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Ballistic model for the prediction of penetration depth and residual velocity in adobe: A new interpretation of the ballistic resistance of earthen masonry

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ABSTRACT

In this paper, a new one-dimensional phenomenological model is developed for the assessment of the ballistic performance of Adobe. Adobe is a masonry largely spread in areas of the world involved in military operations. Addressing fundamental ballistic parameters such as residual velocity or penetration depth for this building technology is necessary. The model follows the hypotheses for the ballistic response of concrete targets to high velocity impacts, provided with a dominant contribution of shear friction typical of soils. The hypotheses at the basis of the model are consistent with all experimental evidence collected by authors on Adobe. Adobe brick and mortar belong to the material class of concrete, whereas the overall mechanical parameters are determined by the internal soil mixture, including the percentage of fibre reinforcement. Despite its relative simplicity, the model is capable of well predicting ballistic test results currently available in literature for Adobe, including the data of an experimental campaign recently performed by the authors on real Adobe walls in the field.

1. Introduction

The recent progression of urban warfare in the world is leading governments to invest in research focused on the ballistic response of building materials. Among these, Adobe, a masonry made of sun dried soil bricks and mud mortar, is a construction type largely spread in areas of the world involved in armed conflicts. Among the possible approaches to interpret the ballistic response of structures, so-called ballistic phenomenological models, analytical models which parametrize the inertial, viscous and bearing strength contributions to the resistance of the target during penetration, are well suited to promptly estimate fundamental ballistic parameters during in field operations, such as depth of penetration or residual velocity for given trajectory, bullet type and striking velocity. Two of these models have been recently proposed to assess the ballistic performance of Adobe masonry (Eq. (1)) [5]. One is based on stationary body motion in medium, consistent with the hypothesis of a pure Stokes' drag force as main resistance to penetration (Eq.(1a)) [1,3]; while the other is based on a shock wave approach, originally developed for simulating hypervelocity impact on graphite targets (Eq.(1b))[2]. Both of them share the same linear dependence between the final depth of penetration of the projectile (P) and its impacting velocity (v_0), which matches the experimental results obtained from laboratory tests on semi-infinite targets of Adobe in Refs. [3] and [5].

$$P \sim \frac{D}{k}\frac{\rho_p}{\rho_t}v_0 \tag{1a}$$

$$P \sim \frac{D}{\alpha C}\frac{\rho_p}{\rho_t}v_0 \tag{1b}$$

Where D is the impactor diameter, k is a calibration constant, ρ is the density (of the projectile p and target t), v_o is the impact velocity

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on target, α is a shape coefficient and C is the bulk wave speed. Both formulas show a linear dependence on the impacting velocity and on the ratio of target and projectile densities [4]. The good agreement using the few sources of data currently available for Adobe in literature is evidence that the response mechanisms of the material to penetration result in a linear relationship between impacting velocity and penetration depth [1,3–5]. However, the hypotheses at the basis of the two models are not consistent with each other and a definite interpretation of the ballistic mechanisms of resistance of Adobe has not been achieved yet [4]. Therefore, a new ballistic campaign aiming at experimentally addressing the ballistic response of real Adobe walls subjected to impacts at striking velocities lower than 1000 m/s using small caliber projectiles was recently performed. Elaboration of results shared in Ref. [4] had confirmed some experimental trends given in Refs. [1] and [3], such as the linear dependence between P and $v_{0,}$ as proved by a decent statistical correlation with experimental data using eqn. (1), considering the natural scatter inherent real shooting tests in the field [4] (Fig. 1). Besides, experiments have also confirmed previous findings by authors on the constitutive nature of Adobe bricks and mortar, which are both inserted in the material class of concrete provided with a major influence of soil granulometry on the values of the overall mechanical properties [6–8]. A new ballistic phenomenological model consistent with experimental evidence is proposed in this paper for Adobe. This is rooted from a model originally developed by Forrestal in 1994 to simulate high velocity penetrations of projectiles into geo-material targets such as concrete [9], adapted in order to include the shear resistance of soil for deep penetration [10]. In the next sections, the model is presented, including its preliminary experimental hypotheses and some practical examples of application.

2. Main evidence from an in-field ballistic campaign performed on Adobe masonry

The model takes its roots from elaboration of the results of a ballistic campaign performed by authors between 2011 and 2013, consisting of more than 150 impact tests on real Adobe walls in the field. Three test series of six shots each involved ten Adobe walls of different thickness (from 40 to 80 cm) built using three typologies of bricks and mortar with different fibre reinforcement (from 3% to 30% by weight) and density (from 800 to 1400 kg/m^3). Impactors included seven small caliber bullets with different geometrical (from 7.82 to 12.7 mm in diameter) and weight properties (from 8 to 45 g). Each wall was shot at a velocity range between 600 m/s and 900 m/s at different temperature and humidity conditions along two years. The reader is referred to [4] for a detailed explanation of the campaign and its results. In the following, only the major findings emerging from elaboration of test results are resumed:

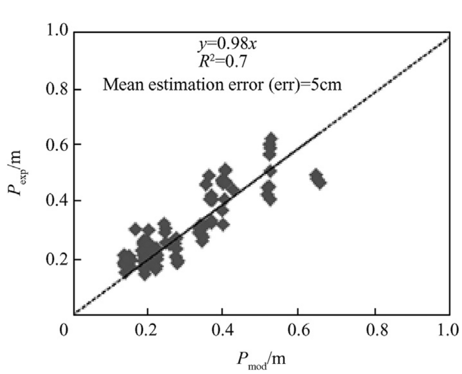

Fig. 1. Experimental-predicted terminal penetration depths using Eq. (1(a)) on data from Ref. [4].

- Penetration process in Adobe walls is characterized by an initial limited crater region with radial cracks followed by a cylindrical region with diameter equal to the impactor's diameter. Impactors do not experience significant deformation during penetration [4] (Fig. 2(a));
- Inertia of target has a minor influence on the ballistic resistance of Adobe for impacting velocities below 1000 m/s (Fig. 2(b)). Also the fact that the diameter of the tunnel region equals the caliber of the impactor confirms that the effect of inertia can be neglected for these impact conditions. This statistical finding confirms data elaboration results from other laboratory tests on Adobe in Refs. [3,5].
- Compression strength is an aleatory parameter for Adobe, varying over seasons and years. This happens because sundried bricks contain water, which varies according to atmospheric conditions, affecting the mechanical properties of the material. This finding confirms previous results achieved for Adobe by the authors, who proposed a compressive strength law for Adobe being negatively dependent on mixture water content [4,6,8] (Fig. 2(c)). Therefore, the use of compressive strength to predict the ballistic response of Adobe in the field is discouraged.
- For a given thickness, the ballistic performance of a wall of Adobe decays proportionally to the number of brick-layers emplaced along its thickness. Comparing tests on walls of different thickness using same types of bricks, bullets and velocity ranges, the penetration depth proportionally increases with the increasing number of layers emplaced along thickness [4]. This finding confirms a phenomena already observed in case of penetration tests on multi-layered concrete targets [14].

3. The Adobe ballistic model

The framework of the well-known ballistic model for concrete targets developed by Forrestal et al. [9] is adopted as a starting point. The model shapes the main mechanisms of resistance activated by concrete targets in front of the nose of high velocity impactors. According to post-test observations, two different regions are taken into account in the model. A “cavity region” with a length of about two projectile shank diameters is followed by a “conical region” with cross diameter nearly equal to the projectile diameter. The resulting equation of motion [9] is resumed in Eq. (2) as a function of depth, and the set of forces exerted on the projectile nose in the two regions of the model are graphically presented in Fig. 3(a):

$$m\frac{\mathrm{d}v}{\mathrm{d}t} = R = \begin{cases} cx & 0 < x < 2D \; (2a) \\ \left(NB\rho_t V^2 + \tau_0\right)\dfrac{\pi D^2}{4} & x > 2D \; (2b) \end{cases} \tag{2}$$

where m is the projectile mass and v is its speed at time t, R is the total reaction force, c is a dimensional constant, x is the horizontal coordinate of the projectile with diameter D and N is a nose shape caliber factor, function of the conical radius head of the impactor.

In the tunnel region, the resisting force results from a combination of compression and shear mechanisms. The compression part was made proportional to the square velocity (v^2) of the projectile through a compressibility function (B), multiplied with the density of the target (ρ_t). According to the experimental finding on the contribution of target inertia given as hypothesis of the model

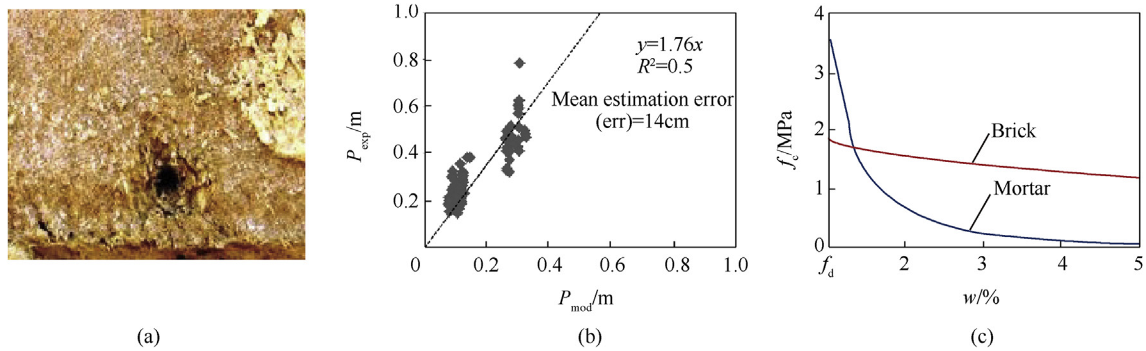

Fig. 2. (a) Example of crater region before tunnelling after test [4], (b) Experimental-predicted terminal penetration depths using the Resal model (which considers the inertial contribution of target resistance) in Ref. [4] and (c) compressive strength (*fc*) law dependent of water content (*w*) found in Ref. [6] for bricks and mortar of Adobe tested in Ref. [4].

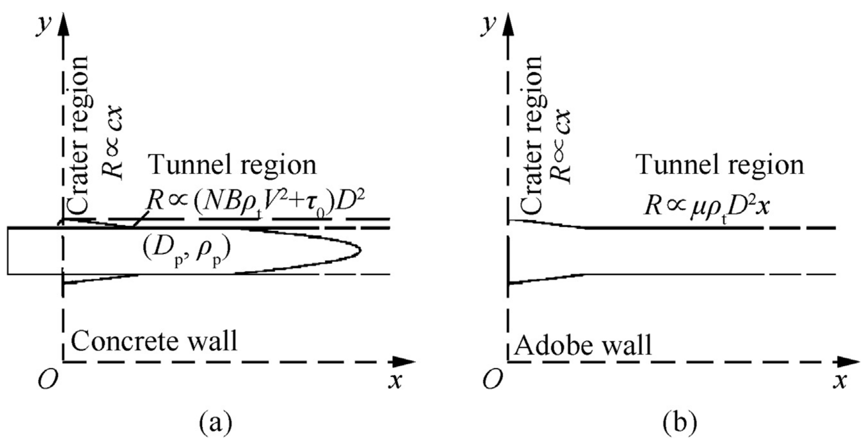

Fig. 3. Forrestal model (a) and Adobe ballistic model (b): proportionality of target reaction forces.

in Sec. 2, the quadratic velocity term of Eq. (2b) is neglected for the new Adobe ballistic model and only shear is thus considered. Experimental research has recently highlighted the relative contributions of the different mechanisms of energy dissipation in deep penetration of high velocity impactors in geo-materials, showing that the highly dissipative phenomenon of shear deformation is dominant [10]. In soil targets, energy absorption in shear is mainly due to friction between grains, enhanced by the high mean stresses experienced in front of the penetrating projectile [10]. In absence of direct tests, in the original Forrestal model the shear strength parameter (τ_o) was related to the unconfined compressive strength of concrete through an empirical function (*S* in Ref. [9]). For the Adobe model, a simple Coulomb friction resisting force linearly depending on the depth of penetration is proposed in the tunnel region [10–12]. It reads $R = \mu\rho_t g A_p x(t)$, where μ is the internal frictional coefficient, A_p is the cross sectional area of the projectile and g is the gravitational acceleration (Fig. 3(b)). Eq. (2) is updated for the crater and tunnel regions. Integration of the updated Eq. (2) with respect to velocity and final depths of penetration (P) larger than 2D, leads to Eq. (3):

$$-m_p \int_{v_0}^{0} v\mathrm{d}v = \mu\rho_t g A_p \int_{0}^{p} x\mathrm{d}x \tag{3}$$

Where m_p is the projectile mass. For the case of an impacting sphere the final penetration depth is:

$$p \sim \sqrt{\frac{D}{\mu}\frac{\rho_p}{\rho_t}} v_0 \tag{4}$$

The Adobe ballistic model is conceptually different in its interpretation from the models recently proposed in Ref. [1] (Eq. (1)), but it is characterized by a similar mathematical formulation for the depth of penetration. They both are linearly proportional on the impacting velocity and they depend on the impactor diameter and ratio between impactor and target densities, despite in Eq. (4) this dependency is rooted. Moreover, this ratio is scaled by the internal frictional coefficient; however these differences would simply affect the value of the calibration factor *k* in Eq. (1a).

4. An application of the model on military tests on Adobe walls in the field

Due to its mathematical structure, the ballistic model in Eq. (4) fits the available sources of data on Adobe available in literature, which address the response of targets with density of 1.8 g/cm^3 to impacts of steel spheres at velocities below 1.5 km/s [1,3,5]. In this section, the model is validated against the results of the ballistic campaign performed on real Adobe walls in the field presented in Sec. 2 and reported in Ref. [4]. For validation purposes, also in the Adobe ballistic model a calibration factor (κ) is introduced as in Eq. (1), which automatically includes g and the constant of friction μ in Eq. (4) in absence of related experimental data. As in the original model proposed by Forrestal et al. [9], due to the different shapes of

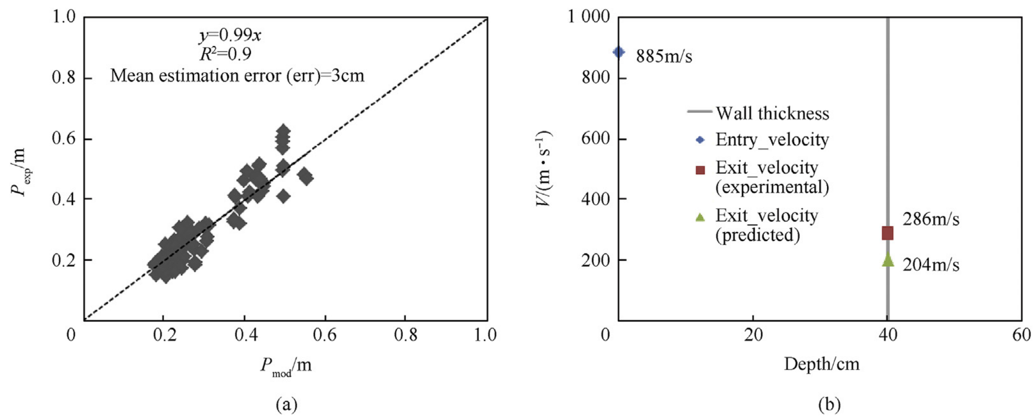

Fig. 4. Experimental-predicted (a) terminal penetration depths considering penetration tests and (b) residual velocity for perforation tests impacting Type B bricks of Wall 40 cm-thick at velocity of 885 m/s.

tested impactors, resistance in Eq. (3) is equipped with a nose caliber factor (N), calculated according to the ACE formula [13]. Due to the different walls layout, this term also includes a linear function depending on the number of brick layers along thickness of the wall (n_{layers}) [14]. The final formula adopted for calibration with respect to all 130 tests is reported in Eq. (5)

$$p = \sqrt{\frac{n_{\text{layers}}}{\kappa N_{\text{ace}}} \frac{m_{\text{p}}}{\rho_{\text{t}} A_{\text{p}}}} v_0 \tag{5}$$

The outcome of the analytical prediction of the experimental terminal depths of penetration is shown in Fig. 4(a). Considering the intrinsic scatter of results inherent in field tests and the simplicity of the model, the Adobe ballistic model (κ~180) is capable of predicting the terminal penetration depth on Adobe with high accuracy (coefficient of determination higher than 0.9 and mean absolute error of predictions lower than 5 cm). The Adobe model predicts the penetration depth with a mean error always smaller than 6% of the target thickness. For 40 cm thick walls, the mean error is 2.5 cm and for 80 cm walls the error is 4.8 cm. The model properly captures experimental results for all types of bricks and mortar tested, despite possessing significantly different physical-mechanical properties (Fig. 5). The calibrated model is subjected to a further validation with respect to the performed experimental campaign in terms of residual velocity (v_{r}). In fact, few shootings tests resulted into perforation (ten cases). Among them, five hit Type B bricks of 40 cm walls using the same type of projectile and therefore they were considered for analysis. Their range of impact velocities was relatively modest (25 m/s) and thus experimental results were averaged. The penetration depth was compared with respect to the results of the integration of Eq. (5) over the total thickness of the wall H (40 cm). The resulting formulation starting from Eq. (3) combined with Eq. (5) is given in Eq. (6). The result of the calculations reveals a value for residual velocity consistent with the one experimentally observed (Fig. 4(b)). Differences in values might be caused by the effects of projectile exit at boundaries.

$$v_{\text{r}} = \sqrt{\frac{m_{\text{p}} v_0^2 - k N \rho_{\text{t}} A_{\text{p}} H^2}{m_{\text{p}}}} \tag{6}$$

5. Conclusions

In this paper, a new semi-empirical ballistic model is presented for Adobe for small caliber threat with impact velocities up to 900 m/s. It is developed by adapting a model originally defined for concrete in order to include the dominant frictional resistance experienced by soil targets in deep penetration. The proposed model has a similar mathematical formulation as previously defined models applied for the same material but they differ in the physical interpretation of the resisting mechanisms activated upon impact. The schematization and assumptions of the new model are based on the results of research accomplished by the authors during the last years on Adobe. This model, accounting for the physics of penetration on earthen walls, well predicts the experimental data available in literature for Adobe, including the new

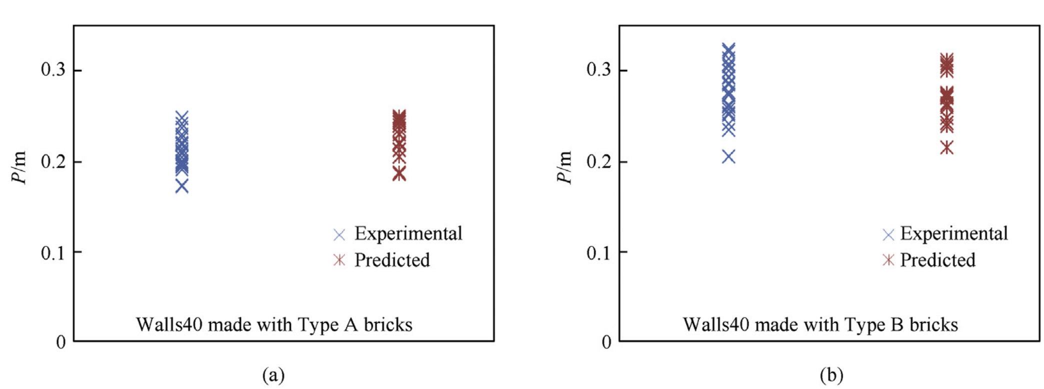

Fig. 5. Experimental-predicted terminal penetration depths considering shot on Type A ($\rho = 1250$ kg/m^3) (a) and Type B ($\rho = 800$ kg/m^3) (b) bricks.

data recently shared by the authors, both in terms of penetration depth and residual velocity.

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