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Numerical Calibration of Constitutive Models for Construction Materials against Blast Threat by Means of Ballistics Tests †

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Abstract: The design of infrastructure protections against ballistic and blast fragment impact requires a series of tests which are costly. In this study, the authors propose a methodology based on a practical approach with the aim of facilitating the attainment of parameters of a constitutive model, representative of the behavior of the main structural materials used in common constructions, as clay or concrete, with the objective of being able to make the hypotheses that are considered convenient at a moderate cost. To this end, the proposed methodology interpolates the parameters of the target material using ballistics tests framed in values of related materials contrasted with those existing in the literature.

Keywords: blast; numerical model; ballistic curve

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1. Introduction

Designing secure infrastructures, in addition to considering the conventional design loads that the building must withstand during its service life, must pursue complete structural integrity to minimize personal and material damage in the presence of potential extreme loads that may occur, whether they are of voluntary or accidental origin. Therefore, when facing events with direct consequences on individuals and material assets, such as ballistic impacts and explosions, it is necessary to understand the appropriate application measures that help minimize their effects and implement them during the design phase.

Specifically, when evaluating the case of projectiles, complex phenomena come into play both in the projectile launching process and in its impact against the target. When they are in the trajectory of a projectile, common materials used in the construction of structures add to the complexity of their mechanical behavior the effects produced by a high-speed impact and, therefore, their strain-rate dependance. For this reason, having the more complete constitutive models is key to improving protection.

However, most observable phenomena and their interaction require simplifications and pragmatic approaches to draw conclusions that can be applied in the field. This fact has been confirmed by many authors. Johnson and Holmquist showed that one of the main disadvantages of their phenomenological model was the difficulty to obtain the relationship between pressure and volumetric deformation [1]. Also, Zhang et al., recently made an attempt to define a complete group of parameters for Riedel-Hiermaier-Thoma (RTH) constitutive model, concluding that some parameters should be assumed in order to simulate clay behavior.

Additionally, the economic and time costs of experimentation make it impractical in many cases to obtain directly and verify these parameters in the field.

Interest raises as, recently, several research use new composite materials to develop brick units. New components, mostly of organic nature, have been included in the base materials for clay bricks. These materials, some of them presented in Table 1, mixed with clay and heated up to 1000 °C, improve the properties of the bricks, or simply produce good characteristics with very economical costs while using residual materials:

Table 1. Material properties for composite materials used in manufacturing clay bricks.

Composite material	Compressive strength	Reference	Standard
Rice husk	17.1 MPa	[2]	TS-EN-772-1
Borogypsum	~25–45 MPa	[3]	-
Pumice	18.5–32.9 MPa	[4]	TS-EN-771-1
Galvanic sludge waste	86 MPa	[5]	UNE-EN-772-1
Waste glass	19.3–24.65 MPa	[6]	ASTM C62-13a
Olive mill waste	9.03–55.41 MPa	[7]	TS-EN-771-1
Biomass	10.1 MPa (*)	[8]	-
Waste marble	6.2–34.2 MPa	[9]	TS-EN-771-1

These types of bricks have been mechanically characterized in quasi-static conditions but not at high strain rate, due to the testing difficulties. As can be seen in Table 1, paying attention to their compressive strength in comparison to conventional materials, they can be considered as potentially promising protective materials given their **compressive strength**.

Hence, in this work, a methodology is proposed for obtaining constitutive model parameters for common construction and protective materials, allowing for the rapid and economic characterization of any type of material by performing ballistic tests and using bibliographic background.

2. Material Model

The model chosen by the authors was developed by Johnson and Holmquist in 1993 (JH-2). The reason for choosing this model is its phenomenological nature specifically defined for numerical codes applied to brittle materials subjected to large strains.

Firstly, to be able to apply the methodology described, it is necessary to know the relationship between the sensitivity of the model and its effect on the ballistic penetration curve. To this end, the authors have developed a series of numerical models from which the corresponding ballistic curve is obtained by varying one of the parameters in each case.

The model used are clearly oriented towards the application in numeric hydrostatic codes. From the outset, it is well known that there is no direct procedure for obtaining the variables of the model, and that the model is sensitive to slight variations in their value [9], a fact that is not incompatible with being able to apply an inverse adjustment of the variables from the ballistic curve of the material.

From the proposed approach, the JH2 model can be considered that transforms the incident velocity into a residual velocity. If the solid resists the impact of the projectile, the exit velocity (V_r) is zero. Whereas if the solid has been unable to withstand the pre-shock produced by the projectile, residual velocity is greater than zero ($V_r > 0$).

This approach requires to understand the sensibility of the model and its response to changes. In a first stage, the variation in residual velocity is checked when changes take place in one parameter. Secondly, parameters have been grouped and studied the variation produced in the residual velocity. One of the conclusions is that Johnson-Holmquist model shows small sensibility to changes in one parameter, whereas changing groups of variables lead to greater changes. This is an advantage of the model that the authors have seized to reach enough agreement between numerical Lambert-Jonas curves and tests.

Johnson-Holmquist model has been described frequently by several authors [1,10], counting on very interesting reviews and improvements [11]. Here, just the fundamental equations will be described. The model consists of three different equations, one describing the material, another describing the damage accumulation, and the last one relates the pressures and the volumetric strain, following detailed.

Table 2. Johnson-Holmquist 2 model expressions.

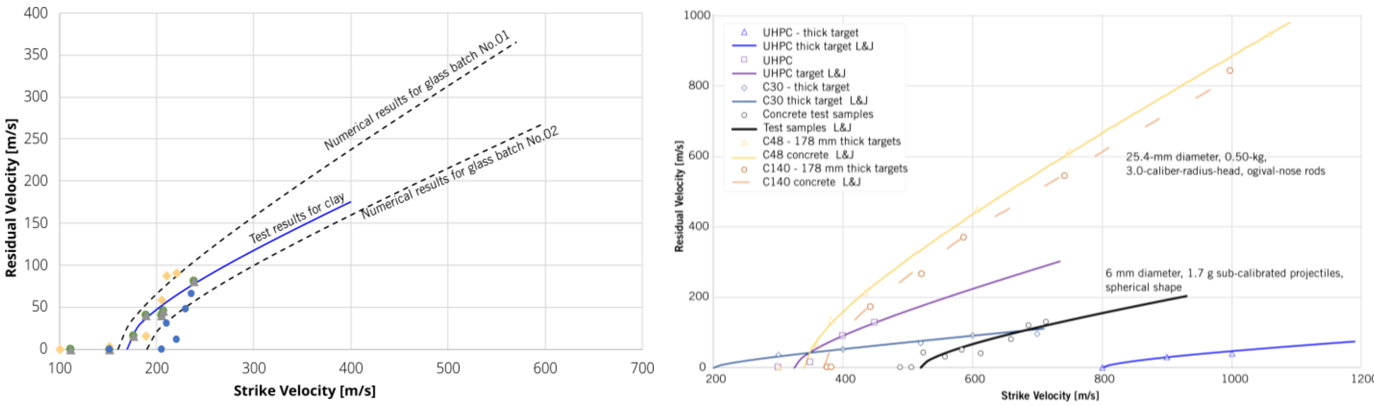
Description of Strength of Material	Description of Behavior under Progressive Damage	Dependence on the Pression EOS, Volumetric Strain and Hydrostatic Pressure
$\sigma_i^* = A(P^* + T^*)^N(1 + C\ln\dot{\varepsilon}^*)$	$D = \sum \frac{\Delta\varepsilon_p}{\varepsilon_p^f}$	$\mu = \frac{\rho}{\rho_0} - 1$
$\sigma_f^* = B(P^*)^M(1 + C\ln\dot{\varepsilon}^*)$	$\varepsilon_p^f = D_1(P^* + T^*)^{D_2}$	$P = K_1\mu + K_2\mu^2 + K_3\mu^3 + \Delta P$ when $D > 0$ and $\mu > 0$
$\sigma^* = \sigma_i^* - D(\sigma_i^* - \sigma_f^*)$		$P = K_1\,\mu$ when $\mu < 0$
σ_i^* = Intact strength	C = Strain rate dependence	D1,D2 = Damage parameters
σ_f^* = Failure strength	D = Damage behavior	K1,K2,K3 = EOS coefficients
A,N = Intact strength parameters	$\dot{\varepsilon}^*$ = Strain rate	P^* = Normalized pressure
B,M = Failure strength parameters	$\Delta\varepsilon_p$ = Variation in plastic strain	T^* = Normalized tensile strength

In parallel, Lambert and Jonas developed an adjustment expression to represent the ballistic curve as a function of impact velocity and residual velocity.

$$V_r = \begin{cases} 0, & 0 \le V_s \le V_l \\ a\left(V_s^p - V_l^p\right)^{1/p}, & V_s > V_l \end{cases}$$

The above is then applied to both clay and concrete samples. In Figure 1a, two ballistic curves obtained numerically with two sets of parameters of the JH-2 model published in the literature can be seen. By superimposing both curves next to the one obtained by ballistic penetration tests, it lies between the two. One of the advantages of doing so is that both the numerical models and the tests performed by the authors have the same characteristics of the projectile used and the sample. In Figure 1b, both the thickness and dimensions effect are shown for C30 class and Ultra High-Performance Concrete (UHPC) numerical curves together with C48 and C140 class concrete impact tests produced with different thickness samples and projectiles. Thus, sample thickness and the characteristics of the projectile have an important effect on the resulting ballistic curve.

We see that values by the tests carried out by the authors, lay between the ballistic curves from two batches of numerical curves made of residual velocities using two different parameters for glass from the literature. Hence, the values now are an interval between both, and it is just needed to modify one of both to yield an approximate curve for clay.

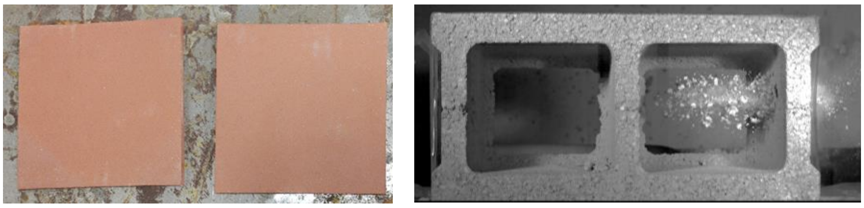


(**a**) (**b**)

Figure 1. Comparison of curves obtained using own generated numerical models using JH-2 parameters from the literature compared with the curve obtained performing penetration tests. (**a**) for two batches of glass (**b**) for concrete.

3. Experimental Methodology

The experimental methodology used consisted of testing 8 different types of construction materials under spherical projectile ballistic impact. Specifically, two of them were chosen the present the methodology: clay slabs and cement blocks (Figure 2).



(**a**) (**b**)

Figure 2. Samples used in ballistic penetration tests: (**a**) Clay slabs, (**b**) Concrete blocks.

The impact tests were carried out at the Structural Impact Laboratory of the Universidad Carlos III de Madrid, using mild steel spherical projectiles of 7.5mm diameter and 1.6g mass, launched using a Sabre Ballistics gas-gun (see Figure 3).

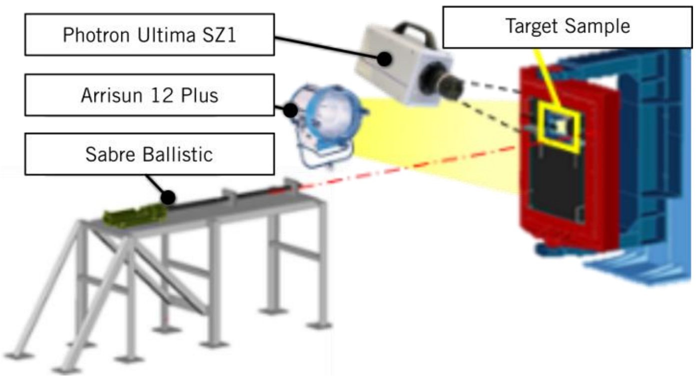
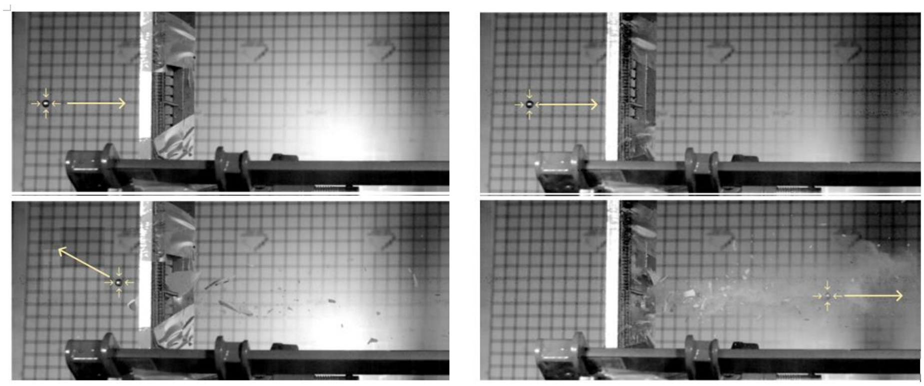


Figure 3. Testing device.

The projectile is propelled by compressed helium, reaching impact velocities of up to 850 m/s. Using a high-speed camera system, capable of acquiring up to 2.1e6 FPS (frames per second) and an illumination system, both qualitative and quantitative information of the impact process has been obtained, determining the impact velocity of the projectile, V_s^p, and the residual velocity after impact, V_r with a measurement error of about 15 m/s.

To minimise the effects of impact inertia that often lead to premature fracture of the sample, the slabs are taped to a metal frame. The system is sufficiently solid to reduce the generation of additional debris that would impede the tracking of the projectile. In the case of concrete blocks, the fixing is more complex since, due to their size, it is not possible to use a metal frame and it must be ensured that the impact does not dislodge the block.

The procedure followed to obtain the critical velocity was that described by Jonas and Lambert in their report on the standardisation of ballistic curves [4]. It should be noted that, for all the materials tested, clay slabs and the concrete blocks produced the most visible results (See Figure 4).



(**a**) (**b**)

Figure 4. Impact tests. (**a**) Impact at 111 m/s: projectile rebound. (**b**) Impact at 205 m/s. penetration and debris clouds of material.

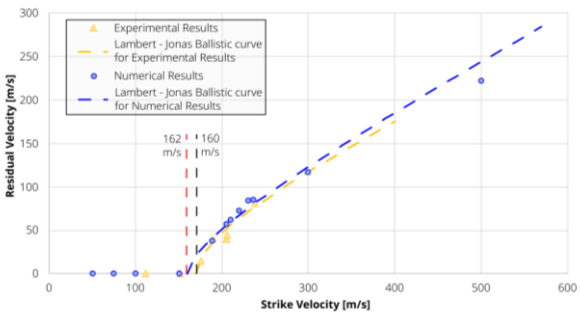
4. Numerical Models

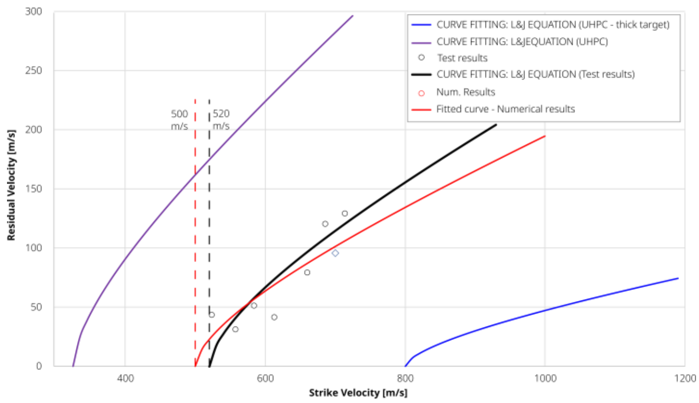
Numerical models were carried out include a study of sensibility related to the ballistic curve. Previous works evaluated the sensibility of other testing techniques like impact disc, Hopkinson's pressure bar, but none, to the authors' knowledge, have been performed on ballistic penetration curves related to the variation of the JH-2 variables.

One of the main conclusions of the sensibility study is that the limit velocity is highly dependent on the combination of the couple damage variables $D(D_1, D_2)$. Therefore, adjusting both variables at the same time is key to yield the corresponding displacement of the curve to match the experimental result is firstly depending on the variation of these two parameters.

5. Results and Discussion

The ballistic curve of two materials frequently employed as construction materials, as depicted in Figure 5, have been empirically derived through the utilization of a JH-2 constitutive model. In both cases the values used led to a conservative numerical ballistic limit velocity value of less than 2% of deviation for clay, and 4% for concrete, which improves substantially the initial proposal. The model parameters have been obtained based on previously documented values from the literature to closely match the experimental outcomes. Subsequently, a comparison has been conducted between the ballistic curves of concrete and clay and their respective experimental counterparts.





(**a**) (**b**)

Figure 5. Comparison of the results obtained by numerical models with respect to the ballistic impact tests. (**a**) for clay (**b**) for concrete blocks.

6. Conclusions

As a conclusion, the model demonstrates a commendable level of precision in predicting the ballistic limit, making the acquired parameters well-suited for applications exposed to impulsive loads characterized by similarly high strain rates, such as blast impact scenarios, all the while preserving cost-effectiveness. Consequently, the employment of ballistic impact tests has proven to be an efficient approach for enhancing the performance of ceramic material constitutive models, leading to improved outcomes when applying published parameters within these models.

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