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Anisotropy and compressive strength evaluation of solid fired clay bricks by testing small specimens

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ABSTRACT

A study is presented on the use of a non-standard 40 × 40 × 40 mm^3 specimen for the experimental measurement of the compressive strength of solid fired clay bricks extracted from existing masonry buildings. The viability of such specimen has been assessed by comparison with experimental results obtained with the standard 100 × 100 × 40 mm^3 specimen. The use of the non-standard 40 × 40 × 40 mm^3 has two main advantages. First, it significantly reduces the volume of sampled material, which can be severely restrained in architectural heritage buildings. Second, it allows carrying out tests in the three brick dimensions (length, width and thickness), and therefore investigating the anisotropy that clay bricks can exhibit depending of their manufacturing process. The experimental campaign has focused on three different types of solid fired clay bricks, namely mechanically extruded, hydraulic press moulded, and handmade units, with a total amount of 461 specimens. Using the mentioned small cubic specimen, a detailed research on the compressive strength and the anisotropy of different solid clay brick types has been carried out by applying a statistical approach. The experimental results and the statistical processing have shown that the proposed specimen can be utilized for a reliable estimation of the compressive strengths along the three main directions of solid fired clay bricks.

1. Introduction

A large part of the built stock of many regions in the world consists of modern and historical masonry structures still in use and in need of maintenance and conservation interventions. Many of such structures are considered as architectural heritage due to their cultural value and to their contribution to the identity of historical towns and urban centers. The structural verification of masonry buildings, aimed to their maintenance or refurbishment, requires a detailed analysis of the performance against both gravity loads and horizontal actions. The analysis of existing masonry buildings, however, faces significant difficulties due to the complexity of masonry as both construction technology and structural material. One of the main difficulties lies in the realistic characterization of the mechanical properties and, more specifically, of the masonry compressive strength, which has often a critical influence on the structural performance of masonry members. The masonry compressive strength depends largely on the compressive strength of components (units and mortar) [1]. In specific, knowledge on the compressive strength of bricks (along with that or mortar) may enable an estimation of that of masonry using available empirical or analytical equations [2,3].

The most common materials in historical masonry buildings are stone, solid clay bricks, adobe, and lime mortar. Solid fired clay brick masonry has been one of the most recurrent construction technologies for centuries. Generally, brick masonry has not deserved a research attention (including experimental research) comparable to that devoted to more modern structural materials such as concrete or steel. Despite encouraging advancements, significant additional research is still needed for an accurate and efficient characterization of the mechanical properties of masonry components in existing buildings.

The mechanical characterisation of solid fired clay bricks from samples extracted from existing buildings poses specific challenges due to the limited thickness of bricks, which in some geographical locations may be of the order of only 40 mm or less. In addition, sample extraction may be severely restricted in architectural heritage buildings. Testing in the laboratory small samples from solid clay bricks faces specific difficulties. First, the reduced height of the samples may induce excessive confinement when tested in a press machine, which may largely influence on the measured compressive strength. Second, the material heterogeneity and the possible material or geometrical imperfections also influence on the compressive strength and may compromise the

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Nomenclature

t	thickness
w	width
l	length
f_c	Experimental compressive strength
f_{c100}	Experimental compressive strength of 100 × 100 × 40 mm^3 specimen
f_{cC40}	Experimental compressive strength of 40 × 40 × 40 mm^3 specimen
CV	Coefficient of variation

representativeness of the measurements. Finally, the brick manufacture process can also influence on the strength by inducing anisotropy effects [4,5].

With regard to the confinement effect due to the specimen shape, recommendations for concrete can be found in the available scientific and technical literature. In specimens with height/diameter (or width) ratio greater than 2.0, the effect of confinement does not reach their central portion, which therefore experiences a uniaxial compression condition [6,7]. For specimens with slenderness under 1.5, the measured strength increases due to the restraining effect exerted by the testing machine. In particular, for concrete specimens with slenderness 1.0, the apparent strength is approximately 1.2 times larger than that obtained in specimens with slenderness 2.0, as indicated by Neville [6] and Schickert [7]. The only recommendations for bricks are offered by Page [8] who investigated the influence of the slenderness on calcium silicate units. Page [8] measured the brick unconfined compressive strength by testing the specimen with steel brush bearing platens. Page found that measuring the compressive strength with conventional bearing testing machine required tests on specimens with slenderness 3.0 in order to obtain values similar to those yielded by test carried out with the steel brush bearing platens. For specimens with slenderness 1.0 he found an apparent compressive strength 1.43 times higher than the one measured with specimens with slenderness 3.0. Reaching the slenderness that would be required to avoid confinement effects, however, is not possible in flat bricks characterized by a reduced thickness, as it would require tests on extremely small specimens or stacked specimens. The small volume of the specimen largely increases the risk of sampling errors due to the unavoidable heterogeneities normally induced by the mixing and manufacturing procedure. The stacked specimens are allowed by the EN 772–1+A1 [9] standard, but require the use of a larger amount of material, which is often not possible in the case of heritage buildings. Nevertheless, tests on low-slenderness specimens become necessary in spite of their possible drawbacks. Both the ASTM C67-20 [10] and EN 772–1+A1 [9] standards concerning brick testing in compression propose specimens with reduced slenderness (1.0 to 0.33) for bricks with thickness below 50 mm. These standards foresee, in specific, the possibility of testing different specimen types in flatwise position.

Testing entire bricks or flat specimens does not allow a satisfactory characterization of the possible material anisotropy. The measure of the compressive strength along different brick orientations would be largely compromised by the very different slenderness shown by the unit along its different dimensions and would yield non-comparable measures. Previous research has focused on tests on whole bricks by applying the load perpendicular to the stretcher, header or bed dimensions [11,12] with the aim to measure the global brick strength as an entire unit. This type of tests, however, are oriented to measure global brick properties and are not useful to accurately characterize the material's anisotropy. Some other researches have more specifically focused on the measurement of the material anisotropy by testing comparable cubic or prismatic specimens along different brick dimensions. Aubert et al. [13] studied four types of extruded earth bricks by testing twelve 50 × 50 × 50 mm^3 specimens from each brick in two orientations (perpendicular and parallel to the extrusion plane), obtaining the highest strength in the direction perpendicular to the extrusion plane. Oliveira et al. [14] tested four 40 × 40 × 120 mm^3 specimens of mechanically produced solid clay bricks in flatwise and lengthwise brick positions. Fódi [12] measured the compressive strength of extruded solid clay bricks on eight 50 × 50 × 50 mm^3 specimens in each load direction. Krakowiak et al. [4] tested cylindrical specimens along the three brick directions, considering two types of extruded bricks with extrusion along the height and along the length respectively. Oliveira et al. [14], Fódi [12] and Krakowiak et al. [4] also obtained larger compressive strength along the extrusion plane. Finally, Salvatoni and Ugolini [15] carried tests on 40 × 40 × 40 mm^3 specimens of a modern handmade brick and found similar compressive strengths along the three directions.

This paper proposes the use of a small 40 × 40 × 40 mm^3 cubic specimen for the experimental measurement of the compressive strength of solid clay bricks along the three brick dimensions, enabling therefore the characterization of the material anisotropy. The interpretation of the experimental results is carried out according to a detailed statistical analysis. Among other advantages, by reducing the sample volume (compared to testing of entire bricks or larger specimens) this approach overcomes possible limitations arising from the relatively small number of brick samples that can be extracted from existing buildings, especially when they belong to architectural heritage.

Sampling errors induced by the small specimen size (related to excessive heterogeneity, geometrical imperfection or inadequate failure) can be avoided by adapting well-known criteria, used in the case of concrete, for the selection and acceptance of appropriate specimens. The criteria adopted for concrete in the selection and testing of cubic brick specimens are described in the standards EN 12390–1 [16] and EN 12390–3 [17]. They concern the maximum acceptable aggregate diameter and satisfactory failure modes. In addition, the cubic specimen allows a slenderness (equal to 1.0) significantly larger than that of an entire unit and therefore is subjected to a lesser confinement effect during the test. Moreover, the cubic specimen enables an accurate characterization of the material anisotropy by using samples with the same slenderness through the three orientations (length, width and thickness). The interpretation of the experimental results has been carried out by means of a detailed statistical analysis, using well-known statistical tests, in order to detect possible outlier values and to decide about the comparability of experimental results corresponding to different samples.

The experimental campaign was carried out on three different solid clay bricks types characterized by different manufacturing procedures. The different brick types correspond to (1) mechanically extruded units, (2) hydraulic press moulded units, and (3) handmade units, including both modern and historical handmade bricks extracted from existing masonry buildings. The historical bricks were extracted from six 19th and early 20th century buildings in Barcelona (Spain), one of them with an extension built at the beginning of the 20th century. The case-studies include three residential buildings, two industrial facilities and one market. The case studies allowed a broader comparison of the experimental results obtained from the proposed cubic specimen with those derived from a standardized 100 × 100 × 40 mm^3 specimen defined in EN 772–1+A1 [9].

The research pays special attention to the use of the nonstandard 40 × 40 × 40 mm^3 specimen with the following specific objectives: (1) Analysing the consistency and reliability of the results obtained, as well as the acceptability of the experimental scattering; (2) Exploring the anisotropy in the compressive strength and comparing with previous experimental research results; (3) Characterizing the influence of the specimen shape on the estimation of the compressive strength by comparing the results obtained from the proposed cubic specimen with those yielded by the standard 100 × 100 × 40 mm^3 normalized specimen. The research has been based on the execution of a broad experimental campaign including tests on 323 40 × 40 × 40 mm^3 cubic specimens and additional 138 tests on standard 100 × 100 × 40 mm^3 specimens for the sake of comparison.

This paper is structured in four sections. After this introduction, Section 2 presents the experimental campaign performed on brick units, including the description of the material, the specimen preparation and the test procedure. Section 3 describes the experimental results. Section 4 analyses the influence of the anisotropy in the different manufactured units, the statistical analysis of the anomalous experimental results, and the shape-effect influence. The paper ends with Section 5 presenting some conclusions and proposed future works.

2. Experimental study

This section presents the experimental campaign carried out on solid fired clay bricks manufactured according to three different procedures, corresponding to (1) mechanically extruded, (2) hydraulic press moulded and (3) handmade manufactured bricks. The handmade manufactured bricks include both modern and historical bricks, the latter collected from existing buildings. Details are provided on the description of the materials, the preparation of the proposed specimen, its geometry, and the testing setup. As mentioned above, the historical samples were collected from historical buildings, including three residential ones, two industrial ones and a market structure in Barcelona (Spain). Three of these buildings were built in the early 20th century and the other three were built in the 19th century. One of the industrial buildings from the 19th century includes a 20th century building extension. All experimental tests were carried out at the Laboratory of Technology of Structures and Materials of the Technical University of Catalonia (UPC-BarcelonaTech).

2.1. Materials

As mentioned, in this research, solid fired clay units manufactured according to three different procedures were studied (Fig. 1). The first type of bricks, corresponding to modern clay ones produced by mechanical extrusion, are identified herein with the acronym ‘Ex’. The second type, corresponding to modern clay bricks produced by hydraulic press moulding, are identified with the acronym ‘Hy’. The third type includes handmade modern and historical bricks. The modern handmade solid clay bricks include, in turn, three different subtypes, identified with the acronyms ‘Mo_1’ ‘Mo_2’ and ‘Mo_3’. Although provided by the same manufacturer, the three types of modern handmade bricks correspond to different manufacturing series and show differing mechanical properties. The historical solid clay bricks were collected from seven different masonry walls from six buildings, following the RILEM recommendation LUMD1 for removal and testing specimens from existing buildings [18]. The historical bricks collected from the industrial buildings are identified with the acronyms ‘Hi/I’, while the ones taken from residential buildings are identified with the acronyms ‘Hi/R’, and those collected from the market building are identified with the acronym ‘Hi/Ma’. The ‘Mo’, ‘Hi/I’, ‘Hi/R’ and ‘Hi/Ma’ were traditionally manufactured in a brickyard by moulding. According to the traditional procedure, the ‘Mo’ bricks were shaped in a wooden mould sprinkled with dry fine sand and, after being extracted from the mould, the bricks were fired into a coal-fired kiln. The modern mechanical type, ‘Ex’ and ‘Hy’ were produced in an automated process. ‘Ex’ bricks were extruded along the thickness. They were cut and dried by mechanical automatized tools before being fired in a tunnel kiln with controlled heat conditions. The ‘Hy’ bricks were mechanical pressed on their beds into a mould. The mechanically extruded (Ex), hydraulic press moulded (Hy) and modern handmade (Mo) gave the possibility to test a larger number of specimens. However, the number of clay brick samples collected from historical buildings (‘Hi/I’, ‘Hi/R’ and ‘Hi/Ma’) was limited due to the restrictions imposed by their consideration as cultural heritage. Table 1 presents a description of the sampled materials in terms of origin, acronym, number of samples collected and average dimensions measured according to EN 772-16 [19].

2.2. Preparation of specimens and testing procedure

The motivation behind the proposal of a new test specimen for the derivation of the compressive strength from solid clay bricks lies in the

Table 1
Sampled bricks in terms of origin, acronym (Acr.), number of samples collected and average dimensions. Values in brackets correspond to the Coefficients of Variation.

Sampled materials			
Origin	Acr.	Num. bricks	Av. Dimensions (mm)
Mechanically Extruded	Ex	11	272 [0.4%] × 132 [0.9%] × 45 [0.7%]
Hydraulic Pressed	Hy	10	291 [0.0%] × 141 [0.0%] × 38 [0.1%]
Modern Handmade	Mo_1	13	306 [0.5%] × 147 [0.9%] × 46 [3.4%]
	Mo_2	6	311 [0.6%] × 149 [1.7%] × 46 [4.6%]
	Mo_3	6	306 [1.4%] × 146 [1.5%] × 46 [2.7%]
1878 Industrial	Hi/I_1	24	295 [1.3%] × 148 [2.8%] × 44 [4.3%]
Early 20th c. Industrial	Hi/I_2	6	293 [1.3%] × 140 [4.2%] × 49 [5.8%]
1927 Industrial	Hi/I_3	15	288 [0.7%] × 141 [1.5%] × 49 [5.8%]
1933 Market	Hi/Ma	6	285 [0.8%] × 139 [1.2%] × 47 [4.3%]
1840 Residential	Hi/R_1	8	294 [0.7%] × 145 [1.8%] × 45 [2.1%]
1880 Residential	Hi/R_2	6	294 [0.6%] × 145 [0.4%] × 56 [3.3%]
1930 Residential	Hi/R_3	6	394 [0.4%] × 145 [0.5%] × 49 [5.2%]

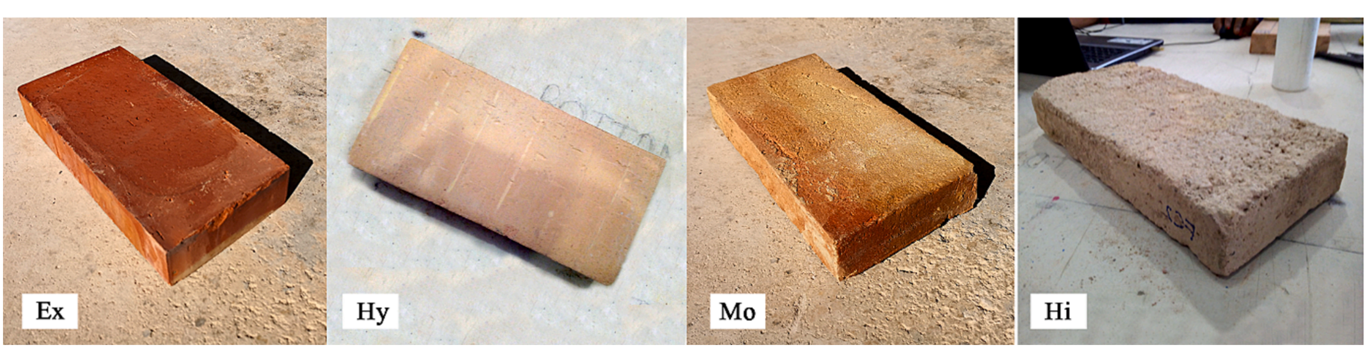

Fig. 1. Modern mechanically extruded solid clay brick (Ex), modern clay brick produced by hydraulic press moulding (Hy), modern handmade solid clay brick (Mo), and historical solid clay brick from existing building (Hi).

brick geometry (the limited brick thickness) and the restrictions normally encountered in extracting samples from existing buildings.

Historical brick beds usually present irregularities caused by their manual manufacture. In particular, the bed surface may have material depressions that diminish its cross-sectional thickness irregularly. These geometric conditions make it difficult to test historical brick specimens flatwise without any surface preparation. To overcome this problem, standard EN 772-1+A1 [9] recommends to grind or cap with cement mortar the specimen bearing surfaces. Following the standard, in the present research the surfaces of the bricks were subjected to grind until the requirement of flatness and parallelism was achieved. After the grinding process, the remaining height of the samples was close to 40 mm due to the bed irregularities of the solid clay bricks collected from the existing buildings (with raw thickness ranging between 44 mm and 56 mm). The 40 mm height of test samples is referenced in the standard EN 772–1+A1 [9]. The 'Hy' had an original thickness less than 40 mm, but the industrialized production offered flatness and parallel beds. In this latter case, polishing of the surfaces was possible with a grinding below 1 mm.

To comply with the aims specified in Section 1, it is proposed to test two specimen types. The first one, with dimensions 100 × 100 × 40 mm^3, is identified as '*100*'. The second one, measuring 40 × 40 × 40 mm^3, is identified as '*C40*' and is characterized by a slenderness equal to 1. For a specimen with height of 40 mm, the standard EN 772–1+A1 [9] allows a width value ranging from 50 mm to 100 mm. Therefore, the '*100*' specimen satisfies the standard requirements. An alternative to the standard specimen is the '*C40*' nonstandard specimen. The considered 40 mm cubic specimen this research is based on the proposal by Binda et al. [11] to measure the masonry material properties at a large scale. The 40 mm cubic specimen is sufficiently large to mitigate the possible effects due to the presence of inclusions and voids, as also suggested by Lourenço et al. [5]. Due to its limited volume, this cubic specimen requires only a small portion of the brick, leaving most of its material for other mechanical or physical characterisations. In addition, the proposed '*C40*' specimen can be tested along the thickness (t), width (w) and length (l) dimensions with the same slenderness, allowing in this way the evaluation of the brick anisotropy. In the present research, at least three '*C40*' specimens were obtained from each brick to test along each of the three directions.

Once the '*C40*' specimens were obtained, a visual inspection of their surfaces was carried out. This examination was necessary to disregard specimens showing material imperfections (inclusions and voids) or an excessive aggregate diameter. To determine the acceptable aggregate diameter, the relationship between the diameter and the specimen edge, indicated in the concrete standard EN 12390–1 [16], was taken as a reference. The specimens with a ratio between the edge length and the diameter of the aggregate under 3.0 were discarded, leading to a maximum aggregate diameter of 11 mm. The standard EN 12390–1 was chosen because it is more restrictive than ASTM C42 [20], which allows a minimum edge equal to twice the nominal size of the aggregate. Fig. 2 presents the surfaces of some accepted and discarded '*C40*' specimens based on the observed edge length to aggregate diameter ratio.

The extraction of the historical bricks from the existing building was carefully carried out with a chisel and a mallet, as shown in Fig. 3. First, a jackhammer was used to remove the plaster and a neighbouring brick. Then, a thin chisel was used to remove the lime mortar joints around the brick to be extracted. Finally, a chisel was inserted under the brick bed with a metal mallet to separate and lever the brick. While levering the brick up, the chisel was inserted in different positions along the brick, trying to avoid any crack appearance in the clay unit. The bricks were extracted from inside the building to avoid masonry samples exposed to meteorological phenomena or ground moisture. The mortar remaining on the surface of the extracted bricks was removed manually using a wire brush with metal bristles without damaging the unit. Finally, the extracted bricks were packaged, labelled and transported to the laboratory.

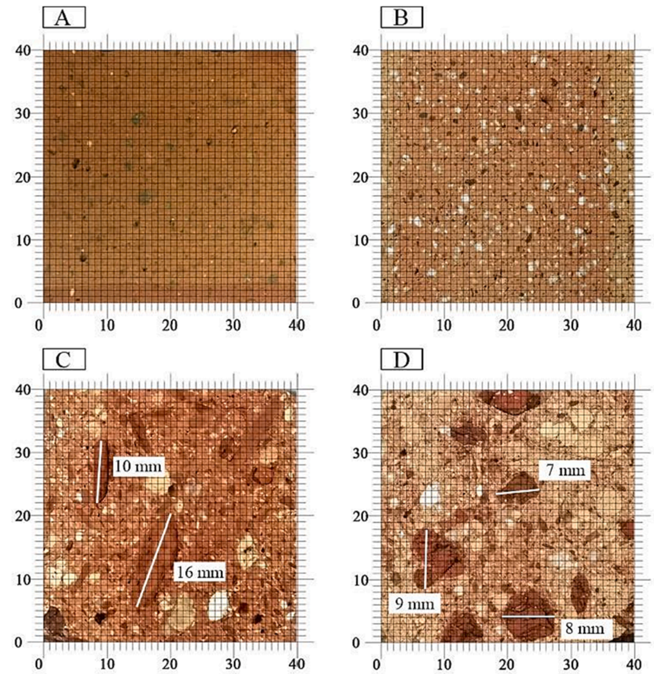

Fig. 2. Examples showing the edge length to aggregate diameter condition (grid values in mm) in '*C40*' specimens: (A) 'Ex' specimen with aggregate diameter under 2 mm; (B) 'Mo' specimen example with aggregate diameter under 2 mm; (C) 'Hi/R_3' discarded specimen with aggregate diameter over 11 mm; (D) 'Hi/R_2' accepted specimen with aggregate diameter under 11 mm.

Fig. 3. The extraction process of bricks from existing masonry walls: (A) first, the plaster was removed using a jackhammer; (B) then, the jackhammer was used to break and remove a neighbouring brick; (C) next, a thin chisel was used to remove all the lime mortar joints around the brick; (D) finally, a chisel was inserted under the bed of the brick to lever the brick.

The proposed specimens described above were prepared in the laboratory according to the procedures specified in European Standards EN 772–1+A1 [9]. First, the brick beds were polished by a grinder equipped with a rotary disc until obtaining a constant thickness of 40 mm (Fig. 4a). This operation was aimed to guarantee the smoothness and flatness of the loading surfaces and any bearing surface imperfection. Next, two different specimen types (the '*100*' and '*C40*' specimens) were extracted from each grinded brick using a table saw equipped with a water jet (Fig. 4b). The specimens were obtained from the central parts of the bricks, avoiding the extraction of these from the perimeter. Then,

Fig. 4. Manufacturing process of the specimens: (A) the grinder equipped with a rotary disc to polish the bricks until obtaining a constant thickness; (B) the table saw equipped with a water jet to cut the specimens; (C) the specimens in the oven at a constant temperature of 105 ± 5 °C for 24 hours; (D) 100 × 100 × 40 mm^3 specimen tested in the hydraulic press.

the specimens were dried in an oven at a constant temperature of 105 ± 5 °C for 24 hours (Fig. 4c). Finally, the specimen dimensions were measured using a calliper with a precision of ± 0.1 mm according to EN 772–16 [19]. A total amount of 138 standard '*100*' specimens and 323 nonstandard '*C40*' specimens were obtained, including 39 'Ex', 30 'Hy', 103 'Mo' and 289 'Hi' (130 'Hi/I_1', 24 'Hi/I_2', 47 'Hi/I_3', 18 'Hi/Ma', 26 'Hi/R_1', 22 'Hi/R_2' and 22 'Hi/R_3').

The specimens were tested making use of an Ibertest testing machine equipped with a load cell of 200 kN (AUTOTEST 200/10 SW) for the '*C40*' specimens and 3000 kN (MEH-3000) for the '*100*' ones, and connected to a MD5 electronic module for data acquisition. The specimens were centred on the steel plates with the grinded surfaces orthogonal to the direction of the loading, and tested under force control at a rate of 0.15 MPa/s or 0.30 MPa/s (Fig. 4d). The rate was selected from EN 772–1+A1 to guarantee a test duration of 60 s at least. The tests were stopped manually after registering the post-peak response.

3. Experimental results

Table 2 presents the number of specimens and the average compressive strength of the tested standard '*100*' specimens with dimensions 100 × 100 × 40 mm^3 ($f_{c,100}$), and of the '*C40*' cubic specimens with dimensions 40 × 40 × 40 mm^3 ($f_{c,C40}$), with their coefficients of variations (CV). The same table shows the compressive strengths of the latter in the different load orientations (t, *w* and *l*). The compressive strength of the samples was calculated by dividing the maximum compressive load by the cross-sectional area of the specimen. The displacement during the test was measured with the transducer installed in the actuator.

The coefficients of variation obtained in the measurement of the compressive strength range between 3.4% – 14% for mechanically extruded samples, 5.5% – 21% for hydraulic press moulded ones, 6.2% – 24% for modern handmade ones, and 11% – 29% for historical ones. The higher variation in historical bricks is due to the large inhomogeneity caused by their non-industrialised manufacturing. The lowest CV values are obtained for the 'Ex' and 'Hy' samples, with the exception of the 'Hy' '*C40*' ones tested along the length, for which significant variation has been obtained. Mechanized extruded (Ex) and hydraulic press moulded (Hy) bricks exhibit higher average strength than both modern and historical handmade types. Among the historical bricks, 'Hi/I_2' and 'Hi/R_1' show the highest average strength, probably due to the higher quality of the material, while the historical bricks 'Hi/R_3' present the lowest average strength. The '*C40*' specimens of the 'Hy', 'Mo_1' 'Mo_2' and 'Mo_3' bricks present similar strength averages among the tested unit directions (*l*, *w* and *t*). Conversely, different strengths $f_{c,C40}$ have been observed in the extruded (Ex) and historical (Hi/Ma) bricks along the different directions. Both the 'Ex' and the 'Hi/Ma' bricks showed the lowest strength $f_{c,C40}$ along their width, and the largest strength $f_{c,C40}$ along their thickness. The ratios between the compressive strength of the '*100*' and '*C40*' specimens along the thickness ranges from 1.32 (Hi/R_1 series) to 1.96 (Hi/I_1 series). Section 4 presents the in depth discussion about the effect of the specimen's shape and anisotropy on the compressive strength.

Fig. 5 shows the stress-displacement curves of the '*100*' and '*C40*' samples (along the thickness) of the extruded (Ex) and modern handmade (Mo_1) brick types. The stresses acting on the specimens were computed as the ratio between the applied load and their cross-section area. The curves show an initial segment with increasing stiffness in all stress-displacement curves. This behaviour may be attributed to fact that the displacement was measured with the actuator and may be caused by the adjustment of the platens to the faces of the brick specimens. Beyond this initial segment, all curves present an approximately linear branch up to the maximum compressive strength. The 'Mo_1' '*C40*' specimens present an almost horizontal final branch before reaching the maximum. The linear branches of the 'Ex' '*C40*' specimens are contained within the dispersion range exhibited by the '*100*' ones. This overlap

Table 2
Average compressive strength of the '*100*' samples ($f_{c,100}$) and '*C40*' samples ($f_{c,C40}$), and ratio between the compressive strength measured on '*100*' and '*C40*' samples $f_{c,100} / f_{c,C40}$. Values in parentheses indicate the breakdown of '*C40*' specimens tested along the three dimensions (t, *w* and *l*). Values in brackets indicate the coefficients of variation.

Tested specimens							
Origin	'*100*'		'*C40*'				$f_{c,100} / f_{c,C40}$
	Num. of specimens	$f_{c,100}$ (MPa)	Num. of specimens	$f_{c,C40}$ (MPa)			
				thickness (*t*)	width (*w*)	length (*l*)	
Ex	6	75.3 [3.4 %]	33 (12/9/12)	51.1 [14.1 %]	43.9 [8.8 %]	50.1 [10.6 %]	1.47
Hy	–	–	30 (10/10/10)	48.3 [5.5 %]	49.8 [16.0 %]	49.8 [21.0 %]	–
Mo_1	13	24.9 [8.6 %]	39 (13/13/13)	15.7 [6.2 %]	14.0 [13.6 %]	15.8 [11.1 %]	1.59
Mo_2	6	34.9 [8.2 %]	27 (14/6/7)	19.8 [15.0 %]	19.4 [9.9 %]	19.2 [20.9 %]	1.76
Mo_3	–	–	18 (6/6/6)	10.5 [15.1 %]	10.3 [24.2 %]	9.7 [17.8 %]	–
Hi/I_1	42	30.3 [25 %]	88	15.4 [25.5 %]	–	–	1.96
Hi/I_2	10	46.0 [21 %]	14	26.5 [29.2 %]	–	–	1.73
Hi/I_3	24	28.2 [15 %]	23	15.8 [20.2 %]	–	–	1.78
Hi/Ma	–	–	18 (6/6/6)	18.1 [22.8 %]	13.3 [10.8 %]	14.7 [15.2 %]	–
Hi/R_1	13	46.1 [23 %]	13	35.0 [25.6 %]	–	–	1.32
Hi/R_2	12	24.0 [20 %]	10	15.7 [21.5 %]	–	–	1.53
Hi/R_3	12	15.1 [16 %]	10	9.7 [18.5 %]	–	–	1.56

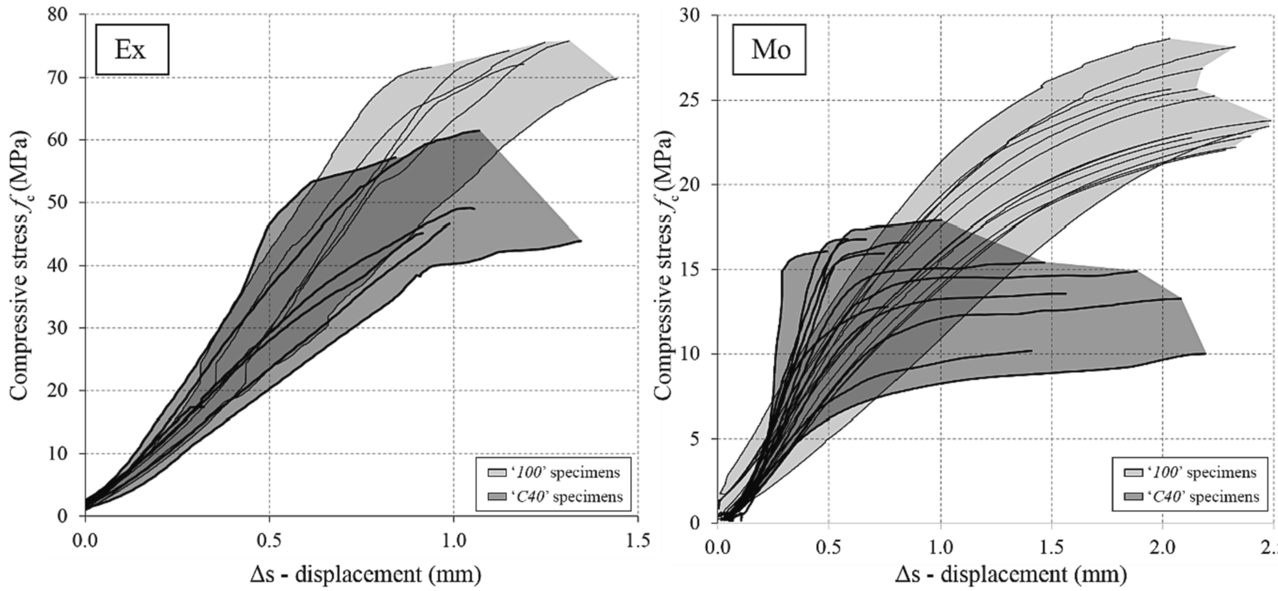

Fig. 5. Stress-displacement curves of the 18 mechanically extruded samples (Ex), and of the 26 modern handmade samples (Mo_1) under uniaxial compression test along the brick thickness.

shows that both specimens behave according to a similar elastic modulus, which suggest that their shape does not have a significant influence on the stiffness measured during the test. Conversely, in the case of the 'Mo_1' specimens, the linear branches of the '*C40*' and '*100*' specimens yield significantly different elastic moduli, suggesting that their stiffness may be influenced by the shape of the specimen.

The observed failure mode in both specimen types follows an hourglass shape, as shown in Fig. 6a, b, c, d, e and f, causing the complete separation of the outer parts. This failure mode is due to the confinement induced by the limited slenderness of the specimens. The acceptability of the failure modes in the '*C40*' specimens was evaluated according to the recommendations of the concrete standard EN 12390–3 [17] for cube specimens. Following this standard, satisfactory failures should show similar (approximately equal) cracking in the four exposed faces with little damage on the perimeter of the faces in contact with the platens. In turn, unsatisfactory failures present irregular cracked faces, tensile cracks or asymmetrical separation of the outer parts. Specimens showing this type of unsatisfactory failures should be disregarded. Following this approach, in the present research two specimens, respectively showing a tensile crack (Fig. 6g) and an asymmetrical separation of the outer parts (Fig. 6h), were discarded.

4. Discussion

This section presents two different studies based on the experimental results described in Section 3. The first study focuses on the anisotropy of the material and the influence of the brick direction in the resulting compressive strength. In addition to the experimental campaign carried out within the present research, this study also considers experimental results from the available literature in the field. The second study is aimed to the derivation of an experimental correlation allowing the estimation of the compressive strength of the normalized standard '*100*' specimen from that obtained with the proposed '*C40*' specimen. The section also includes a specific statistical analysis of outlier values potentially related with anomalous experimental results.

4.1. Study on brick anisotropy

The experimental campaign on '*C40*' specimens allowed the comparison of the compressive strength in the three brick orientations (t, *w* and *l*). This study has been performed on the mechanically extruded 'Ex', hydraulic press moulded 'Hy', modern handmade 'Mo' and historical 'Hi/Ma' specimens.

In fact, and as shown in Table 2 (Section 2) and in Fig. 7, close values were found in each group for the three brick orientations. Fig. 7 presents in a boxplot the distribution of the data based on the quartiles (being the second and third quartiles coloured inside the boxes), and shows the median (depicted as a horizontal line inside the box), the average (depicted as a cross) and the possible outliers. The boxplot presents the distribution of the statistical data. Results in Fig. 7 shows that the statistical distribution of the compressive strength values has, in almost all cases, an asymmetrical shape with either positive or negative skew. Asymmetrical distributions are identified by having neither the median nor the average in the centre of the box. Positive skewness occurs when the median falls below the average while negative skewness occurs in the opposite case. In addition, a larger spread in both value range and interquartile range is observed in industrialized bricks ('Ex' and 'Hy'), compared to the handmade ones. A light-tailed distribution can be seen in the handmade bricks ('Mo_1', 'Mo_2', 'Mo_3' and 'Hi/Ma') indicating a low kurtosis. It is recalled that kurtosis provides the measure of the sharpness of the peak in a data distribution in which the data values are concentrated around the average. Negative kurtosis means that the distribution has higher standard deviation than the normal distribution.

The boxplots present two potential outliers: (1) the minimum value within the 'Hy' specimens tested along the length, and (2) the maximum result within the 'Mo_2' specimens tested along the thickness. The analysis of these outliers is addressed in Section 4.2.

The scientific literature discussed in Section 1 includes only a limited number of references dealing with the experimental testing of brick specimens in compression under different orientations. Moreover, available references dealing with anisotropy in clay bricks focus mostly on mechanically extruded units. Fig. 8 shows experimental compressive strength values in different specimen orientations obtained by Aubert et al. [13], Salvatoni and Ugolini [15], Oliveira et al. [14], Fódi [12] and Krakowiak et al. [4]. The results from the references including all the experimental values are presented in a boxplot graph, while those corresponding to works that that only indicate the mean and standard deviation are presented as a point (mean) with a line calculated from the CV. Aubert et al. [13] obtained the largest strength in the direction perpendicular to the extrusion plane in extruded earth bricks. Oliveira et al. [14], Fódi [12] and Krakowiak et al. [4] also obtained the largest values through the extrusion plane in mechanically extruded solid clay

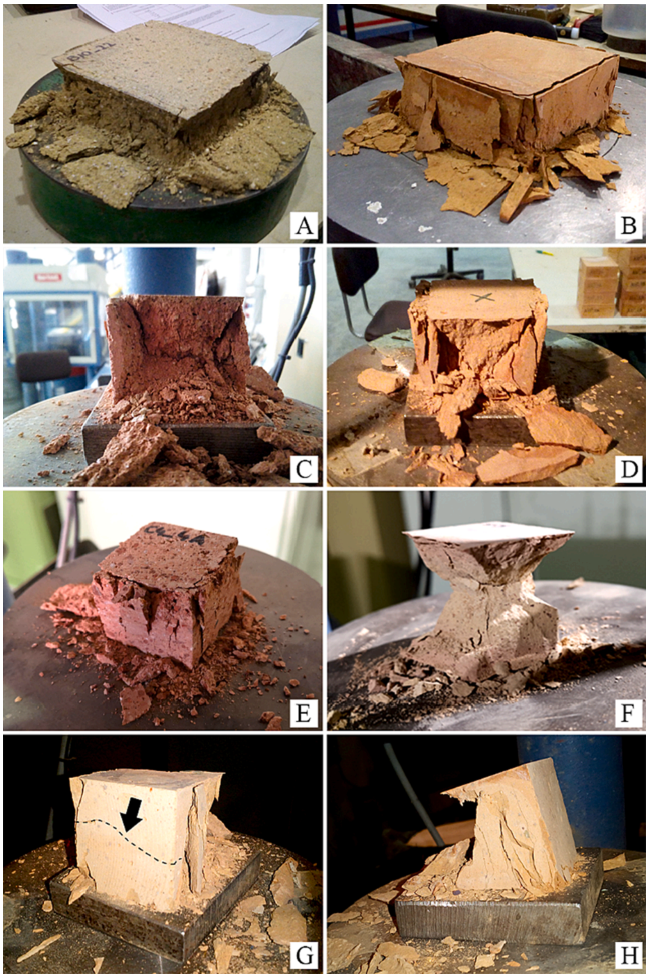

Fig. 6. Satisfactory and unsatisfactory failure modes: Satisfactory failures obtained for (A) 'Mo''*100*' specimen, (B) 'Ex''*100*' specimen, (C) 'Mo''*C40*' specimen, (D) 'Ex''*C40*' specimen, (E) 'Hi''*C40*' specimen, and (F) 'Hy''*C40*' specimen. Unsatisfactory failures obtained for (G) 'Ex''*C40*' specimen having a tensile crack, and (H) 'Ex''*C40*' specimen presenting an asymmetrical separation of the outer parts.

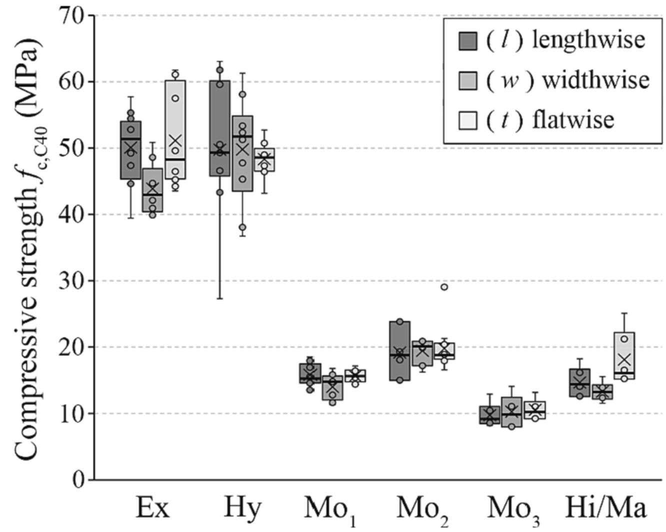

Fig. 7. Boxplot with lengthwise, widthwise and flatwise compressive strength values ($f_{c,C40}$) for the 'Ex', 'Hy', 'Mo$_1$', 'Mo$_2$', 'Mo$_3$' and 'Hi/Ma' '*C40*' specimens. Inside the boxes, the medians are represented with a horizontal line and the averages are represented with an X.

bricks. In Krakowiak's research [4], bricks with two extrusion techniques showed maximum strength in relation to the extrusion plane as well. Finally, Salvatoni and Ugolini [15] obtained similar compressive strength values on modern handmade bricks regardless of the load direction. Thus, the literature reviewed indicates that an anisotropic response is normally observed in extruded bricks with the largest strength perpendicular to the extrusion plane. However, this anisotropic behaviour has not been found in handmade moulded bricks.

The anisotropy of the brick types considered in the present study has been investigated through a statistical analysis. Fig. 9 shows the obtained histograms with the resulting probability distribution functions and Table 3 shows the skewness and kurtosis determined for the different group samples. The probability functions Fig. 9 are only a tentative adjustment as the samples of each group are limited in size. The histograms show symmetrical (with different kurtosis) and asymmetrical (with positive or negative skewness) distributions. More specifically, Table 3 indicates positive kurtosis for the 'Hi/Ma' (*l*) samples and close to zero or negative for the other cases. In addition, Table 3 indicates a general symmetry or moderate skewness for all the cases. Skewness values under 0.5 (in absolute value) in the 'Hy' (*t*) (*w*), 'Mo$_1$' (*t*) (*l*) (*w*) and 'Mo$_2$' (*t*) (*l*) samples indicate a symmetric distribution. Absolute values between 0.5 and 1.0 indicate moderate skewness, either positive or negative, in the 'Ex' *(l)* (*t*) (*w*), 'Hi/Ma' (*l*) (*w*), 'Ex' (*l*) and 'Hy' (*l*) samples. Finally, absolute values over 1.0 indicate a high degree of skewness, positive in the 'Mo$_3$' (*l*) and 'Hi/Ma' (*t*) samples and negative in the 'Mo$_2$' (*w*) ones.

Schueremans [21] observed a positive skewness in a large campaign carried out with 50 handmade brick samples, whose results could be adjusted with a lognormal statistical distribution. However, the results obtained in the present research cannot be adjusted with lognormal distribution due to the large variability obtained in terms of kurtosis and skewness. Likewise, normality test and histogram analysis may have an insufficient capacity to detect whether the samples conform normal distribution due to the limited sample size.

A graphic verification allows the detection of possible anisotropy in some of the sample series. As can be seen in Fig. 10, three linear regressions were performed pairing (*t*) – (*l*), (*t*) – (*w*) and (*l*) – (*w*) values for each type of brick. The trend line of each paired values was compared with the ideal line of 45°denoting equal strengths along the two considered directions. Fig. 10. shows the similarity of compression strengths along thickness and length for the 'Ex' samples, while strength values along the width are meaningfully lower than those obtained along the other two directions. The 'Hy' series shows similar strength values in the three cases. The three 'Mo' series almost overlap the 45-degree regression line. The 'Hi/Ma' series also overlaps the 45-degree line for the paired strength values along length and width, while higher strength values are obtained along the thickness.

A new statistical evaluation was carried out to identify meaningful strength differences among the orientations, and to confirm the possible anisotropy of some brick types. A non-parametrical analysis was applied since the data could not be adjusted to a normal distribution and the number of samples in each population was small. Two nonparametric tests that can be used for this purpose, i.e. the Kruskal-Wallis test [22], and the Wilcoxon Sum Rank test [23]. The Kruskal-Wallis test [22] was used to compare the three data sets corresponding to the dimensions *t*, *w* and *l*, and determine whether they belong to the same data population. The Kruskal-Wallis test provides the probability of fulfilling the statistical hypothesis that the data sets belong to the same data population. Probabilities below 5 % lead to reject the hypothesis while probabilities above 5% lead to accept it. The Wilcoxon Sum Rank test [23] compares two data sets and determines if the values of a reference data set are lesser, equal, or larger than the values of the other data set. The paired data sets tested were (*t*) – (*l*), (*t*) – (*w*) and (*l*) – (*w*).

The Kruskal-Wallis test indicated that the data sets along the three

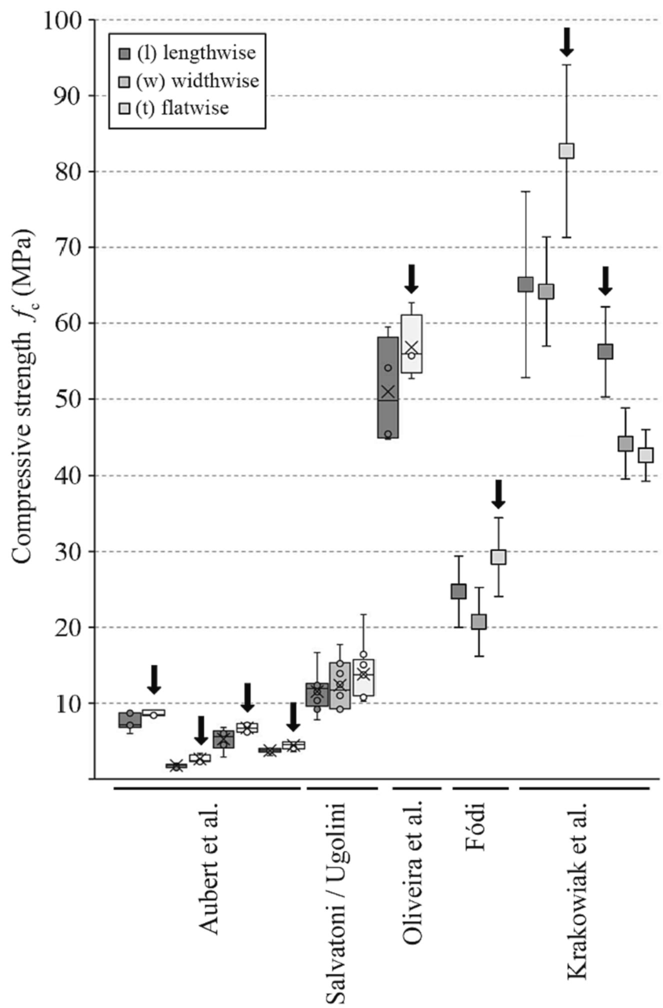

Fig. 8. Experimental compressive strengths along the different dimension of the brick as found in five available experimental programs in the literature Aubert et al. [13], Salvatoni and Ugolini [15], Oliveira et al. [14], Fódi [12] and Krakowiak et al. [4]. The arrows mark the cases of extruded units tested perpendicularly to the extrusion plane.

brick directions are coincident (i.e., correspond to a single population) for series 'Hy', 'Mo$_1$', 'Mo$_2$' and 'Mo$_3$', while series 'Ex' and 'Hi/Ma' are non-coincident data sets. The 'Ex' and 'Hi/Ma' series showed the lowest coincidence probability (2%), meaning that their compressive strengths along their three orientations can be assumed to be different. Coincidence probabilities above 5% were obtained for series 'Hy', 'Mo$_1$', 'Mo$_2$' and 'Mo$_3$' (50.5%, 7.2%, 79.9% and 56.7% probability respectively).

The Wilcoxon Sum Rank test was executed considering brick sample series for which the Kruskal-Wallis test indicated that the data sets were non-coincident, i.e. in series 'Ex' and 'Hi/Ma'. This complementary test indicated that the compressive strength along the thickness is larger than those along the length and width, and that the compressive strength along the length is larger than that measured along the width ($t > l > w$) in these series.

Using the previously presented statistical and graphical tests allows some conclusions on the anisotropy of the investigated brick types. Moderate anisotropy has been found in the extruded bricks 'Ex', in which the lowest compression strength is obtained along the width. In turn, the 'Hi/Ma' bricks show larger strength along the thickness than in the other two directions. In the rest of the brick series tested ('Hy', 'Mo$_1$', 'Mo$_2$' and 'Mo$_3$') no significant difference among the compressive strength is observed along the three orientations (t, *w* and *l*).

The anisotropy of extruded clay units has been investigated by other authors. Habelitz et al. [24] and Viani et al. [25] focused on the microstructure of extruded bricks. Krakowiak et al. [4] concluded that the micro-porosity exhibits a preferential orientation along the extrusion direction, directly affecting brick properties such as the water absorption, the modulus of elasticity and the strength. Kubiś et al. [26] and Bourret et al [27] observed these microstructure irregularities and concluded that the anisotropy influences the thermal conductivity and the elastic properties. Makoond et al. [28,29] studied the dynamic elastic properties in extruded bricks using ultrasonic pulse velocity testing, revealing different relative dispersions (indicating different elastic properties) among the different brick directions. Research on other materials produced by extruded techniques showed anisotropy in physical and mechanical properties, as in Maillard et al. [30] on earth bricks, Antal et al. [31] on Illite-Based ceramics, and Boussois et al. [32] on ceramics. The anisotropy of these materials was derived from the analysis of the manufacture process and the orientation of the clay mineral particles of the feeding material [33,34]. In general, the conclusions obtained by previous researchers are consistent with the anisotropy detected in the present study for extruded bricks.

4.2. Analysis of outliers to detect anomalous experimental results

The visual criteria considered in disregarding inadequate specimens have been indicated in Sections 2.2 and 3. These criteria have been actually applied in order to disregard specimens deemed inadequate because of the presence of material imperfections (inclusions and voids), excessive aggregate diameter or inadequate failure modes. In spite of this previous selective effort, additional statistical criteria have been also applied to disregard anomalous cases that might not have been visually recognized and may manifest as statistical outliers. Such outliers might be related to anomalies not easily detectable during the experiments, as for instance possible small load eccentricities causing an unexpected tensile failure mode, the lack of parallelism between the bearing surfaces, or excessive confinement exerted by the press platens.

As mentioned in the previous section, two possible outliers can be identified in this experimental campaign, as shown in Fig. 7, corresponding to (1) the minimum value within the 'Hy' specimens tested along the length and (2) the maximum value within the 'Mo$_2$' specimens tested along the thickness.

A careful evaluation of outliers requires an ad-hoc statistical analysis. Two tests are proposed to identify the potential outliers: the Grubbs test [35] and the Murphy test [36]. The Grubbs' test is used to determine whether a single outlying value within a set of measurements falls sufficiently apart from the average as to be statistically classified as not belonging to the same population (outlier). In this case, the value can be omitted in subsequent calculations. The Murphy's test determines whether the two largest observations within a set of measurements should be considered as outliers and omitted from the data set. The Murphy's test is applied to avoid the statistical masking and swamping effects [37,38] that may appear when two close outliers are present. Since the outlier tests are based on the assumption of normality, it is necessary to convert the obtained asymmetrical distribution into a normal one. Although, as mentioned, the brick samples investigated in this study do not comply, in general, with a lognormal distribution, this kind of distribution can in fact be utilized to model the 'Ex' (*t*) (*w*), 'Mo$_3$' (*l*), and 'Hi/Ma' (*t*) (*l*) (*w*) samples owing to its positive skewness and adequate kurtosis. The corresponding lognormal distributions can be translated into a normal one using a logarithmic conversion, causing high data to compress and low ones to expand. In turn, the distributions of series 'Ex' (*l*), 'Hy' (*l*), 'Mo$_2$' (*w*), characterized by negative skewness, can be translated to a normal distribution using a square value conversion, which compresses the scale for low data and expands it for high ones.

The application of the Grubbs' test confirms the already identified potential two outliers with a critical value over 2.5%. This value indicates the threshold of statistical significance defining the upper and

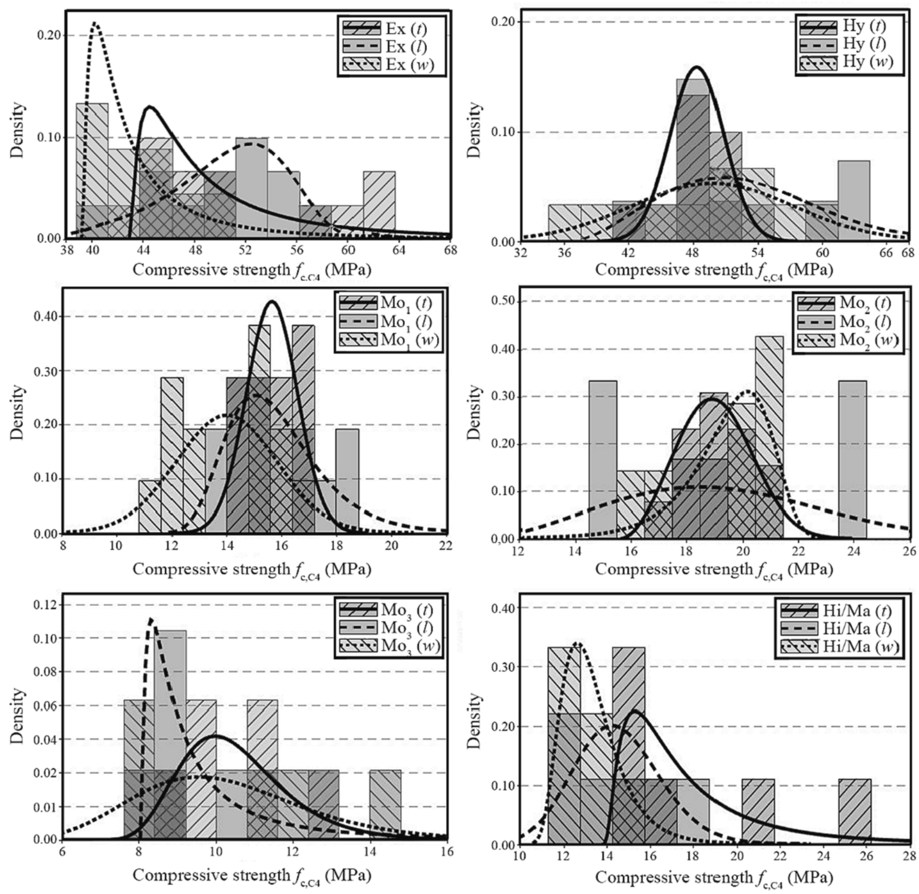

Fig. 9. Histograms and statistical distributions for the tested samples.

Table 3
Skewness and kurtosis of the statistical distributions for the tested samples.

	Ex			Hy			Mo1			Mo2			Mo3			Hi/Ma		
	(*l*)	(*w*)	(*t*)	(*l*)	(*w*)	(*t*)	(*l*)	(*w*)	(*t*)	(*l*)	(*w*)	(*t*)	(*l*)	(*w*)	(*t*)	(*l*)	(*w*)	(*t*)
Skewness	−0.6	0.8	0.7	−0.8	−0.5	−0.3	0.3	−0.1	0.0	0.3	−1.1	0.2	1.5	0.6	0.9	0.7	0.5	1.3
Kurtosis	−0.1	−0.4	−1.5	−1.4	−0.5	0.7	−1.2	−1.7	−1.2	−1.9	−0.5	−0.2	2.2	−1.1	−0.1	−0.2	−0.2	0.2

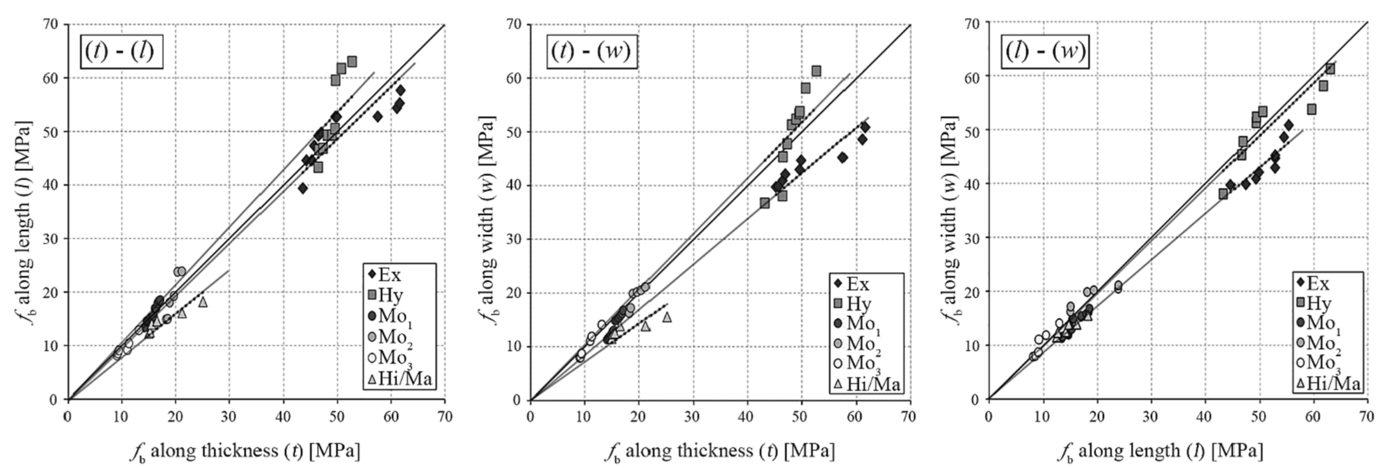

Fig. 10. The linear regression relating (*t*) – (*l*), (*t*) – (*w*) and (*l*) – (*w*) pairs of testing directions for 'Ex', 'Hy', 'Mo_1', 'Mo_2', 'Mo_3' and 'Hi/Ma' specimens.

lower bounds of the confidence interval. Moreover, the Murphy's test did not identify any additional outlier. After extracting the outliers, the 'Hy' (*l*) series has a modified average of 52.3 MPa (CV of 13.9%), and the 'Mo_2' (*t*) series has a modified one of 19.1 MPa (CV of 7.1%). The extraction of the outliers reduces the CV almost by half, while the averages remain practically the same in both cases (with variations of + 5% and + 3.5% respectively).

4.3. Compressive strength correlation between standard and nonstandard specimens

Based on the experimental campaign presented, it has been possible to derive a correlation between the experimental compressive strength measured with the '*100*' specimen with that measured with the '*C40*' (*t*) one ($f_{c,100}$ / $f_{c,C40}$ ratio). This study has been performed on the 9 brick types indicated in Fig. 11. An average value of the $f_{c,100}$ / $f_{c,C40}$ ratio equal of 1.65 has been obtained for the set of the different brick series, with an standard deviation of 0.20 (CV of 12%). The $f_{c,100}$ / $f_{c,C40}$ ratio has been determined for different types of bricks produced with similar handmade manufacturing process, except the 'Ex' type. However, the 'Ex' samples show a ration (1.47) similar and within the range of the handmade ones. As shown in Table 2 (Section 2) and Fig. 11, the ratio ranges between 1.32 and 1.96.

The boxplot graph in Fig. 11 shows two features already discussed apropos of Fig. 7, namely the generalized asymmetry of the distributions and the potential presence of outliers, the latter being apparently visible in the 'Hi/I_1' series. However, the application of the Grubbs and Murphy tests, as in Section 4.2, indicated that such extreme values cannot be actually considered as outliers in this case.

A statistical analysis of the experimental $f_{c,100}$ / $f_{c,C40}$ ratios was carried out in order to undertake a more detailed analysis of its variation, For this purpose, the histogram distribution of the $f_{c,100}$ / $f_{c,C40}$ ratios was determined as shown in Fig. 12. The normality of the distribution was checked using the Shapiro-Wilk test [39], which confirmed that the experimental $f_{c,100}$ / $f_{c,C40}$ ratios follow a normal distribution. However, the histogram of Fig. 12 shows an empty column in the range 1.60 – 1.70 where the average (1.65) is positioned. This peculiarity does not show any relationship with brick types (i.e. with their manufacture process) and is attributed to a purely random effect.

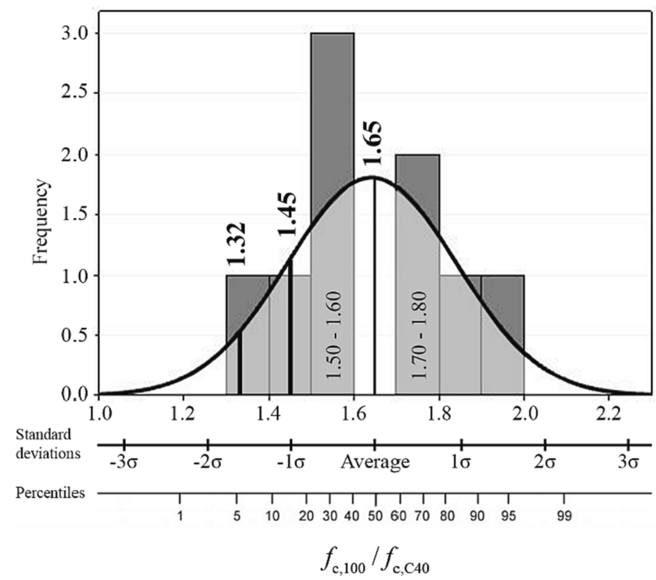

Fig. 12. Histogram and probability distribution function for $f_{c,100}$ / $f_{c,C40}$ ratios.

A modified estimate of the $f_{c,100}$ / $f_{c,C40}$ ratio, intended to be considered for an engineering estimation of the compressive strength of bricks from the '*C40*' specimen, can be calculated based on the normal density distribution (Fig. 12). Specifically, the proposed engineering value is calculated as the value of the ratio for the −1σ standard score. The standard score (or z-score) is the number of standard deviations (σ) by which a value is above or below the average. Thus, the proposed engineering $f_{c,100}$ / $f_{c,C40}$ ratio, located at the safe side with respect to the average, and corresponding to the score −1σ, is equal to 1.45. Fig. 12 shows its location in the normal distribution. As shown by the figure, the proposed value is a safe one in comparison with a large part of the values occurring according to the density distribution. Another possibility for an engineering estimation could consist in adopting the value corresponding to the 5% percentile. This second possibility is considered as too conservative in this case, as it yields a value equal to 1.32, which falls at the lower bound of the full set of experimental values.

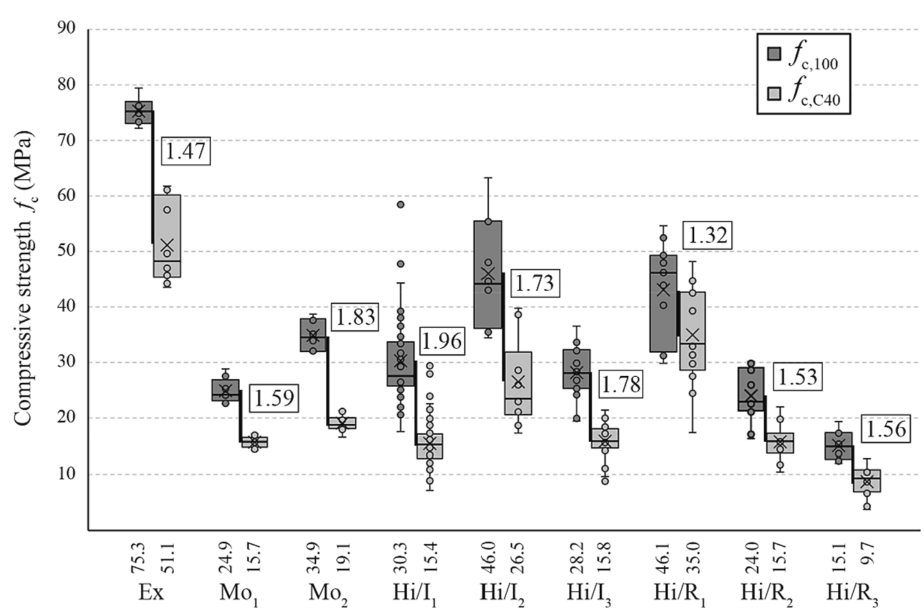

Fig. 11. Boxplot with $f_{c,100}$ and $f_{c,C40}$ values for the 'Ex', 'Mo', 'Hi/I' and 'Hi/R' samples. The numbers in the squares indicate the relation between the compressive strength averages of the '*100*' and 'C40' specimens ($f_{c,100}$ / $f_{c,C40}$) along the thickness. Inside the boxes, the medians are represented with a horizontal line and the averages are represented with an X. The numbers in the horizontal axis indicate the compressive strength averages for each sample.

5. Conclusions

A study has been presented on the viability of determining the compressive strength of solid clay bricks by testing non-standard small cubic specimens of dimensions 40 × 40 × 40 mm^3 (labelled as *'C40'*). The use of this small specimen allows the measurement of the compressive strength along the three brick dimensions (length, width and thickness). Therefore, the *'C40'* specimen has enabled the investigation of the anisotropic response that is observed in some brick types depending on their manufacturing process. Moreover, the use of this small specimen allows reducing the volume of material sampled from existing structures, which may be severely restricted in the case of architectural heritage. The viability in the use of the '*C40*' sample has been investigated by comparing experimental results with those obtained with a standard 100 × 100 × 40 mm^3 specimen (labelled as '*100*').

The viability of the nonstandard '*C40*' specimen was validated through an experimental campaign on mechanically extruded, hydraulic press moulded, modern handmade and historical handmade bricks, the latter extracted from six 19th century and early 20th century buildings in Barcelona (Spain). The following conclusions can be drawn from the experimental procedures and the analysis of the experimental results:

- A relatively easy and efficient procedure could be implemented to extract the historical bricks from existing walls. Common electric tools were employed, such as a jackhammer to remove the plaster, together with manual chisel and a nylon hammer for the careful extraction of the bricks.
- The failure mode of the 40 × 40 × 40 mm^3 specimen showed a characteristic hourglass shape. Successful failure modes were judged following standardized criteria for concrete cube specimens.
- A specific methodology has been proposed and applied for the post processing of the experimental results. The proposed methodology is based on a statistical analysis of the experimental data and includes the application of nonparametric statistical tests. This methodology could be similarly applied to extend the research to other brick types.
- The study shows that the extruded solid clay bricks investigated present a moderate anisotropy due to their manufacturing process. The smallest strength is obtained along the width and the largest one along the direction perpendicular to the extruded plane (which can be the thickness or the length depending on the manufacturing process). This observation has been corroborated from data found in the scientific literature. However, an almost isotropic behaviour has been obtained for the three handmade moulded bricks and the hydraulic press moulded ones herein investigated.
- The results of the experimental analysis show that the compressive strength measured on the two specimen types (the standard '*100*' and nonstandard '*C40*') can be correlated by an average ratio $f_{c,100}$ / $f_{c,C40}$ equal to 1.65 (CV of 12%) ranging between 1.32 and 1.96. This ratio allows the estimation of the compressive strength of the standard '*100'* specimen from that measured from the *'C40'* one on solid fired clay brick. However, a more conservative and engineering ratio equal to 1.45 is proposed based on statistical considerations. The mechanically extruded specimens 'Ex' show a ratio (1.47) very similar to that of the handmade ones.
- The proposed '*C40*' specimen has provided an advantageous technique for the evaluation of the compressive strength of solid clay bricks in existing masonry structures. In practical applications oriented to the characterization of existing brick masonries, it is suggested to test at least a set of twelve specimens from six different units to obtain a reliable estimation of the compressive strength.

Future works could address the extension of the experimental database to a largest sample of solid clay bricks, as well as a detailed study of the possible influence of the material's porosity on the compressive strength and anisotropy. This extension would allow a deeper confirmation of the results herein presented regarding the suitability of the proposed specimen and the anisotropy of different brick types.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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