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**The Ballistic Resistance of Adobe Masonry:
An analytical model for impacts on mud bricks and mortar**

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The resulting information was collected and organized into a database. It was used as statistical basis to develop an analytical predictive model capable of correctly addressing the terminal ballistic depth, namely penetration length, in case of small calibre impacts on Adobe targets. The proposed phenomenological model, that belongs to a class of models based on Newton's 2nd law, parametrizes the sources of energy dissipation during penetration through a linear dependent bearing resisting force model. The properties of the targets were experimentally determined during an additional experimental characterization campaign performed on Adobe components in 2016 in the Netherlands.

The paper presents the experimental data, the analytical model developed and the calibration of parameters, providing the relation between the experimental and the predicted penetration lengths.



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Keywords: phenomenological model; small caliber; ballistic impact; penetration length; Adobe; wall; bricks; mortar; resistance; dynamic strength.

INTRODUCTION

The study on penetration of projectiles into media is an ancient discipline [1]. However, research in the field progressively ceased after the second world war [2]. Only in the last decades it has gained new attention, mainly focused on modern materials like concrete or composites [3]-[4]. Nowadays, the change in warfare is leading experts to explore the ballistic response of buildings spread in areas involved into military operations [5], among which Adobe is one of the most relevant [6]. Adobe is a traditional form of masonry whose components are made of sun dried cast soil bricks and mud mortar [7]. Unfortunately, the mechanical properties of Adobe components are still poorly understood but recently systematic research has been performed [8]. Assessing the dynamic performance of this material at high velocity loadings such as ballistic impacts is a challenging task. The study of the ballistic response of building materials towards projectile impact can be approached in three ways: empirical, analytical or numerical [9]. Although numerical simulations are the only ones that can evaluate the actual mechanisms active in the material in detail, the development of simple formulations, despite their intrinsic limitations, are necessary for practical applications [10]. In fact, the prediction of ballistic parameters such as the residual velocity or penetration length is a topic of primary interest for both civil and military purposes [11]. The purpose of this paper is to present a new analytical model for the prediction of the penetration length in Adobe. This model is based on the results of an extensive experimental campaign conducted in the Netherlands between 2013 and 2016. It consisted of physical and mechanical tests performed on Adobe bricks and mortar with different soil composition and moisture content used to assemble the targeted walls. They were subjected to small caliber ballistic impacts. The paper is organized in two parts: The first part briefly explains the experimental campaign and the results achieved, followed by the presentation of a framework of the main analytical and empirical models developed for building materials so far. The second part contains the statistical elaborations

of the ballistic tests together with the presentation and calibration of the new analytical model proposed for Adobe.

THE EXPERIMENTAL REFERENCE

From July 2012 to July 2013, a ballistic campaign was performed at the ASK in 't Harde (The Netherlands). It consisted of three shooting test series during the year in the months of November, March and July, so different temperature and humidity conditions were taken into account. Each test series consisted of more than five shoots in average impacting a specific sector of the target (*Figure 1(a)*). Six different small caliber bullets were used. Their properties are reported in *Table 1*.

Table 1. Diameter, mass and total length of impactors

Projectile	Properties	Projectile	Properties
7.62AP	Diameter: 7.82mm Mass: 9.5g Length: 32.55mm	.50Ball	Diameter: 12.7mm Mass: 41.8g Length: 58mm
7.62Ball	Diameter: 7.82mm Mass: 9.44g Length: 28.54mm	.50KB	Diameter: 12.7mm Mass: ~21g Length: ~25mm
7.62x39 API	Diameter: 7.89mm Mass: 7.64g Length: 27.70mm	.50 API	Diameter: 12.7mm Mass: 42.9g Length: 58.7mm

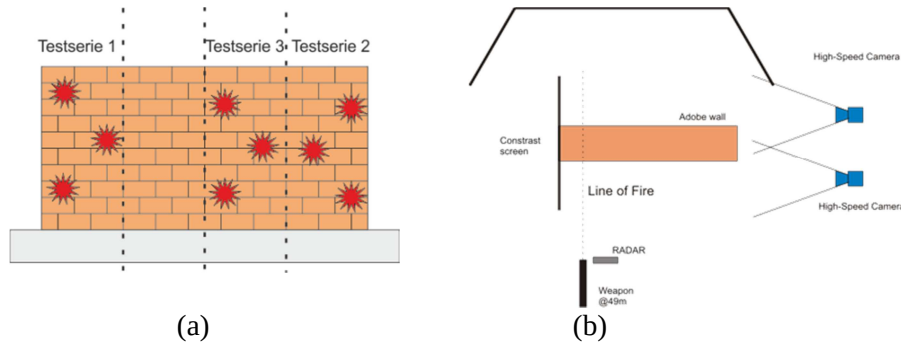


Figure 1. Test serie impacting sectors (a) and experimental setup (b)

The targets consisted of ten 40- or 80-cm thick Adobe walls built using two different types of bricks and the same mud mortar, ordered at a private company in Germany. The bricks and the mortar differed in terms of their internal soil composition. Their physical properties were determined by means of granulometric and density tests, while uniaxial compressive tests and three point bending tests on both air dried and oven dried samples were performed to derive the main static mechanical parameters in compression and tension. In particular, the elaboration of experimental load-displacement curves revealed softening behaviour in compression and tension that could be addressed using constitutive models developed for unreinforced concrete [12], as shown in *Figure 2*. In *Table 2* the mean values are specified for each physical and mechanical property and for each type of brick (connoted with letters A, B) and mortar (M). From the table it is evident that the mechanical parameters depend on moisture content. In [8], eq. (1) was presented as a relation between the air dried strength f_{ca} and the oven dried strength f_{co} with the water content w of the mixture. The moisture content levels for each walls and test series are reported in *Table 3*.

Table 2. Mean values of properties for air-dried and oven dried bricks (A,B) and mortar(M)

Type	Clay, Silt, Sand, Fiber (bw)	Density	f_{ca}	f_{co}	E_{ca}	E_{co}
	%	Kg/m^3	MPa	MPa	MPa	MPa
A	24-25; 47-48; 27-28; 17-18	1234	1.3	1.7	102	141
B	18-19; 43-46; 30-33; 32-37	799	0.2	0.3	12	14
M	11-12; 66-68; 21-22; 3-5	1414	1.6	1.9	206	//

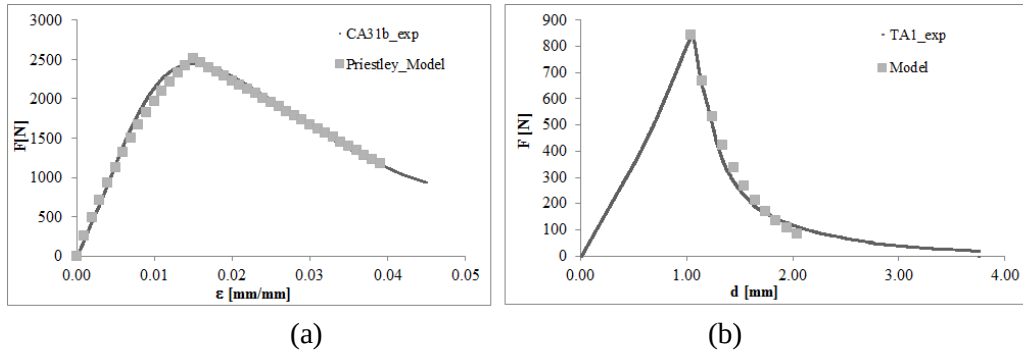


Figure 2. Typical stress strain curves in compression (a) and tension (b), derived from analytical models for concrete

$$f_{ca} = f_{co} w^{-b} \quad (1)$$

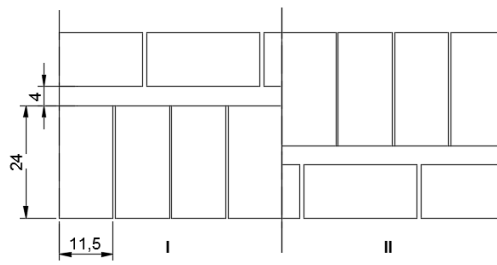
The complete list of tested walls with the indication of the thickness and the used bricks is reported in *Table 3*. A picture of an Adobe wall is reported in *Figure 3(a)*. Each wall was built with the repetition in height and thickness of two different brickwork layouts, graphically reported in *Figure 3(b)*.

Table 3. List of targets, with indication of geometrical measurements and adopted brick and mortar Type and impacting projectile and average moisture contents for the three test series

Target	LxHxT	Brick Type	Mortar Type	Munition Code	Mean moisture content (for each test series)
1	2x1x0.4	B	M	7.62AP	8 % 11 % 8 %
2	2x1x0.4	B	M	7.62Ball	8 % 10 % 6 %
3	2x1x0.4	B	M	7.62API	8 % 10 % -
4	2x1x0.4	B	M	0.50Ball	13 % 6 % 7 %
5	2x1x0.8	B	M	0.50API	10 % 12 % -
6	2x1x0.4	A	M	7.62AP	7 % 7 % 5 %
7	2x1x0.4	A	M	7.62Ball	7 % 5 % 5 %
8	2x1x0.4	A	M	7.62API	6 % - -
9	2x1x0.4	A	M	0.50Ball	6 % 8 % 5 %
10	2x1x0.8	A	M	0.50API	10 % 8 % 6 %



(a)



(b)

Figure 3. An example of 40cm thick-Adobe wall target (a) and view from the top of the two different brick-mortar layout (b)

The experimental setup consisted of a zero angle inclined weapon with respect to the target, shot normally from 50 meters at velocities in a range of 700 m/s to 900 m/s. For each wall, the velocities were approximately constant among the following test series. Two high velocity cameras at the opposite layers of the target were emplaced in order to record the impacting velocity (*Figure 1(b)*). For each test, the penetration length of the projectile in case of penetration or the residual velocity in case of the perforation was measured. More than 150 shooting tests were performed. Little or no deformation of the projectile was revealed in all tests.

PRELIMINARY ELABORATION OF BALLISTIC TEST RESULTS

Considering either all the performed tests (Figure 4(a)), each wall (Figure 4 (b)), or each impactor results separately (Figure 4 (c)), a clear correlation between penetration depths and impact velocity was not obtained. Trends were not clearly visible even considering each test series individually (Figure 4 (d)). The results showed significant scatter. Considering tests on 40cm walls, the penetration length in case of impact on Type A bricks ranged between 15cm and 25cm (average of 20cm), on Type B between 20cm and 38cm (average of 28cm), and on mortar joints between 14cm and 30cm (average of 19cm). Considering 80cm thick walls, the penetration length in case of impacts on Type A bricks ranged between 37cm and 51cm (average of 46cm), on Type B between 43cm and 62cm (average of 51cm) and on mortar joints between 31cm and 78cm (average of 43cm). Thus, the results in case of impact on Type A bricks and on mortar were similar, while larger values characterized impacts on Type B bricks.

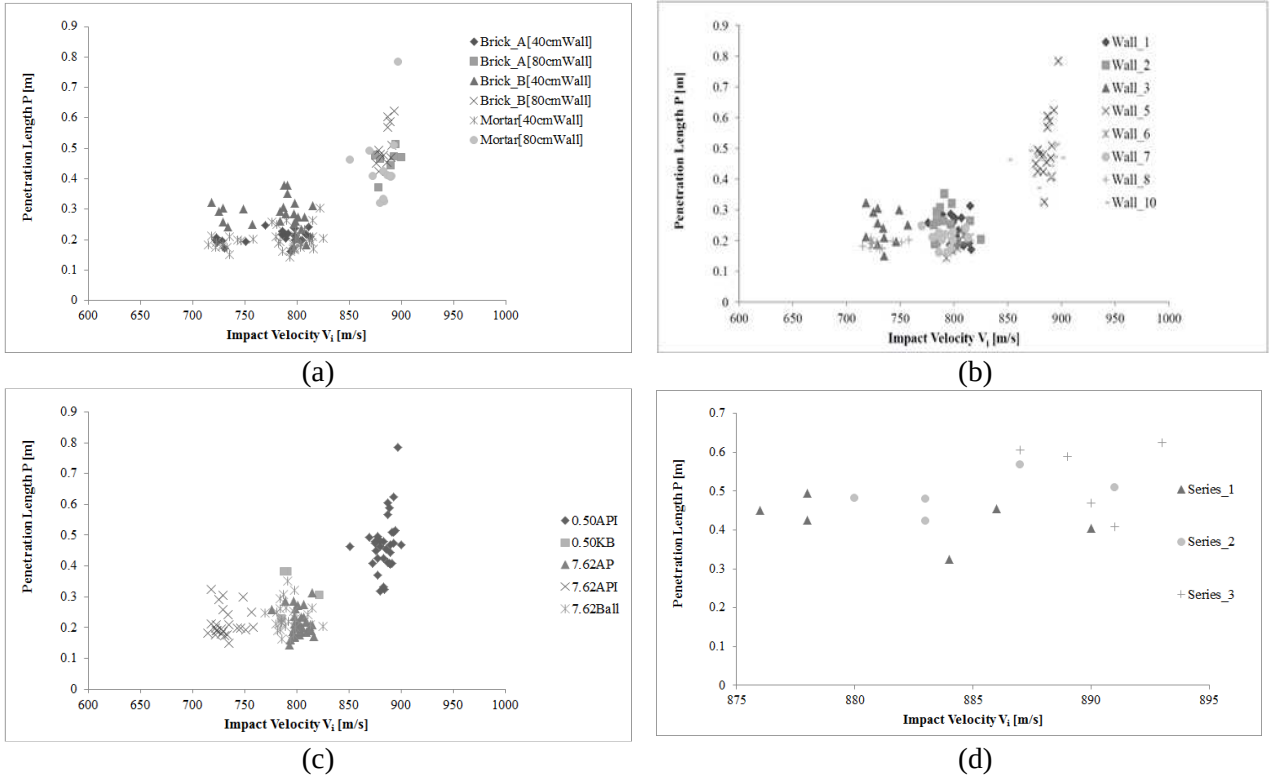


Figure 4. Penetration length and impact velocity considering all tests (a), each wall (b), each impactor (c) and the results of the different moisture contents for Wall no.4 (d)

BALLISTIC PHENOMENOLOGICAL MODELS

The ballistic models are described in the following according to two main classes.

Class of Analytical Models

The majority of ballistic models are based on Newton's second law of motion [13]-[9]. The resistance to penetration can be decomposed into three components as in eq.(2).

$$-m_p \frac{dv}{dt} = R = av^2 + bv + c \quad (2)$$

where the squared velocity-dependent term represents the contribution of inertial stress, the velocity dependent component controls the contribution of viscous resistance and the constant term is related to the bearing strength of the target (see the Nomenclature section). These models are based on basic assumptions not always straightforward in practical applications: the projectile is assumed to remain intact during penetration, with stable and straight trajectory. The earliest analytical model is from Robins-Euler in the

middle of XVIII century, who both assumed a constant resistance over penetration [14]. Integration in order to determine the penetration length of the projectile in the target results in eq. (3a). One of the most widely used model nowadays, especially for sandy and concrete materials, was presented by Poncelet in 1839 [15], who defined the resistance of penetration as the sum of an inertial and bearing component eq. (3b). Ignoring the bearing strength leads instead to the penetration length in eq. (3c), developed first by Resal (1895).

Robins- Euler ($a, b=0$)

$$P = \frac{m_p v_i^2}{2c} \quad (3a)$$

Poncelet ($b=0$)

$$P = \frac{m_p}{2a} \ln \left(1 + \frac{av_i^2}{c} \right) \quad (3b)$$

Resal ($c=0$)

$$P = \frac{m_p}{a} \ln \left(1 + \frac{av_i}{b} \right) \quad (3c)$$

The material parameters a and b may be related to dimensionless drag coefficients in aero and fluid dynamics employing momentum transfer and Newton's third law [13]. In this sense, a can be related to the quadratic drag force model developed by Newton as in eq. (4a), while b is linked to the Stokes' drag law for cylindrical bodies as in eq. (4b) [11]. Translated to solids, the first term represents the "dynamic pressure" determined by the inertia of the material in front of the projectile while the second term is the shear-resistance of the target material activated along the projectile. The dynamic resistance c is assumed to be proportional to the static strength of the target. In literature different strength formulations are assumed, dependent on the target material but also in relation to the impactor geometry and velocity regime [16]. In granular media it was recently found out to be depth dependent [17]. According to the available experimental data on Adobe, for the current research the bearing term c was initially assumed to be constant and proportional to the compressive strength of the material [18].

$$a \sim \rho_t A_p \quad (4a)$$

$$b \sim 6\pi \eta_t \max(l_p, \sqrt{A_p}) \quad (4b)$$

$$c \sim f_c \quad (4c)$$

Class of Empirical Models

Empirical formulae fit significant amounts of experimental data as function of mechanical or geometrical parameters of target and projectile. They still represent the most straight forward approach to design protective structures [19]. Nevertheless, they do have shortcomings: most of them are unit dependent and have a limited validity according to the range of velocity for which they are developed. The majority of them can be written in the form of (5a) [20]. The most popular formulations for concrete, as the Army Corps of Engineers formula (ACE) and the modified formula off National Defence Research Committee (NDRC) among others can be written in this form using the material parameters reported in Table 4 [21]. A different empirical model widely implemented is the Petry equation [21], developed in 1910 for unreinforced concrete as in (5b).

$$P = D(\alpha \frac{m_p v_i^{\gamma_1}}{D^{\gamma_2} f_c^{\gamma_3}} + \beta) \quad (5a)$$

$$P = 0.0005 \frac{m_p}{D^2} \log \left(\frac{1 + v_i^2}{20000} \right) \quad (5b)$$

Table 4. Penetration depth function values according to the different models

Formula	α	β	γ_1	γ_2	γ_3
Beth	0.00036ψ	0.5ψ	1.5	2.8	0.5
ACE	0.00035ψ	0.5	1.5	2.8	0.5
NDRC	0.000038ψ	1	1.8	2.9	0.5
Bernard	$0.254 \rho_p^{0.5}$	0	1.0	3.0	0.5

Where ψ is a function of conical radius (CHR) differently accounted according to the different models [19].

INVESTIGATION OF ADOBE TEST RESULTS ACCORDING TO EXISTING MODELS

The analytical and empirical models presented in eq. (3) and eq. (5) were implemented within the “Adobe ballistic Database”, that for each performed test resumed the information on the impactor, targeted brick or mortar, and their interaction, in terms of velocity and location of impact, besides the final penetration length values. In order to provide a trustworthy set of data for a semi-infinite target investigation, results of projectiles penetrating above the 85% of the target thickness were excluded. In eq. (4a), the density of the impacted brick or mortar was used. If the trajectory of impact was likely characterized by the significant penetration of the projectile into two different media, which means for more than 50% of the final penetration length, averaged values of density between the hit brick’s and mortar ones were used. Thus, the density value of the majority of tests impacting bricks in the configuration *Figure 3(b)-II-* was averaged. The bearing strength in eq. (4c) was implemented as in eq. (1) using the data from available measurements on moisture content (*Table 3*). In fact moisture content values were not available for all the targeted bricks and mortar. In absence of own data, the viscosity coefficients values were taken from literature for clays within the ranges of 150-400 Pa s [22]. Using this set of values, statistical correlation of the models with respect to experimental results was investigated, revealing a lack of correspondence for both empirical (*Figure 5(a-c)*) and analytical (*Figure 5 (e-f)*) models. Among the analytical models, the best fit was found for the Resal model (*Figure 5(f)*).

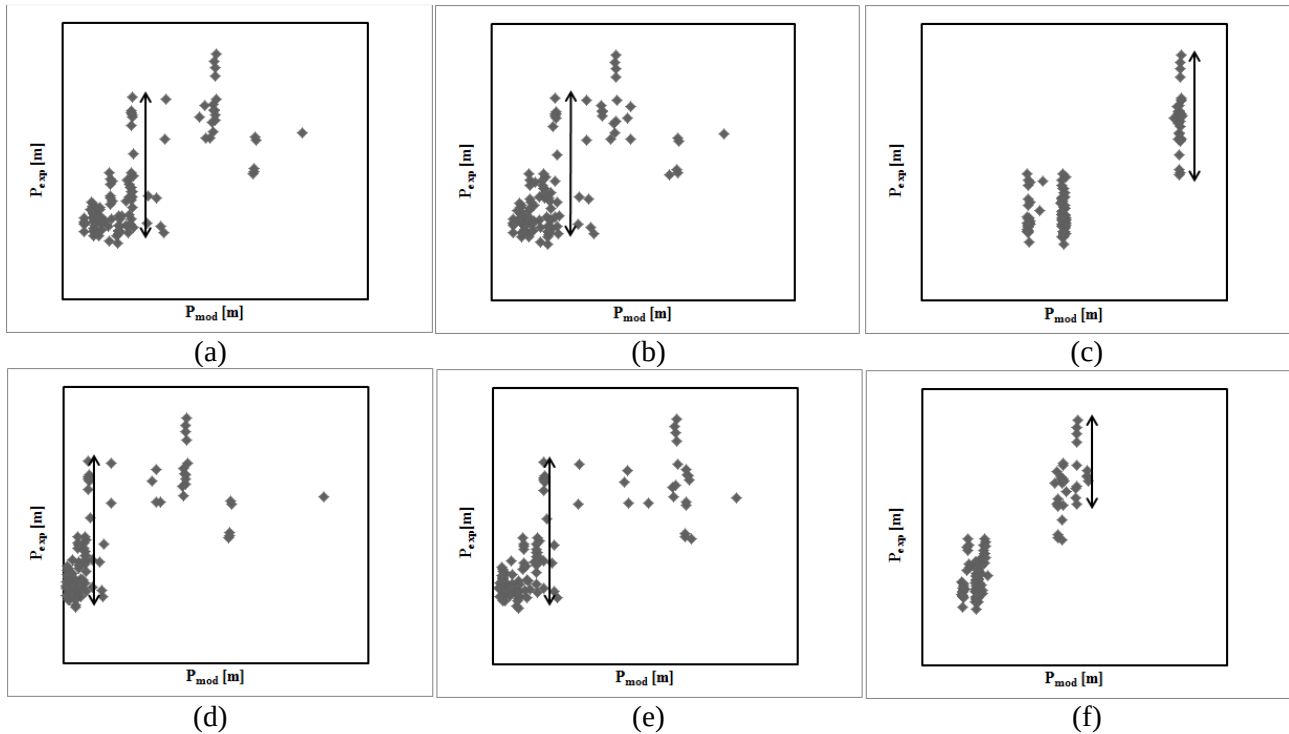


Figure 5. Experimental-analytical comparison for Beth (a), Bernard (b), Petry (c), Euler (d), Poncelet (e) and Resal (f) models

Resal’s approach was the starting point of the model used by Heine in 2011 to address the penetration length of impacting steel spheres on semi-infinite targets of Adobe [23]. In particular, extracting the different velocity contributions from eq. (3c), Heine came to the formulation in eq.(6a). Fitting the data, it was referred that the v^2 -term only played a significant role for impact velocities above 1000m/s and a v -dependent penetration depth equivalent to a pure Stokes’ drag force was considered sufficient to address the ballistic results [6]. Using the resulting formulation in eq. (6b), a good experimental-analytical correlation was revealed also with respect to the experimental data contained in the Adobe Ballistic Database (*Figure 6(a)*). In 2016, Heine proved also a good correlation between impact results on Adobe and a penetration model developed for polycrystalline graphite targets subjected to high velocity steel spheres impact [4]. Based on a shock wave approach, also this penetration model is linearly dependent on impact velocity according to the

formulation proposed in eq. (6c). The latter model did not produce a clear correlation with our set of results (Figure 6(b)).

$$P = \frac{4D}{3} \left(\frac{1}{B_1} \frac{\rho_p}{\rho_t} v_i - \frac{B_1}{B_2} \frac{\rho_p}{\rho_t} v_i^2 \right) \quad (6a)$$

$$P = \frac{8m_p}{B_1 \pi D^2 \rho_t} v_i \quad (6b)$$

$$P = \frac{2Dm_p}{3d\psi\rho_t C_t} v_i \quad (6c)$$

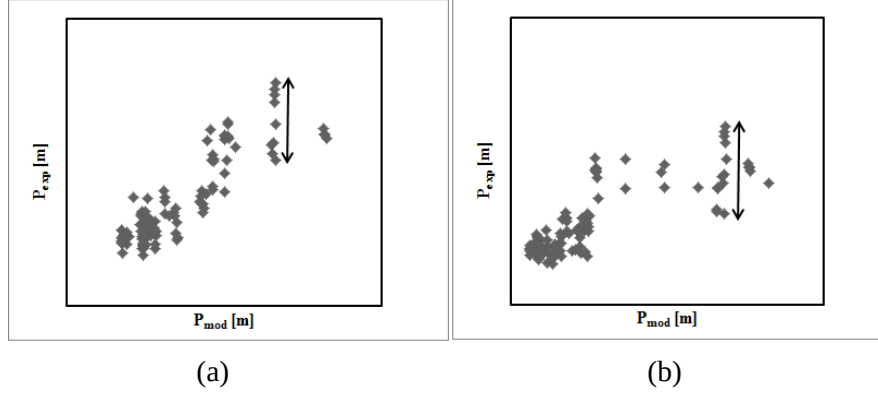


Figure 6. Experimental-Analytical comparison for Heine (a) and Seisson (b) models

A NEW MODEL FOR ADOBE AND FINAL CALIBRATION ANALYSIS

The analysis of the ballistic campaign results showed that penetration depth models including the inertial v^2 -contribution did not produce a clear correlation with experimental data. Moreover, it emphasized a good experimental-analytical correlation using a penetration length model being linearly dependent on impacting velocity. These findings confirm the results of other ballistic laboratory research on Adobe [6]. In his research, Heine proposed a model that neglects the contribution of bearing strength and treats the material's response to high velocity penetration as a Stokes fluid. On the other hand, he proved a significant correlation with experiment also using a model based on shock wave, which is a different approach. Thus, this study questions if either of the proposed models are correctly interpreting the nature of the material response, besides the linear v -dependency that has been confirmed experimentally also herein. In fact, considering only the contribution to resistance of the shear layers activated along the penetrating projectile implies neglecting the effect of Adobe ahead of the impactors. Moreover, the results of the static campaign performed on bricks and mortar in 2016 discourages the use of mechanical parameters such as compressive strength and elastic modulus to calculate the penetration length, because they have been found significantly dependent on moisture content, that is not a straightforward measurement in the field. On the other hand, an alternative way to achieve a v -dependent penetration length model can be derived from interpreting the resistance of Adobe ahead of the projectile. Using the same approach as in eq. (2), a new analytical-empirical model for Adobe was developed. In the model, the resistance to penetration in eq. (7a) is governed by the bearing strength of the material, that in turn is assumed to be depth dependent, like often found for impacts into soil targets [24]. The proposed model resembles the approach developed by Forrestal for concrete targets subjected to high velocity impacts [25], if in the tunnel region (after 2D) the inertial contribution of the resisting force is neglected and a dominant shear Coulomb friction is considered as in eq. (7b). Integrating the equation with respect to velocity and depth in eq. (7c), the maximum depth of penetration is obtained in eq. (7d). As a further simplification, since the impactors were all small calibers projectiles and the density of Adobe is low in comparison to impactors, it was considered plausible to neglect the contribution of the first two diameters of energy dissipation in eq. (7c). Therefore, the final penetration length is calculated as the right end side of eq. (7d), where the calibration factor includes the friction coefficient and the shape factor takes into account the decrement in ballistic performance observed for multi-layered concrete targets

subjected to hard ogival impactors [26]-[27]. Thus, a linear penalty function was set according to the number of brick layers in each wall (Figure 3(b)).

$$R = \mu \rho_t g \psi A_p x(t) \quad (7a)$$

$$-m_p \frac{dv}{dt} = \mu \rho_t g \psi A_p x \quad (x > 2D) \quad (7b)$$

$$-m_p \int_{v_1}^0 v \, dv = \mu \rho_t g \psi A_p \int_{2D}^P x \, dx, \text{ where } (v_1^2 = v_i^2 - \frac{4D^2 \mu \rho_t g \psi A_p}{m_p}) \quad (7c)$$

$$P = \frac{1}{d} \sqrt{\frac{m_p v_1^2}{\rho_t g \psi A_p} + 4D^2} \sim \frac{1}{d} \sqrt{\frac{m_p}{\rho_t g \psi A_p}} v_i \quad (7d)$$

$$\psi = \frac{2}{A_t} (CRH - 0.25)^{0.5} = \frac{2}{A_t} N_{ace} \quad (7e)$$

The proposed model was investigated and finally calibrated with respect to the performed tests. Similarly, the formulation used in eq. (6b) was calibrated with the experimental results [6]. The graphical comparison between experimental and predicted penetration lengths are evaluated in Figure 7.

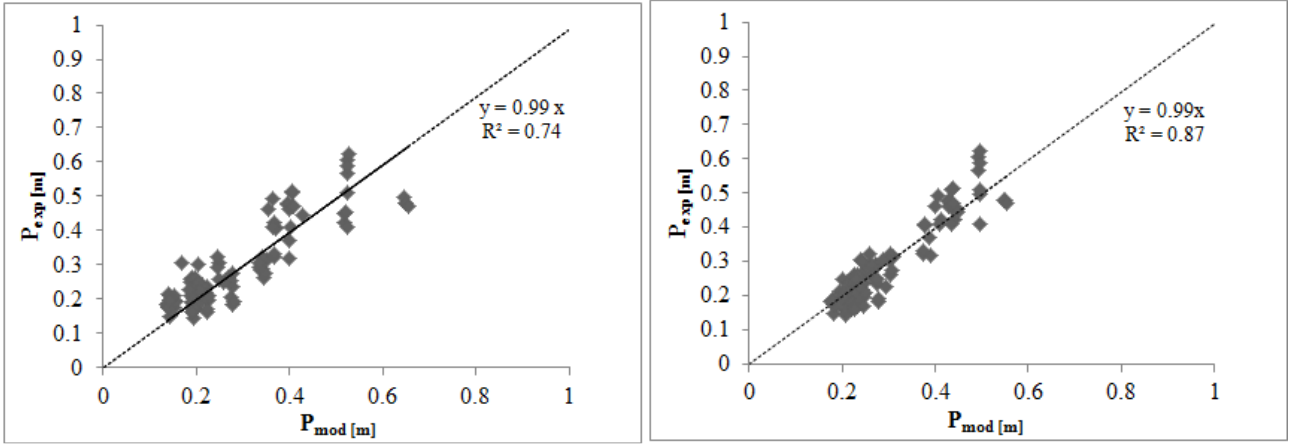


Figure 7. Analytical calibration using eq. (6b) [6] (a) and the Adobe ballistic (c) models

Both calibrated models show a good agreement with experimental data, and in the case of the Adobe ballistic model the coefficient of determination is almost equal to 0.9. The best fit calibration factor d for the Adobe ballistic model was about 960 (900 considering only the third test series). Using the viscous model in eq. (6b) with our dataset, the inferred value of B_l was 1150. The analytical-experimental errors in terms of penetration length were calculated and in Table 5 they are presented also with respect to the thickness of the targeted walls. Both models can predict the penetration depth of Adobe with a relative error less than 10% of the thickness of the target. In particular the Adobe ballistic model proved to be effective also in case of very thick walls, as shown by the low mean errors and related standard deviations.

Table 5. Experimental-Analytical penetration length mean errors, standards deviation and percentage errors with respect to target thickness for the two models

Thickness	Heine [23]			Adobe Ballistic Model		
	Mean Error	S.d.	Mean / thickness	Mean Error	S.d.	Mean / thickness
m	$ m $	$ m $	%	$ m $	$ m $	%
0.4	0.035	0.02	~9	0.027	0.02	~7
0.8	0.077	0.05	~9	0.048	0.03	~6

CONCLUSIONS

The paper presents the results and analysis of a ballistic campaign performed on Adobe. Ten Adobe walls built with different types of bricks and mortar were subjected to shooting tests using a wide range of small calibers impacting the targets at velocities between 700-900m/s at different locations of the wall and climatic conditions. The single bricks and mortar were also experimentally characterized, mechanically and physically. Assessing the static and dynamic material performance of Adobe is a challenging task. Soil mixture and fiber reinforcement are randomly mixed in the field, with possible scatter in the composition among bricks of the same type. Moreover, the static experimental campaign revealed that the properties of sun dried bricks depend on the moisture content, that in turn is likely to change along the year and to depend on the clay mineralogical family of the mixture. For these reasons, the good correlation results of the analysis with the proposed model are even more striking. It has been shown that for the analysed range of impacting velocities, v -dependent penetration models are able to address the ballistic performance of real Adobe walls, independently from shooting the bricks of different composition or the mortar joints. This finding confirms the results of the only other laboratory research performed on Adobe that the authors are aware of. In fact, interpreting the resistance of Adobe for high velocity impact as a Stokes fluid led to an appreciable agreement also with the experimental results of the present campaign. On the other hand, the research of this paper questions the true nature of the Adobe ballistic response. In fact, different approaches can lead to v -dependent penetration models. The analytical model in this paper presented an alternative view to the solution: the ballistic performance of Adobe is considered to be governed by the resistance of the material opposite to penetration ahead of the projectile. The material strength is assumed to be linearly dependent on penetration depth as found in case of penetration in soil. Also this approach leads to a penetration length formulation linearly dependent on the impacting velocity but the dependence on the impactor/target densities ratio is less than linear. The analytical-experimental comparison is characterized by a significant correlation factor. This model recalls some features of the framework developed by Forrestal for concrete, if after the crater formation, the resistance is assumed to be governed by shear. Also in statics, the response of Adobe was addressed using constitutive models developed for concrete. Together with other statistical inference, such as the ballistic performance decay for multi-layered targets in dynamics, the findings so far indicate that Adobe responds more as a solid material than as a fluid to high velocity impacts. But only further experimental investigations and numerical simulations can confirm or deny the response mechanisms of Adobe to ballistic impact.

NOMENCLATURE SECTION

a inertial parameter [kg/m]
 A cross area [m²]
 b viscous parameter [kg/s]
 B calibrating parameter (Heine)
 c strength parameter [N]
 C bulk sound velocity [m/s]
 d calibrating constant
 D projectile Diameter [m]
 E elastic modulus [MPa]
 f compressive strength [MPa]
 g acceleration of gravity [m/s²]
 H total height of the wall [m]
 l projectile length [m]
 L total length of the wall [m]
 m Mass [kg]
 N nose caliber
 P penetration length [m]
 R total resistance to penetration [N]

t time [s]
 T total thickness of the wall [m]
 v projectile instantaneous velocity [m]
 x projectile depth at instant t [m]
 w water content [%]
 α, β, γ empirical Dimensionless constants
 Δ number of target layers
 ρ density [kg/m³]
 μ friction coefficient
 η viscosity coefficient [Pa s]
 ψ projectile nose shape factor function
Subscript
 $_a$ sundried
 $_c$ compressive
 $_i$ impacting time
 $_o$ ovendried
 $_p$ projectile
 $_t$ target
 $_{1,2,3}$ calibrating constant numbers

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