# ASPECTS OF DETERMINING IMPACT INDUCED SHOCK CHARACTERISTICS IN MULTILAYERED BALLISTIC PANEL MATERIALS

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*The choice of materials for manufacturing ballistic panels in order to mitigate the effects produced by detonation of an improvised explosive device largely depends on the purpose of the panel. If the panels are intended for use in open congested spaces (airports, railway stations etc.), the use of porous materials (sand, slag) has the advantage of a reduced cost, under the conditions in which the requirements regarding the mass and dimensions of the panel are much more permissive. The arrangement of the layers within the panels can be done taking into account the shock attenuation characteristics of the component materials. Under these conditions, the present study presents how to use characteristics curve method to determine the induced shock in granular and fiber composites materials upon IED detonation.*

**Keywords:** sand, multilayer panel, impact mitigation, materials shock characteristics

## 1. Introduction

Reducing the effects of IEDs requires continuous development of ballistic protection means and materials. Among these means of ballistic protection stand out those used to reduce the effects of IED detonation in large areas with a high number of people passing through (airports, railway stations, exhibition areas, etc.). The size of these areas and the lack of measures to limit access with hazardous materials to certain zones are the most important aspects to be taken into account when designing ballistic protection for such areas.

The main characteristics of ballistic protection systems intended for use in wide spaces are:

- large size, allowing for a reduction effect on as wide an area as possible;
- the use of materials that are as cheap as possible and that have a high shock wave and shrapnel attenuation capacity;

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- symmetrical arrangement of layers within the panel;
- allow quick and easy handling and be easily integrated into the architecture of the spaces for which they are intended.

The most commonly used materials for shock absorption in the event of an explosion or impact are composite fibers, foam materials, magnetorheological fluids and porous materials [1]. In most cases, these materials are used in the form of layers within sandwich structures, in which the characteristics of these materials are combined to increase the shock absorption or attenuation capacity.

The most common composite fibers for ballistic protection applications are glass fibers, carbon fibers, aramid fibers (Kevlar and Twaron) and ultrahigh molecular weight polyethylene (UHMWPE, of which Dyneema is the best known) and are used in the reinforcement phase to produce composite materials. There are numerous papers dealing with the behavior of composite fiber materials to shock and impact actions, such as for glass fibers [2-3], for carbon fibers [4-6], for aramid fibers [7-10] and for UHMWPE fibers [10-13]. The use of magnetorheological fluids is so far limited to low velocity applied loads [14-15] while foam-type materials are more suitable for blast shock wave attenuation [16-17] and less suitable for projectile impact shock wave attenuation.

However, there is another category of materials that have proven to be good attenuators for blast and projectile impact shock waves namely, granular materials. Thus, Borvik et al. [18-19], Bragov et al. [20] and Holmen et al. [21] conducted experimental studies on the behavior of dry or wet sand on impact with projectiles of different shapes, while Ben-Dor et al. Al [22] and Britain et al. [23] analyzed the attenuation produced by granular materials on the shock wave.

The choice and arrangement of material layers in multi-layer ballistic panels must take into account that the attenuation of penetrator velocity requires much more careful analysis than in the case of blast shock wave action. Thus, Poh [24] proposes a panel consisting of three layers: the first layer of a high-strength material to slow down the projectile and deform it significantly plastically, a second layer to produce lateral scattering of the shock wave generated on impact relative to the penetrator axis, and a third layer of a porous material to produce wave attenuation by compacting it.

In the case of multi-layer ballistic protection panels intended for open spaces, the symmetry of the arrangement of the layers, the low cost and the small dimensions practically require the use of one layer of granular material and one of composite fibers. Omidivar et al [25] showed that when a projectile penetrates the sand, its forward speed will be slowed down by the formation of a network of particles, which through particle arrangement, opposes projectile forward movement.

Under these circumstances, the aim of this work is to study the arrangement of layers formed by sand and Dyneema fabric using the shock polars method. The study will consist in determining the amount of pressure induced in the layers of the ballistic protection panel by the projectile impact according to the layers' materials nature. The basic case where the outer layers are made of Dyneema fabric, and the middle layer of dry sand will be studied and compared with the case where dry sand would be replaced by wet sand.

## 2. Theoretical aspects

For any fragment, shrapnel or projectile hitting a target, the shock characteristics induced in the target can be determined using the shock polar equations. Since the ballistic panel will consist of several layers, the choice of layers and their arrangement will be determined by taking into account the shock wave transmission between the layers. The analysis of the shock wave transmission process between two media (projectile - first layer and layer 1 - layer 2) is made under the assumption of equal pressure and material velocity on either side of the interface of the two media. How each material behaves depends on the shock characteristics of each medium through the equation of state. This compressive state or rather the final density of the medium can have no influence on the final density of the adjacent medium. The same approach is valid for the temperature, too due to high transient nature of shock phenomenon: in a nontrivial amount of time the two media can be considered to be brought by the shock wave to very different temperatures, without any immediate thermal exchange between the two media.

It should be noted that the shock polars method provides information on the characteristics of the shock induced by a projectile in a target or in the layers of a ballistic protection panel, but in most cases further investigations are needed to fully characterize events such as detonation on contact or impact with a projectile. Thus, in these cases of analysis, the shock polars method does not take into account the momentum associated with these phenomena (blast and impact), the mass of the explosive charge or the mass of the projectile not being taken into account.

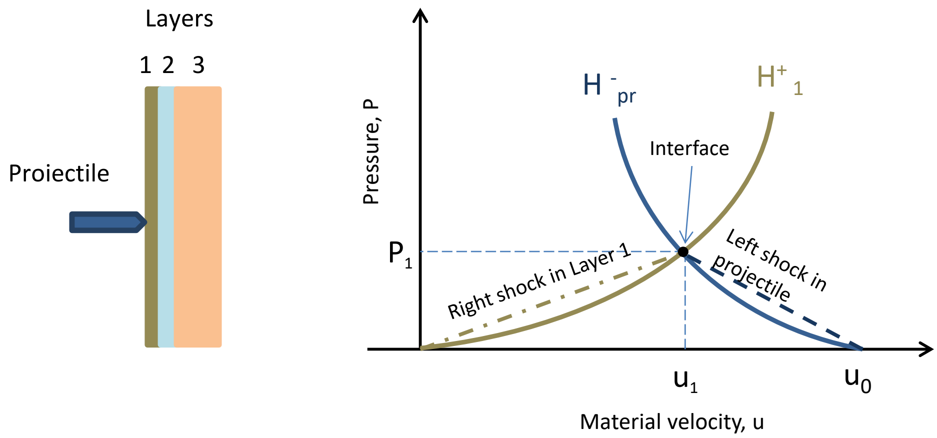
In the case of impact, the shock polars method will provide the characteristics of the induced shock by the impact of the projectile on the panel, but does not describe the phenomena related to the penetration/deflection of the projectile into/from the target. These phenomena need to be studied separately and will depend on projectile mass, impact angle, etc.

Consider a projectile impacting a multi-layer panel, Fig. 1a. Accounting for the projectile velocity and shock characteristics of the impacted first layer material and projectile material, one can write the shock polar equations (1) and (2) by neglecting $p_0$ since the pressure generated by the impact is much higher than the atmospheric pressure ( $p >> p_0$ ):

$$P_{pr} = \rho_{pr} \cdot (u_0 - u) \cdot \left[C_{pr} + s_{pr} \cdot (u_0 - u)\right] \quad (1)$$

$$P_{t1} = \rho_{t1} \cdot u \cdot \left(C_{t1} + s_{t1} \cdot u\right) \quad (2)$$

where: *pr* subscript denotes projectile, $t_1$ subscript indicates first target layer, $\rho$ is density, $u_0$ express initial projectile material velocity, $u$ is projectile/first target layer interface material velocity, $C$ indicates sound velocity and $s$ is a constant depending on the material nature.




a) Interaction projectile – multilayer panel b) P-u Hugoniot for projectile and Layer 1

Fig. 1. Interaction projectile – Layer 1 of multilayer panel

On contact between the projectile and the first layer of the panel, due to the high impact velocity, a shock wave is generated in both the projectile and the panel. The shock characteristics of the first panel layer are found on the shock polar of the material of this first layer, whose graphical representation is given by the curve, Fig. 1b.

The shock wave transmission conditions between two media are represented by the equality of the material pressures and velocities on either side of the interface, as follows:

$$P_{pr} = P_{t1} = P_1 \quad (3)$$

which leads after redistribution of the terms to the following relationship:

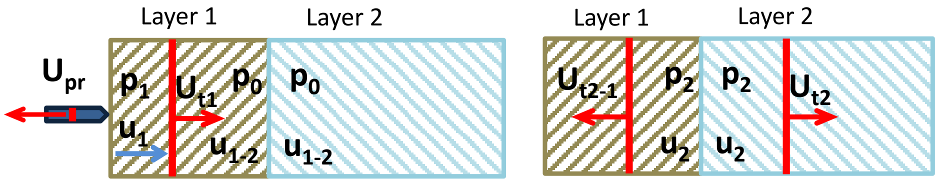
$$\left(\rho_{pr} \cdot s_{pr} - \rho_{t1} \cdot s_{\cdot t1}\right) \cdot u^2 - \left[\rho_{pr} \cdot U_{.p} + \rho_{t1} \cdot C_{t1}\right] \cdot u + \rho_{pr} \cdot u_0 \cdot \left(U_p - s_{pr} \cdot u_0\right) = 0 \quad (4)$$

where $U_p = C_{pr} + 2 \cdot s_{pr} \cdot u_0$.

Solving equation (4) will lead to two solutions for the material velocity at the interface, namely:

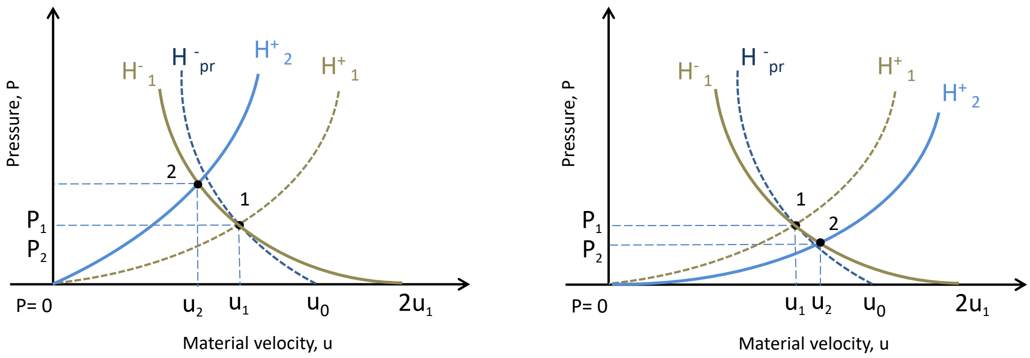
$$u_{1,2} = -\frac{C_{t1}\cdot\rho_{t1} + \rho_{pr}\cdot U_p \pm \sqrt{\left(\rho_{pr}U_p + \rho_{t1}C_{t1}\right)^2 + 4\rho_{pr}u_0\left(U_p - s_{pr}u_0\right)\left(\rho_{t1}s_{t1} - \rho_{pr}s_{pr}\right)}}{2\cdot\left(\rho_{t1}s_{t1} - \rho_{pr}s_{pr}\right)} \quad (5)$$

In choosing the correct solution it shall be taken into account that the material velocity at the interface cannot be higher than the projectile velocity on impact with the target, $u_0$. Passing through the first target layer the shock wave induced by the impact can be determined investigated in the second target layer. The shock generated by projectile impact will be transmitted to layer 2 of the panel as shown in Fig. 2. The shock from the projectile will be transmitted through layer 1 (we will hypothesis that the shock passing through layer 1 won't attenuate itself) to layers 1-2 interface. Before the shock wave reaches the interface, the second layer can be considered to be at atmospheric pressure ($P = P_0$) and at rest ($u = u_{t1\text{-}2} = 0$), Fig. 2a.




a) Shock wave travel through medium 1 to the interface with medium 2

b) Shock wave transmission from medium 1 to medium 2




c) Status at interface 1-2 for $Z_2 > Z_1$ (medium 2 is less compressible than medium 1)

d) Status at interface 1-2 for $Z_2 < Z_1$ (medium 2 is more compressible than medium 1)

Fig. 2. Status at interface material layer 1 – material layer 2

Upon shock wave arrival to interface (first stage), the following events take place, Fig. 2b:

1. A shock wave is transmitted into the second layer of the panel (the

transmitted wave is of the same nature as the wave reaching the interface);

2. A shock wave or rarefaction wave will be reflected from the interface, depending on the ratio of the shock impedances of the materials of layers 2 and 1. The reflected wave will be a shock wave if the shock impedance of the material of layer 2 is greater than the shock impedance of the material of layer 1 (medium 2 is less compressible than medium 1), Fig. 2c and a rarefaction wave if the shock impedance of medium 2 is less than the shock impedance of medium 1, Fig. 2d.

Considering equation (1) and (2) and the course of events presented in the previous paragraph, the following equations can be written:

- for the material of layer 1 of the panel:

$$P_{t1} = \rho_{t1} \cdot (2 \cdot u_1 - u) \cdot \left[C_{t1} + s_{t1} \cdot (2 \cdot u_1 - u)\right] \tag{6}$$

- for the material of layer 2 of the panel (subscript *t2* denotes the second layer of the target):

$$P_{t2} = \rho_{t2} \cdot u \cdot \left(C_{t2} + s_{t2} \cdot u\right) \tag{7}$$

Shock wave transmission conditions at the interface are the same (equality of material pressures and velocities on either side of the interface), Fig. 2b:

$$P_{t1} = P_{t2} = P_2 \text{ and } u_{t1} = u_{t2} = u_2 \tag{8}$$

which will lead to the equation:

$$\left(\rho_{t1}s_{t1} - \rho_{t2}s_{t2}\right) - \left(\rho_{t2}C_{t2} + \rho_{t1}C_{t1} + 4\rho_{t1}s_{t1}u_1\right) + 2\left(\rho_{t1}C_{t1}u_1 + 2\rho_{t1}s_{t1}u_1^2\right) = 0 \tag{9}$$

From the solutions obtained by solving equation (9), the one that falls between the projectile velocities and the velocity of the projectile-first layer interface, depending on the impedances of the two layers of the panel, shall be chosen.

## 3. Application of the method

### *3.1 Materials used*

The considered materials embedded in ballistic protection panel architecture are presented in Table 1 and Table 2. Table 1 refers to protective materials while Table 2 accounts for granular materials. The data presented in the literature points to the fact that there are several sorts of sand and they can have different degrees of water saturation, as stated in Table 2 and Fig. 3. It should be noted that the degrees of water saturation are expressed differently by different authors. Thus, for Perry et al. [30] the saturation degree is defined as the ratio of the masses of each phase per unit volume of the composite material, i.e. 0% for dry sand, 10% for wet sand and 23% for saturated sand. Also, according to Thiel et al. [31] the 20% saturation corresponds to a mixture of 96% sand and 4% water, the 50% saturation corresponds to a mixture of 90% sand and 10% water, and the 100% saturation corresponds to a mixture of 81% sand and 19% water. The percentages of the degree of saturation were calculated taking into account the densities of the sand in the dry state (1620 kg/m$^3$) and those of the sand with different degrees of saturation shown in Table 2.

*Table 1*

**Shock characteristics of possible materials to be used for the protective panel**

| Material | $\rho_0$, [g/cm$^3$] | $c_0$, [km/s] | s | Reference |
|---|---|---|---|---|
| Polyurea 1000 | 1.098 | 2.901 | 2.13 | [28] |
| Kevlar EPDM | 0.923 | 1.660 | 2.03 | [29] |
| Dyneema | 0.950 | 1.770 | 3.45 | [27] |
| Steel | 7.850 | 4.722 | 1.44 | [26] |
| Polyethylene | 0.915 | 2.901 | 1.48 | [26] |
| Polystyrene | 1.044 | 2.746 | 1.32 | [26] |

The graphical representation of equations (1) and (2) for materials in captured in Table 1 and Table 2 is presented in Fig. 3. Since the projectile is represented by the shrapnel resulting from the IED detonation, and the metal shrapnel has the strongest effect, the nature of projectile in the present study was assumed to be steel.

The analysis of the shock polars in Fig. 3 shows that the shock polars for the materials in Table 1, with the exception of steel, are grouped at the bottom of the graph in the same category as the dry sand shock polars, which is an advantage in terms of their shock absorption behavior. In other words, materials such as Kevlar, Dyneema, polyureas and granular materials such as sand or slag, with as low moisture content as possible, can be chosen as constituent materials of the multi-layer ballistic panel. It is also found that there is a grouping of the shock polars according to density, namely: those with the highest degree of saturation (GS) (sand 200μm with GS of 23%, sand 74-150μm with GS of 100% and sand 425-500 μm with GS 100%) are grouped at the top of the graph, followed by the shock polars for sand 74-150μm with GS of 50% and then the group of shock polars for sands with low degree of saturation and at the bottom the shock polars for dry sands. The size of the sand particles does not produce such a large dispersion of the shock polar. Thus, only the influence of moisture will be considered for the study.

### *3.2 Determination of shock characteristics*

By intersecting the shock polar for the reflected wave at the interface and travelling through the projectile, the shock characteristics induced by the projectile in various materials can be determined graphically, Fig. 3. For the determination of the projectile velocity it was taken into account that the velocity of a steel ball (considered to be the shrapnel that can reach the highest velocity, for the same shrapnel mass) propelled by detonation of an IED is approximately 700 m/s [10].

*Table 2*

**Shock characteristics of sands of different grades and degrees of water saturation**

| Material | Granulation | Humidity | $\rho_0$, [g/cm$^3$] | $c_0$, [km/s] | s | Reference | Speed range, km/s |
|---|---|---|---|---|---|---|---|
| Sand | 200μm | Dry | 1.380-1.450 | 0.56 | 1.69 | Perry et al. [30] | |
| | | 10% saturation | 1.600-1.640 | 0.36 | 1.72 | | |
| | | Saturated 23% | 2.000-2.030 | 0.78 | 2.53 | | |
| Sand | 200μm | Dry | 1.570 | 0.243 | 2.348 | Brown et al. [33] | |
| Sand | 150-210μm | Dry | 1.60 | 0.402 | 1.60 | Proud et al. [35] | |
| Sand | 74-150μm | 20% | 1.720 | 1.56 | 1.28 | Thiel et al. [31] | |
| | | 50% | 1.840 | 2.11 | 1.20 | | |
| | | 100% | 1.980 | 2.56 | 1.24 | | |
| Sand | 425-500μm | Dry | 1.733 | 2.15 | 0.275 | Lajeunesse et al. [32] | 0.35-1.50 |
| | | | | 1.325 | 1.019 | | 2.5-3.0 0 |
| | | 100% | 2.077 | 2.124 | 2.262 | | 0.25-1.20 |
| | | | | 1.526 | 1.887 | | 2.00-3.1 0 |
| | 75-100μm | Dry | 1.724 | 2.205 | 0.214 | | 0.35-1.35 |
| | | | | - | - | | - |
| | | 100% | 2.063 | 2.116 | 2.237 | | 0.25-1.2 0 |
| | | | | 1.656 | 1.019 | | 2.00-3.1 0 |

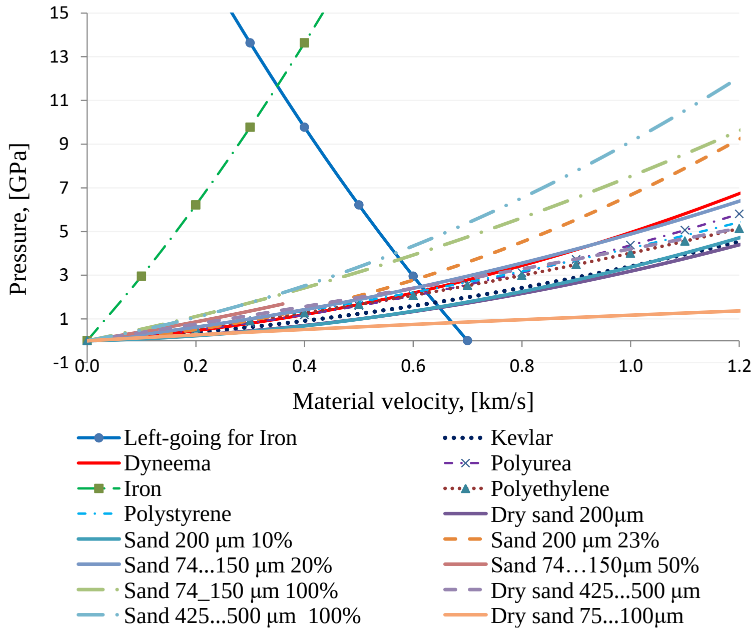



Fig. 3. Characteristics of the shock induced by a steel projectile with an impact velocity of 0.7 km/s in the potential materials of a protective panel

Considering the presented theoretical aspects and the data detailed in the previous tables, the present study will be focus on the characteristics of the shock induced by steel shrapnel with a velocity of 700 m/s in a ballistic panel material consisting of two layers (Dyneema and 150-210 μm dry sand). It should be noted that the determination of the characteristics of the shock induced in the second layer (sand) is made under the assumption that the Dyneema layer does not attenuate the shock generated by the projectile due to its reduce thickness. The shock characteristics at the projectile-Dyneema interface and Dyneema-sand interface are detailed in Table 3.

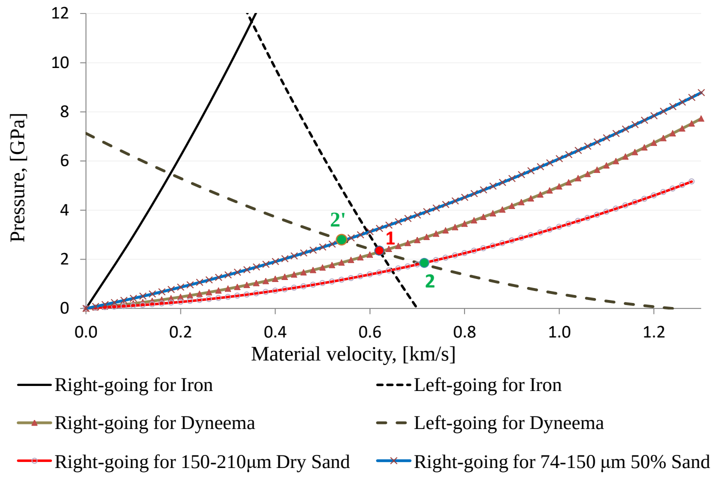



Fig. 4. Transmission of the shock wave generated on impact between a steel projectile and layer 1 - Dyneema (point 1) and the shock wave from layer 1 - Dyneema to layer 2 - sand (point 2)

*Table 3*

**Characterization of wave transmission between projectile and panel**

| Case | Destination | Transmitted wave | Reflected wave from interface | Shock characteristics | | | Fig. |
|---|---|---|---|---|---|---|---|
| | | | | P [GPa] | u [km/s] | U [km/s] | |
| Projectile – layer 1 impact | Projectile | - | Shock wave | 2.35 | 0.620 | 4,764 | Fig. 2a |
| | Layer 1 | Shock wave | - | 2.35 | 0.620 | 3.909 | Fig. 4a |
| Shock wave transmission from *Layer 1* to *Layer 2* | Layer 1 | Shock wave | Rarefaction wave | 1.85 | 0.715 | 4.236 | Fig. 2b Fig. 4a |
| | Layer 2 | Shock wave | - | 1.85 | 0.715 | 1.546 | |

### *3.3 Interpretation of results*

Analysis of the data in Table 3 and Fig. 4 points to the fact that:

1. The steel shrapnel generates at the interface with the first Dyneema layer of the panel (state 1 in Fig. 4a) a shock that has a pressure of 2.35 Gpa, a material velocity of 0.62 km/s and is transmitted into it at a velocity of 3.909 km/s;

2. At the same time a shock wave with a velocity of 4.764 km/s will be reflected from the interface into the steel projectile, which will increase the its pressure from atmospheric pressure to the value at the interface, i.e. 2.35 GPa;

3. The shock wave propagates through the Dyneema layer (and which is not attenuated according to the established assumption) towards the layer 1 - layer 2 interface (state 2 in Fig. 4b). This interface is at atmospheric pressure and has zero material velocity. When the shock wave reaches the interface, the pressure and material velocity on either side will change and have values of 1.85 GPa and 0.715 km/s, respectively. The wave transmitted into layer 2 will be a shock wave travelling through it at a speed of 1.546 km/s. From interface 1-2 a rarefaction wave will be reflected back to medium 1, leading to a pressure drop from 2.35 GPa to 1.85 GPa.

4. If instead of dry sand, water-saturated sand would have been used, Fig. 4b, then the induced shock would bring the interface to a pressure of 2.8 GPa and a material velocity of about 0.54 km/s. It can be seen that the presence of this medium has resulted in increased pressure at the interface (state 2' in Fig. 4b) due to the fact that medium 2 is now less compressible due to the presence of water. Under these conditions, the reflected wave from the interface will be a shock wave, which will increase the pressure in medium 1 from 2.35 GPa to 2.8 GPa. The existence of layers with different shock characteristics can thus explain the detachment and displacement of parts of the panels in the direction from which the incident shock wave comes.

## 4. Conclusions

Reducing the effects of IEDs detonation in confined spaces with large openings (airports, railway stations, and exhibition halls) requires the use of larger multi-layered ballistic panels to provide a reduction effect over a wide area. They have a dual role: on the one hand, they mitigate the effects of shock waves and fragments produced by IEDs and, on the other hand they can be used for partitioning and to support advertising materials. The choice of materials for such panels is constrained by the requirement that the arrangement of the layers (symmetrical to the vertical central plane of the panel) and by the cost of materials, given the dimensions of the panel. Under these conditions, this work has considered the use of Dyneema fabric layers on the outside and a sand layer inside the panel. The shape of the shock polars for granular materials of different sorts and moisture content showed that the greatest influence on shock wave attenuation is the moisture content while variation in grain size is less predominant. The arrangement consisting of a Dyneema fabric as a exterior layer was based on the fact that the application of the shock polar method implies that Dyneema fabric does not attenuate the shock wave. The value of the pressure at the shock wave front induced by the projectile in the Dyneema layer and propagated through it to the interface with the sand layer is 21% less than that generated at impact. Also, the use of a higher density inner layer (sand with a higher percentage of water or another material) will produce a higher pressure at the interface.

The choice of materials that can go into a multi-layer panel using the shock polars method is a qualitative method because it does not take into account the thickness of the layers. The determination of the thickness of the inner layer of granular material (sand or slag) to attenuate the penetration and passage of kinetic penetrators will be done taking into account the ballistic limit and will be the subject of a separate work.

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