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SMALL SCALE TEST METHOD TO DETERMINE THE CAPACITY OF THE BALLISTIC PROTECTION MATERIALS TO MITIGATE THE BLAST OVERPRESSURE

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Abstract: *In order to design and implement ballistic protective equipment, several common stages in developing any product must be taken (technical studies, technological demonstrators, prototypes, etc.). The final stage should be the testing-assessing of development phase, followed by the homologation of the product obtained, which is a compulsory stage. In order to characterize the properties of shock waves passing through various materials and media (air, water, materials for ballistic protection), certain techniques and working procedures were established. The most common method is testing in the shooting range where the real conditions of a detonation can be faithfully reproduced. Such tests, however, despite being the most accurate and reliable way to check the shock waves mitigation properties of materials, in addition to being extremely dangerous activities, most often require expensive materials and full-scale structures. In the first stage of development, the new materials have to be selected through the small scale tests performed in laboratory. This paper presents one test procedure that could be used to determine the capacity of the ballistic protection materials to mitigate the effects of the shock wave in laboratory conditions and at low cost.*

Keywords: shock waves, mitigation, ballistic protection

1. Introduction

One of the destructive effects of an explosion is the shock wave. Of all known explosives, those that produce the most intense shock waves are those whose main form of transformation is detonation. Detonation waves are huge shock waves in amplitude, causing devastating effects on the environment in which they propagate, but especially on the various types of obstacles that they may encounter, such as construction and living beings. Recently, the need to incorporate the schock mitigation materials into structures of individual and collective ballistic protection systems came to the attention of researchers and manufacturers of such equipment on the background of modern warfare, whose main characteristic is the use of improvised explosive devices, the main cause of human losses in theaters. In addition to splinters and fragments that are obvious effects of an explosion of any kind, shock waves may affect to the same extent the construction, vehicles or personnel in the vicinity of an explosion.

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2. General information concerning the procedure for verifying the capacity of materials to mitigate shock waves

A less expensive way to test the mitigation properties of the materials is to use a transparent small tank in order to reproduce the effects of an explosion (mainly, the effect of the shock wave) on a very small scale, using transducers for recording the disturbance values. Generally, this method is used for the characterization of underwater explosions.

In addition to the consequent shock wave, an explosion is characterized by gaseous products which, found initially at elevated pressures and temperatures, are released into the environment. Further development of the reaction products is directly dependent on the explosive chemical energy and the environmental response in which the explosive phenomenon occurs.

The main objectives of the test are:

- recording the pressure versus time profile for a given explosive charge and at certain distances;
- recording the pressure versus time profile for a given explosive charge at the same distance, after passing through various materials of attenuation;
- determining the variation of shock wave front velocity in time;
- determining the attenuation of the shock wave as it passes through certain materials.

The main aspect of a detonation is represented by the formation, transmission and propagation of the shock wave. The pressure peak (overpressure) in this phase is high and lasts very little time, these characteristics depending on:

- the type and mass of the explosive charge;
- the distance at which the pressure is measured (the distance between the blast and the place where the piezoelectric pressure transducer is located).

Based on the profile of an idealized shock wave [1], the most important information that serves the purpose of the present procedure was outlined in Figure 1.

The significance of the notations is shown below:

- Py_1 → undisturbed pressure in the shock wave front, at a certain distance [bar];
- Py_2 → mitigated pressure in the shock wave front, for the same distance [bar];
- Px → normal pressure (ambient pressure - for this procedure Px = 1 bar);
- Δpf_1 → overpressure in the front of the undisturbed shock wave [bar];
- Δpf_2 → overpressure in the front of the mitigated shock wave bar];
- ts_1 → time of increasing pressure occurrence on channel 1 (sensor 1) [ms];
- ts_2 → time of increasing pressure occurrence on channel 2 (sensor 2) [ms].

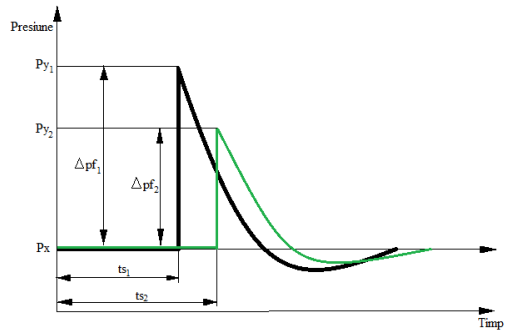

Figure 1: Profile of pressure waves in time - sizes of interest

3. The experimental configuration of the procedure

The procedure involves the reproduction of the conditions of a small-scale explosion (e.g. the distances are expressed in mm). The explosive element is represented by a system consisting of an ignition source/electric inflammatory and a very small amount of plastic explosive (milligrams). The enclosure for initiating the explosive element consists of a tank

made of transparent acrylic plates, with a thickness of 3 mm.

The testing scheme also includes pressure measuring equipment, operating system, software for setting load amplifier, power supply and firing control, high speed photo camera.

The attenuation material is interposed between the explosion and one of the transducers, the second transducer being positioned symmetrically, "face on" (collinear), at the same distance from the explosion, in order to measure the pressure of the unmitigated shock wave. In Figure 3 the configuration needed for testing is outlined.

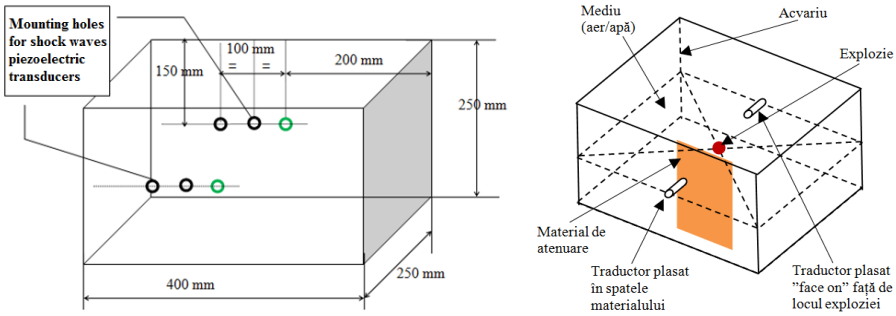

Figure 3: 3D test scheme: Aquarium dimensions and configuration

4. Method of recording and interpreting the results

The results of tests shall be recorded in a form designed specifically for this test. In addition to the data concerning the equipment and materials, the test form will include the acquired data during the test (high-speed camera videos, transducers data, etc.).

The attenuation of the shock wave – meaning the decreasing in intensity or amplitude of the progressive wave passing through the medium – is expressed in percentage and is obtained from the formula:

$$A = \left(1 - \frac{Py_2}{Py_1}\right) \cdot 100 \qquad (1)$$

5. 3D modeling of the experimental configuration

In a first stage, in order to demonstrate the theoretical effectiveness of the method described above, the experimental configuration was modeled using SolidWorks CAD program (Figure 4). The assembly was realised at the real scale indicated in Figure 2, including the following elements: the aquarium, the environment for the shock wave propagation, the explosive material (to simplify the calculation, it has been modeled as a sphere with a 3 mm radius) and a copper board to mitigate the shock wave (thickness of 1 mm was chosen).

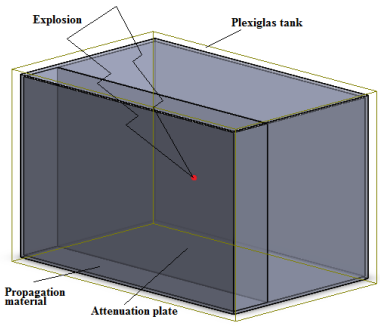

Figure 4: 3D model of experimental assembly – Solid works

The 3D model was meshed in ICEM CFD, a special software from ANSYS. Meshing the aquarium as a system compound was not necessary, because the reaction between the shock wave and the tank walls is not of interest for the purpose of this procedure. Therefore, it was removed from the model. Discretization was performed separately for each element of the configuration, aiming to obtain a finer discretization around the explosive material, and a less fine mesh structure for the wave propagation in the considered environment, as shown in Figure 5.

The meshed assembly had a number of 326362 nodes, 1000 shell type elements and 323551 solid type elements.

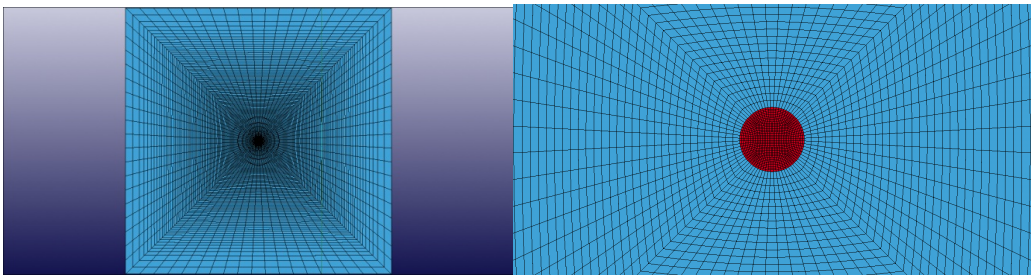

Figure 5: The structure meshed with finite elements for the explosive material and the environment - overall detail (section view)

Two types of simulations were performed, considering the two common propagation medium of the shock waves - air and water. For the explosive material, we chose a high explosive (C4) and, due to the availability of data on material properties, for the attenuation material we have chosen copper.

The mass of the explosive used in the simulations was calculated to be about 0.18 g, a similar amount to that commonly used in such tests, on this scale.

Considering this amount of explosive, we determined the scaled distance, that is a theoretical length which, on the one hand, links the amount and type of the explosive with the atmospheric conditions and, on the other hand, the explosive load with the standard atmosphere, in order to achieve the same effect on spaces equal to the cube of the distance from the explosion to the target. Considering the distance factor equal to 1, we get the following formula:

$$Z = \frac{R}{W^{\frac{1}{3}}} \qquad (2)$$

resulting Z = 1,16 m. From the reference explosion table [2], the equivalent pressure correlated with this distance equals 7.23 bar.

If we calculated the pressure corresponding to R = 12.5 cm, i.e. to the edge of the aquarium, we would obtain a pressure of 1.5 bar. But these theoretical data are adequate to a load of 0.18 g of TNT equivalent. Since in this simulation we used a plastic explosive material that is stronger than TNT, we ought to do a mass conversion using the equivalence factor, which in this case is equal to 1.2 . Thus, for the distance of 6.5 cm between the explosion and the transducer, we will obtain Z = 1.083 m, corresponding to a pressure of 8.4 bar.

These data will be useful in evaluating the success of the simulation made for the detonation in the air (Test 1).

6. The simulation results

The following pressure curves were obtained:

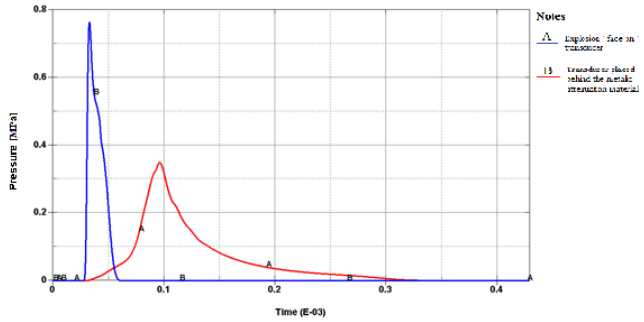

Figure 6: Pressure curves of the shock wave obtained through simulating the detonation of 0.18 g of plastic explosive in air

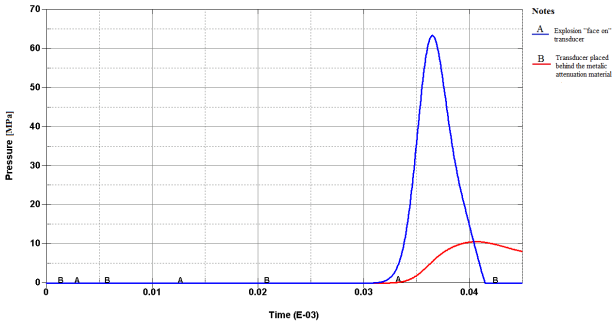

Figure 7: Pressure curves of the shock wave obtained through simulating the detonation of 0.18 g of plastic explosive in water

For both tests, from the graphs we identify the two maximum pressure peaks resulting by applying the formula (1), the amount of attenuation.

The results are reported in Table.

Table 1 Simulation results

Sample no.	Pressure measurement distance [mm]	Medium	Explosive load [g]	Py_1 [bar]	Py_2 [bar]	Attenuation (%)
1	65	aer	0,18	7,62	3,4	55,3
1	65	apă	0,18	632	106	83,22

Next, in the following images we can observe some aspects of the shock wave at different times (cross section).

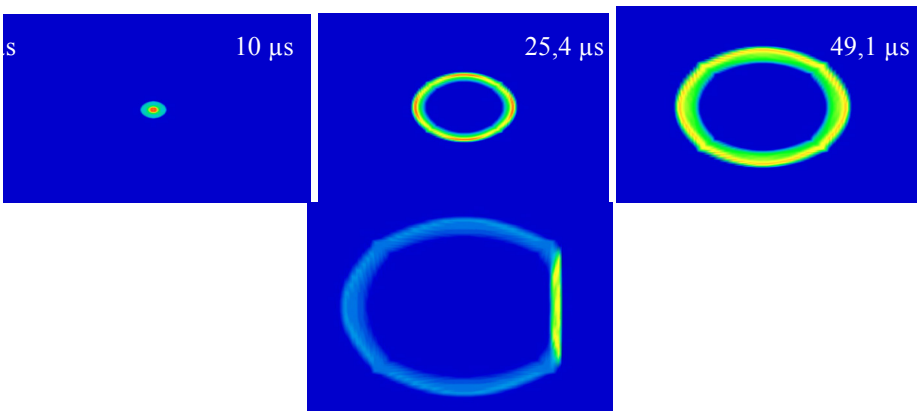

Figure 8: Aspects of the shock wave propagation in air

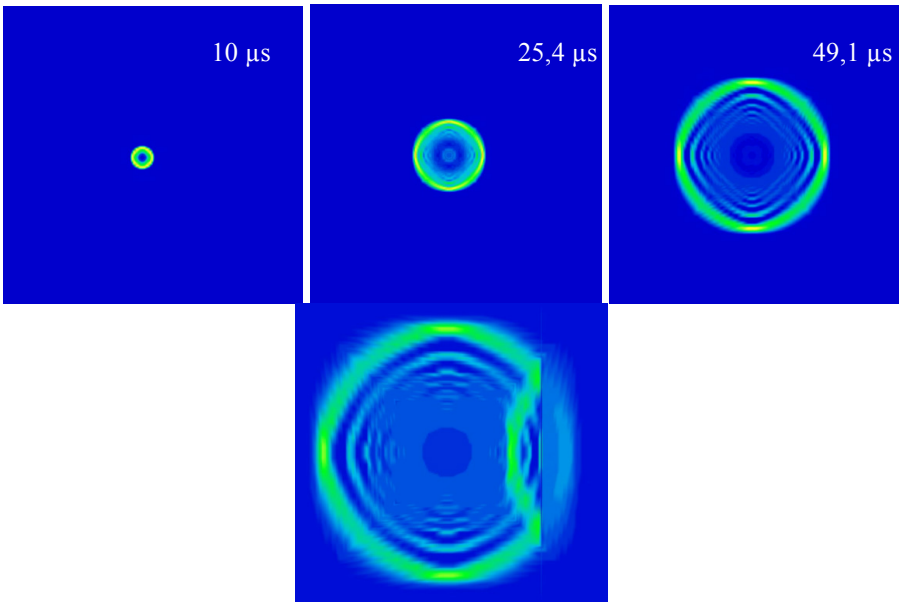

Figure 9: Aspects of the shock wave propagation in water

7. Conclusions

Given the results obtained, we can conclude that this procedure is appropiate for small-scale testing of the materials capacity of attenuation of blast waves.

From the simulation, we can observe that the attenuation level is higher in air than in water, for a given material.

The results highlights, nevertheless, the importance of several parameters in making such observations. First, we remark a stronger effect of the shock wave in water than in air, using the same amount of explosive. This is the direct effect of the density difference between the two media, which also affects the sound velocity. The reflection effect, when meeting an obstacle, is also much more intense in water.

The simulation model can be validated, at this level, by the theoretical model, using the reference explosion found in tables. However, this is only available for air explosion.

The simulation of the underwater explosion indicates very high overpressures, which could lead to suplementary pre-caution rules when performing the test in reality.

One of the advantages that the simulation capacity offers at this stage is the posibility of measuring the pressure in any point of the considered space (the aquarium). Thus, before perfoming the real testing, one could easily determine where would be the best placement for the transducers, so that they are the least affected by the reflexive waves.

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