Experimental Characterization of Solid Clay Bricks: Correlations Among Mechanical Properties

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Abstract. Strengthening interventions on existing structures, especially in the case of Architectural Heritage, require an in-depth knowledge of construction techniques, geometry and materials for an optimal design aiming at the minimum intervention approach ideal. Nonetheless, conservative values of material properties, often derived from codes or literature, might hinder the effectiveness of the design approach. Non-Destructive Tests (NDT) and Minor Destructive Tests (MDT) are fundamental tools for the characterization of existing materials with a minimum or no impact. The paper presents an experimental study that investigated the possibility of defining empirical correlations among the main mechanical properties of solid clay bricks, which are one of the most common unit for masonry load-bearing members. Extruded bricks, typical of modern constructions, and soft-mud bricks, resembling historical units, were tested to cover for the ample variability of solid clay bricks. The examined mechanical properties were compressive, bending, splitting and pull-off strengths. The dataset of mechanical properties allowed calibrating linear correlations expressing one property as a function of another, thus giving the possibility of estimating a set of strengths based on the results of the MDT pull-off test. An innovative aspect consisted in performing the four tests on the same unit, so that the calibrated linear correlations are based on punctual data instead of average values. A practical application can consist in the on-site execution of pull-off tests, which are minor destructive and can be easily performed on a wall surface, for estimating the compressive strength of clay units.

Keywords: Clay bricks · Masonry · Mechanical properties
Experimental testing · Correlation curves

1 Introduction

Restoration of existing Un-Reinforced Masonry (URM) buildings entails an in-depth knowledge of construction techniques, geometry and materials. The survey dataset is the foundation for an optimal design of strengthening techniques aiming at the

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minimum intervention approach [1–4]. Destructive tests are frequently impractical, especially when dealing with Architectural Heritage (AH) buildings. Consequently, the characterization of existing materials via Non-Destructive Tests (NDT) and Minor Destructive Tests (MDT), which have a minimum or no impact on the constructions, are very useful for on-site assessments [5].

Solid clay bricks are one of the most common masonry units of existing URM buildings. The assessment of the mechanical characteristics of bricks is instrumental for the estimation of strengths and elastic moduli of brick masonry [6, 7] and are essential for the bond design according to CNR-DT200 [8] of Externally Bonded Fibre Reinforced Polymers (EB-FRP), which are widely used in strengthening interventions [3]. Nonetheless, for a complete assessment of brick masonry as material, NDT and MDT tests on existing mortars and brick sub-assemblages are necessary [9, 10].

The paper presents an experimental study that explored the possibility of establishing empirical correlations among the main mechanical properties of solid clay bricks and to the MDT pull-off test, which is one of the easiest on-site tests [11, 12] for masonry and concrete [13] substrates. Pull-off tests are mostly used for checking qualitatively the adhesion of EB-FRP [8, 14] or mortar/grout overlays [12, 15], rather than for strength estimations via correlation curves [14, 15].

Extruded bricks, typical of modern constructions, and soft-mud bricks, resembling historical units, were tested to cover an ample range of solid clay bricks. The investigated mechanical properties were compressive, bending, splitting and pull-off strengths. The dataset of mechanical properties allowed calibrating linear correlations expressing one property as a function of another, thus giving the possibility of estimating a set of strengths based on the results of the MDT pull-off test. An innovative aspect consisted in performing the four tests on the same unit, as introduced in [14], so that the six calibrated linear correlations are based on punctual data instead of average values of brick sets. The practical application for professionals can consist in the on-site execution of pull-off tests for estimating the compressive or a set of strengths of clay units.

2 Materials and Methods

This paper presents the results of about 170 3-point bending tests, 95 compression tests, 75 splitting tests, and more than 330 pull-off tests, carried out on 12 sets of different types of solid clay bricks. Bricks were either extruded units (6 sets), relatively strong and stiff, or moulded soft mud units (6 sets), herein indicated as "facing" bricks due to their typical surface finishing intended to remain exposed in the brickwork. Figure 1 shows the typical appearance of extruded and facing bricks, and the main characteristics of the used units are reported in Table 1, where l_{avg}, b_{avg}, t_{avg} and ρ_{avg} are the measured average values of length, width, thickness and apparent density (given by the ratio of mass and exterior volume, pores included), respectively. The types of bricks were selected with the aim of covering a range of strength as wide as possible. They were all commercially available units, except those of set F6, which were historical bricks salvaged before the demolition of a vernacular farmhouse dating back to the second half of the 19th century, presumably fired at temperatures lower than 1050–1100 °C, which is a usual range for modern bricks [16].

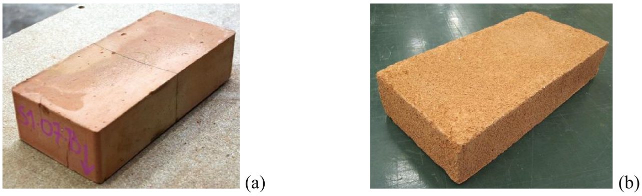

Fig. 1. (a) Typical extruded unit; (b) example of facing unit, in this case without any sand finishing

The number of samples varied between 8 and 20 for each set, according to the availability of units. All bricks were tested in flexure with a 3-point bending test, performed on the entire unit (Fig. 2a). Then, one half of the broken brick was subjected to either a compression (Fig. 2b) or a splitting test (Fig. 2c). The other piece was subjected to a pull-off test (Fig. 2d) on each of the wider surfaces. In this manner, three mechanical properties could be directly measured on the same unit, allowing a more profitable find of possible relations among them as proposed in [14].

The 3-point bending tests were carried out according to the main principles of EN 12390-5 [17] in absence of a specific standard for fired clay masonry units. For brittle and quasi-brittle materials, the calculation of bending strength f_f (often referred to as Modulus of Rupture – MoR) derives from a linear-elastic analysis of the cross section, as reported in Eq. 1 where P_{max} is the maximum recorded load, l_s is the distance between the supports, and b and t are width and thickness of the cross section, respectively. The bending strength was subsequently normalized (f_{fn}) through the coefficient α_{fl}, taken from the Model Code 90 [18] and 2010 [19], aimed at estimating a value closer to the actual uniaxial tensile strength of the material.

$$f_f = \frac{3 \cdot P_{max} \cdot l_s}{2 \cdot b \cdot t^2}; \quad f_{fn} = \alpha_{fl} \cdot f_f; \quad \alpha_{fl} = \frac{1.5 \cdot (t/100)^{0.7}}{1 + 1.5 \cdot (t/100)^{0.7}} \quad \text{as in Model Code 90} \tag{1}$$

The compression tests were carried out according to EN 772-1 [20]. In order to avoid or reduce contact problems with machine steel plates, the surface of each specimen was either ground, when feasible or needed for bending tests, or capped. The compressive strength f_c is calculated (Eq. 2) as the peak load, P_{max}, divided by the cross-sectional area perpendicular to the load direction, being b and l' width and length of the specimen cropped after the bending test, respectively. The compressive strength was then normalized (f_b) through the shape factor d_{EN}, given in EN 772-1, to approach a better estimation of uniaxial compressive strength of the material.

Table 1. Characteristics of the used sets of solid clay bricks

Set	Type	Nominal sizes	l_{avg} mm	b_{avg} mm	t_{avg}* mm	ρ_{avg} kg/m^3
E1	extruded	240 × 110 × 60 mm^3	243	112	59	1700
E2	extruded	240 × 110 × 60 mm^3	245	113	60	1800
E3	extruded	240 × 110 × 60 mm^3	245	112	60	1780
E4	extruded	240 × 120 × 55 mm^3	239	118	56	1960
E5	extruded	240 × 120 × 55 mm^3	240	112	52	1930
E6	extruded	250 × 120 × 55 mm^3	248	117	52	1800
F1	facing	250 × 120 × 55 mm^3	253	119	56	1470
F2	facing	250 × 120 × 55 mm^3	249	119	53	1520
F3	facing	250 × 120 × 55 mm^3	254	120	56	1420
F4	facing	250 × 120 × 50 mm^3	251	120	52	1600
F5	facing	250 × 120 × 55 mm^3	244	115	51	1910
F6	facing	270 × 130 × 60 mm^3	267	128	54	1490

**The planar faces of bricks belonging to sets E5, E6, and F6, were smoothed before bending tests*

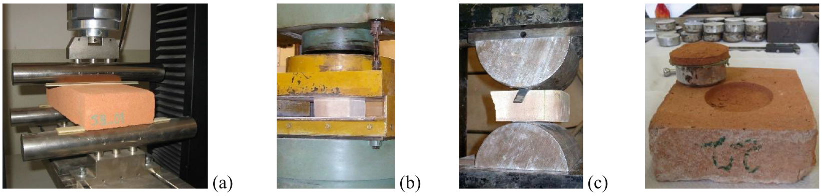
(a) (b) (c) (d)

Fig. 2. Mechanical tests carried out on bricks: (a) 3-point bending, (b) compression; (c) splitting; and (d) pull-off

$$f_c = \frac{P_{max}}{b \cdot l'}; \quad f_b = d_{EN} \cdot f_c; \quad d_{EN} \text{ interpolated from EN 772 - 1} \tag{2}$$

The splitting (or Brazilian) test, performed according to the main principles of EN 12390-6 [21], consists in applying a compressing line load in correspondence of a diametric plane (cylindrical specimen) or a generic cross section (prismatic specimen), which was across the thickness of bricks in this experimentation. Then, a linear elastic analysis gives the estimation of the maximum tensile stress, which is assumed to be the splitting strength (f_s) when the load reaches its peak value, as in Eq. 3 where P_{max} is the maximum recorded load, and b and t are the sizes of the loaded cross section (width and thickness, respectively). The splitting strength was subsequently normalized (f_{sn}), i.e. reduced by the factor 0.9 as in Model Code 90 [18], to obtain a closer estimation of the uniaxial tensile strength.

$$f_s = \frac{2 \cdot P_{max}}{\pi \cdot b \cdot t}; \quad f_{sn} = 0.9 \cdot f_s; \quad \text{as in Model Code 90} \tag{3}$$

The pull-off test, ASTM C1583 [22] and EN 1015-12 [23], consists in applying a tensile force on a superficial portion of a sample, generally circular, isolated from the surrounding material by a cut about 5 mm deep. The load, generated by a manual dynamometer mounted on a tripod, was transmitted through a pin screw mounted on aluminium dollies glued to the brick surface with epoxy. A rigid perforated steel plate, laid upon the sample, was used as support for the tripod. Care was taken to prevent interactions between plate and sample that could affect results [14]. Failures types covered by [22], which envisages not only a plain substrate but also an overlay of repair material, are: (A) inside the substrate, (B) at the interface between substrate and overlay, (C) in the overlay material, and (D) at the interface between overlay and glued plate. Indeed, part of the samples subjected to pull-off testing had been covered in advance with a layer of Fibre-Reinforced Polymers (FRP) in a former research [14] that investigated possible issues related to normal debonding of FRPs. Only failure type A (i.e. inside the substrate) were included in the current dataset, since that failure was assumed not to be affected by the possible presence of FRPs. The tensile pull-off strength f_{po} was calculated (Eq. 4) as the ratio of the peak load P_{max} and the area of the circular cut, being d the diameter measured on each sample.

$$f_{po} = \frac{4 \cdot P_{max}}{\pi d^2} \tag{4}$$

3 Results and Discussion

Failure in most cases was regular, according to the type of test, and only few clear outliers were excluded from the analysis. Concerning pull-off failures, only type A (i.e. tensile failure in the substrate) were taken into consideration. Average results are listed in Table 2 together with the Coefficient of Variation (CoV) in brackets. Figure 3 shows couples of experimental data referring to single bricks, grouped by macro production technology (i.e. extruded or facing). A linear regression analysis, based on Ordinary Least Squares (OLS), was carried out for estimating possible correlations between two different properties. Regression lines are plotted as dashed lines, along with the 90% prediction intervals (dotted lines), which limit ranges are associated with a 90% probability of occurrence for new data.

3.1 Compressive Strength and Apparent Density

The measured compressive strength f_c of bricks varied approximately between 31 and 79 N/mm^2 for extruded bricks, and between 8 and 73 N/mm^2 for facing units, with apparent densities comprised between 1400 and 2000 kg/m^3. After the normalization of f_c, the results presented a rather linear relationship between f_b and ρ_{app} (Fig. 3a). The

Table 2. Average measured results (CV in brackets)

Set	Type	f_{fn} N/mm^2		f_b N/mm^2		f_{sn} N/mm^2		f_{po} N/mm^2	
E1	extruded	2.38	(16%)	28.1	(9%)	–	–	3.03	(19%)
E2	extruded	1.61	(28%)	26.5	(8%)	1.60	(41%)	2.72	(12%)
E3	extruded	2.04	(26%)	30.6	(8%)	3.16	(15%)	2.99	(15%)
E4	extruded	2.80	(6%)	44.6	(8%)	5.30	(6%)	3.68	(8%)
E5	extruded	3.11	(29%)	49.9	(18%)	5.62	(32%)	3.07	(24%)
E6	extruded	1.74	(16%)	35.8	(9%)	3.44	(19%)	2.57	(17%)
F1	facing	2.65	(12%)	16.1	(11%)	–	–	1.78	(13%)
F2	facing	2.82	(4%)	16.5	(6%)	3.62	(6%)	1.59	(18%)
F3	facing	2.34	(8%)	12.6	(8%)	3.05	(5%)	1.48	(15%)
F4	facing	1.74	(4%)	14.7	(3%)	2.21	(11%)	1.03	(12%)
F5	facing	4.19	(8%)	40.8	(16%)	4.61	(16%)	3.03	(17%)
F6	facing	1.95	(28%)	12.6	(27%)	1.79	(35%)	0.89	(49%)

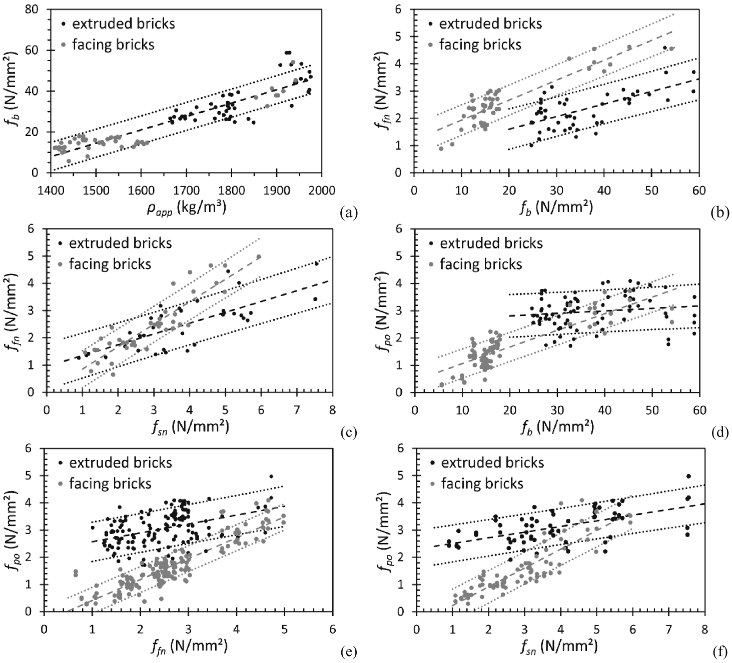

Fig. 3. Linear correlations, computed via OLS regression (dashed line), and their 90% prediction interval (dotted lines): (a) normalized strength vs. apparent density; (b) normalized bending strength vs. normalized compressive strength; (c) normalized bending strength vs. normalized splitting strength; (d) pull-off strength vs. normalized compressive strength; (e) pull-off strength vs. normalized compressive strength; (f) pull-off strength vs. normalized bending strength.

behaviour of extruded and facing units did not appear significantly different, thus a single predictive regression (Eq. 5) was derived.

$$f_b = 0.065 \frac{\mathrm{N} \cdot \mathrm{m}^3}{\mathrm{mm}^2 \cdot \mathrm{kg}} \cdot \rho - 83.8 \frac{\mathrm{N}}{\mathrm{mm}^2}; \quad R^2 = 0.84; \quad \rho_{app} \in [1400; 2000] \frac{\mathrm{kg}}{\mathrm{m}^3} \tag{5}$$

3.2 Bending and Compressive Strength

The measured bending strength f_f of bricks varied approximately between 2.0 and 9.5 N/mm^2 for extruded bricks, and between 1.8 and 9.5 N/mm^2 for facing units. The normalized bending strength f_{fn} revealed a noticeably different behaviour of extruded and facing units, when correlated to the normalized compressive strength f_b, as shown in (Fig. 3b). However, within the tested ranges, a linear regression for each class of units can describe satisfactorily the relation between f_{fn} and f_{cn}. Results of the regression are reported in Eq. 6, together with the range of applicability.

$$f_{fn} = \begin{cases} 0.046 \cdot f_b + 0.683 \frac{\mathrm{N}}{\mathrm{mm}^2}; & R^2 = 0.40; \quad f_b \in [25; 60] \frac{\mathrm{N}}{\mathrm{mm}^2}; \quad \text{extruded bricks} \\ 0.073 \cdot f_b + 1.208 \frac{\mathrm{N}}{\mathrm{mm}^2}; & R^2 = 0.77; \quad f_b \in [10; 50] \frac{\mathrm{N}}{\mathrm{mm}^2}; \quad \text{facing bricks} \end{cases} \tag{6}$$

3.3 Bending and Splitting Strength

The measured splitting strength f_s of bricks varied approximately between 1.0 and 8.4 N/mm^2 for extruded bricks, and between 1.2 and 6.6 N/mm^2 for facing units. The normalized bending strength f_{fn} was correlated to the normalized splitting strength f_{sn} as shown in (Fig. 3c) and revealed a different behaviour of extruded and facing units as in the previous section. Nonetheless, the relation appears rather linear as presumable since both strengths are related to the tensile behavior of the material. Results are given in Eq. 7 with the range of applicability.

$$f_{fn} = \begin{cases} 0.397 \cdot f_{sn} + 0.951 \frac{\mathrm{N}}{\mathrm{mm}^2}; & R^2 = 0.58; \quad f_{sn} \in [1; 8] \frac{\mathrm{N}}{\mathrm{mm}^2}; \quad \text{extruded bricks} \\ 0.825 \cdot f_{sn} + 0.027 \frac{\mathrm{N}}{\mathrm{mm}^2}; & R^2 = 0.79; \quad f_{sn} \in [1; 6] \frac{\mathrm{N}}{\mathrm{mm}^2}; \quad \text{facing bricks} \end{cases} \tag{7}$$

3.4 Pull-off and Compressive Strength

The measured pull-off strength f_{po} of bricks varied approximately between 1.7 and 5.0 N/mm^2 for extruded bricks, and between 0.3 and 4.1 N/mm^2 for facing units. The correlation to f_b revealed a markedly different behaviour of extruded and facing units (Fig. 3d), with the pull-off strength of the former appearing not sensibly affected by the compressive strength, whereas the latter showed a linear trend. Nevertheless, within the tested range of measures, the relation can be represented by a straight line in both cases as reported in Eq. 8.

$$f_{po} = \begin{cases} 0.009 \cdot f_b + 2.629 \frac{\mathrm{N}}{\mathrm{mm}^2}; & R^2 = 0.02; \quad f_b \in [25; 60] \frac{\mathrm{N}}{\mathrm{mm}^2}; \quad \text{extruded bricks} \\ 0.061 \cdot f_b + 0.452 \frac{\mathrm{N}}{\mathrm{mm}^2}; & R^2 = 0.71; \quad f_b \in [10; 50] \frac{\mathrm{N}}{\mathrm{mm}^2}; \quad \text{facing bricks} \end{cases} \tag{8}$$

3.5 Pull-off and Bending Strength

The correlation between f_{po} and f_{fn}, within the tested range of measures, can be represented by a straight line, with different slopes, for both extruded and facing units (Fig. 3e). It can be noted that the latter revealed an almost proportional relation, while the former showed a less sensible correlation. Results of the regression are reported in Eq. 9, together with the range of applicability.

$$f_{po} = \begin{cases} 0.326 \cdot f_{fn} + 2.242 \frac{\mathrm{N}}{\mathrm{mm}^2}; & R^2 = 0.18; \quad f_{fn} \in [1; 5] \frac{\mathrm{N}}{\mathrm{mm}^2}; \quad \text{extruded bricks} \\ 0.768 \cdot f_{fn} - 0.357 \frac{\mathrm{N}}{\mathrm{mm}^2}; & R^2 = 0.81; \quad f_{fn} \in [1; 5] \frac{\mathrm{N}}{\mathrm{mm}^2}; \quad \text{facing bricks} \end{cases} \tag{9}$$

3.6 Pull-off and Splitting Strength

As expected, the correlation between f_{po} and f_{sn} was similar to that between f_{po} and f_{fn}. Indeed, f_{fn} and f_{sn} already showed a linear correlation. Within the tested range of measures, a straight line can be adopted for both extruded and facing units (Fig. 3f). It can be noted that facing units revealed an almost proportional relation, while the extruded showed a less sensible correlation as reported in Eq. 10.

$$f_{po} = \begin{cases} 0.208 \cdot f_{sn} + 2.303 \frac{\mathrm{N}}{\mathrm{mm}^2}; & R^2 = 0.33; \quad f_{sn} \in [1; 8] \frac{\mathrm{N}}{\mathrm{mm}^2}; \quad \text{extruded bricks} \\ 0.689 \cdot f_{sn} - 0.457 \frac{\mathrm{N}}{\mathrm{mm}^2}; & R^2 = 0.76; \quad f_{sn} \in [1; 6] \frac{\mathrm{N}}{\mathrm{mm}^2}; \quad \text{facing bricks} \end{cases} \tag{10}$$

4 Conclusions

The paper presented an extensive experimental investigation that explored the possibility of defining linear correlations among the main mechanical properties of solid clay bricks as the compressive, bending, splitting and pull-off strengths. The dataset allowed calibrating 6 different linear correlations, 3 of which connected to the MDT pull-off test. These last correlations opened the possibility for estimating the main strengths of on-site bricks by carrying out simple and practical pull-off tests. The best linear correlations with R^2 larger than 0.70 were obtained with soft-mud bricks, resembling historical units, while for extruded brick the outcomes were satisfactory. Future evolution of the research consists in the validation of the current strength correlations versus third-party and on-site brick strengths data.

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