):2138-2142, 2011.
[8] *Moldovan M., Lupoae M., Baciu C.*, Breaching in light obstacles, Urbanism Arhitecture Constructions, **vol. 6**, pp. 35-44, 2015
[9] *M. Lupoae, C. Baciu and D. Constantin*, Metallic doors under explosive charges detonation, International Conference on Military Technology, 2017
[10] *** Alford Products - https://www.explosives.net/breaching
[11] *** ANSI/SDI A250.4-2018, Test Procedure and Acceptance Criteria for Physical Endurance for Steel Doors, Frames and Frame Anchors, American National Standards Institute, 2018