Construction and Building Materials 298 (2021) 123626

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Updating mechanical properties of two-leaf stone masonry walls through experimental data and Bayesian inference

Antonio Murano [a,*], Javier Ortega [a], Hugo Rodrigues [b], Graça Vasconcelos [a]

[a] University of Minho, ISISE, Department of Civil Engineering, Guimarães, Campus de Azurém, 4800-058 Guimarães, Portugal
[b] RISCO, Civil Engineering Department, University of Aveiro, Campus Universitario de Santiago, 3810-193 Aveiro, Portugal

HIGHLIGHTS

- A systematic comprehensive review of experimental studies is presented.
- A database compiles results from experimental studies on two-leaf stone masonry walls.
- A Bayesian-based approach allows to define ranges for selected mechancial parameters.
- Results obtained are comparable to the ranges proposed in current standards.
- Results provide a valuable reference for practice-oriented engineering activities.

ARTICLE INFO

Article history:
Received 9 November 2020
Received in revised form 25 February 2021
Accepted 16 March 2021

Keywords:
Stone masonry
Database
Mechanical properties
Two-leaf stone masonry walls
Experimental studies
Sonic testing
MQI
Bayesian updating procedure
Technical standards

ABSTRACT

The work presents the study carried out to build a database of mechanical properties related to the most recurring two-leaf stone masonry wall typologies. The main objectives of this study are: (1) to perform a systematic review of experimental studies (2) to apply a data fusion technique, based on a Bayesian framework, to update the selected mechanical parameter using the information stored in the final database. The results obtained are compared to the ranges proposed in current standard and guidelines. Therefore, the outcomes presented in this work can provide a valuable support in practice-oriented engineering activities addressing the assessment of existing buildings.

1. Introduction

Traditional engineering models based on a deterministic approach have been widely applied over the last decades in professional practice. These models usually consist of simplified rules deduced accordingly to the available experimental data. Despite their effectiveness in terms of cost reduction and overall improvement of structural performance in engineering systems, these approaches only partially account for uncertainty affecting physical quantities (e.g. materials' mechanical properties) by means of conservative values and/or safety factors [1].

In particular, uncertainty may play a considerable role in the assessment of existing buildings such as masonry heritage constructions, due to a significantly greater variability observed in the description of geometry, materials, and acting loads.

When dealing with historical constructions and monuments, a specific assessment procedure is considered effective if it combines a significant level of knowledge with minimum invasiveness of interventions, thus aiming at the conservation of the cultural asset [2]. To tackle this issue, Italian and European guidelines (NTC 2008, Eurocode 8 – Part 3) [3] have traditionally relied on a semi-probabilistic framework that defines Knowledge Levels (KLs). Different KLs are achievable once a defined amount of geometrical, architectonic, constructive, and mechanical data is gathered. The achieved *Knowledge Level* corresponds to a *Confidence Factor (CF)* that, once applied to a specific parameter provided by the code,

*Corresponding author.
E-mail addresses: antoniomurano1987@gmail.com (A. Murano), javier.ortega@civil.uminho.pt (J. Ortega), hrodrigues@ua.pt (H. Rodrigues), graca@civil.uminho.pt (G. Vasconcelos).

https://doi.org/10.1016/j.conbuildmat.2021.123626
0950-0618/

results in a reduction of its value in order to compensate for a biased knowledge of the structure [3,4].

In recent years, there has been a progressive rise of awareness on how to consider variability and uncertainty in the material, geometric and construction characteristics related to the structural assessment procedures of existing buildings, which has led to a relevant upgrade of the standard deterministic method, particularly in the field of seismic safety assessment procedures.

A methodology for the probabilistic assessment of existing building has been proposed by the National Research Council of Italy (CNR) [5]. It models uncertainties based on the classification of three types of variables, namely deterministic (characterized by a negligible margin of uncertainty), random (related to the intrinsic variability of the properties of the structure) and epistemic (related to the lack of knowledge of the structure in terms of mechanical properties) [5].

A significant aspect concerning the application of probabilistic approaches in the construction industry is the acquisition of suitable data and information for the reduction of the global uncertainty characterizing the entire process.

Within this framework, non-destructive techniques and expedited assessment methods based on visual inspections are highly valuable tools for existing buildings' material characterization. They are complementary to minor-destructive and destructive procedures that are not always applicable or advisable (e.g. lack of minimum intervention criterion applied to conservation of heritage constructions).

Hence, recent upgrades in technical guidelines acknowledged the relevance of collecting data from different sources (e.g. non-destructive, minor-destructive and destructive testing procedures). The guidelines envisage the possibility to combine this information by means of advanced statistical techniques, in order to estimate mechanical parameters [6].

To this end, Bayesian inference has been generally adopted due to its effectiveness in reducing uncertainties. It allows, on one hand, to fuse together various types of data and, on the other hand, to further upgrade a given parameter when new information is available [5,6].

Based on the previous considerations, this work presents the research activity carried out to collect data from non-destructive, minor-destructive, and destructive testing procedures by means of literature review. The data was assembled into a large database of mechanical properties related to different historical two-leaf stone masonry types. Successively, using the collected information, Bayesian inference has been applied to obtain range of variation for different mechanical properties of two-leaf stone masonry types. Lastly, the ranges obtained are compared with the ranges proposed in current standards. The outcomes herein presented can provide a valuable support for practice-oriented engineering activities addressing the assessment of existing buildings.

2. Bayesian inference applied to the assessment of existing structures and to uncertainty reduction: Background and motivation

Classic statistic methods are based on a frequentist interpretation of probability according to which frequencies are used as a measure of uncertainties. Conversely, Bayes' theorem is a proposition about conditional probabilities. A probability distribution function describes an unknown parameter, hence the probability itself to provide an estimation of uncertainty.

According to this approach, an initial distribution of data based on a priori information can be updated, obtaining a posterior distribution, when new observations are available [7]. If a value X = x is observed, and h(θ) is the prior distribution, the Bayes theorem is translated as follows:

$$h(\theta|x) = \frac{h(\theta)f(x|\theta)}{\int_{\theta} h(\theta)f(x|\theta)d\theta} \quad (1)$$

where h(θ|x) is the posterior distribution of θ after observing X = x. The initial information is characterized by h(θ) and modified with the observed data by being updated to h(θ|x); f(x) is the prior predictive distribution for X; that is for an observation of X whatever value of θ.

Bayes theorem weighs the prior information with the evidence provided by the new data. The posterior distribution is a compromise with reduced uncertainty between the prior information and the one contained in the new data [8].

The prior distribution should include all plausible values of a certain variable and its parameters can be estimated based on known initial observations (e.g. literature review) and/or subjective knowledge (e.g. personal judgment). It is possible to choose a prior distribution with small standard deviation (good prior knowledge), large standard deviation (limited knowledge) or it is also possible to choose a prior distribution, which reflects a range of situations from no knowledge. Prior distribution and posterior distribution follow the same parametric form (conjugacy property). Therefore, if prior and likelihood functions are normally distributed, the posterior function will be normally distributed as well [8].

The joint probability distribution of the data and the parameter (likelihood) is given by h(θ|x) according to the expression:

$$h(\theta|x) = L(\theta) = \prod_{i} h(x_i|\theta) \quad (2)$$

where i is the number of outcomes of the new data.

The Bayes theorem allows to estimate the density function of the posterior distribution by multiplying the likelihood function and the density function of the prior distribution with subsequent normalization [9].

The posterior density expresses the fusion between prior observation and new data, and it provides a basis for posterior inference regarding θ.

Bayesian inference versatility allowed this method to address different engineering applications, ranging from structural performance assessment to estimation of materials' mechanical properties. In its early stage, research activities involving Bayesian methods mainly dealt with the definition of probabilistic frameworks aimed at the updating of structural models based on dynamic test data [10–12].

Further contributions, concerning the development of a methodology combining Bayesian inference and data obtained from dynamic identification tests, were used to update the probability density function (PDF) of the elasticity modulus in masonry towers [13–15].

Aiming at the definition of capacity models for reinforced concrete components (e.g. bridge columns), Gardoni [16] estimated fragility curves under cyclic load by means of Bayesian update. Successively, research activities based on Bayesian frameworks applied to reinforced concrete structures mainly addressed the reduction of uncertainties in estimating mechanical properties. To this end, the Bayesian method has been applied to combine experimental data and reference values provided by standards and guidelines (e.g. Eurocode and Italian Standards), to overcome the limitations affecting the use of *Confidence Factors* in reducing the mechanical properties depending on the achieved *Knowledge Level*. This code-based approach, in fact, is unable to account for the reliability of information gathered by means of different testing procedures [17–19].

Similarly, advanced statistical methodologies (Bayesian inference and Monte Carlo simulation) have been integrated in code-based assessment procedures for existing masonry buildings to reduce different sources of epistemic uncertainty (e.g. selection of the *Knowledge Level*, selection of location, and results of in-situ tests) [20,21].

Additional contributions addressing the application of Bayesian methods for masonry structures were reported in Campostrini [22]. In this study, the authors developed a probabilistic methodology for the seismic vulnerability assessment at urban scale. Moreover, Beconcini [23] and Conde [24] proposed two different methodologies based on a Bayesian framework for the assessment of ancient constructions, applying their findings to a historical aqueduct and to a masonry arch bridge respectively.

A data fusion procedure, based on the Bayesian framework presented in Miranda [25] for the update of geomechanical parameters, was applied by Ramos [26] to a real case study (St. Torcato Church in Guimarães, Portugal). The goal of the study was to reduce the uncertainties in the estimation of the Young's modulus of the granite stone that compose the masonry walls of the church. The proposed methodology aims to overcome difficulties in selecting the right value for a certain parameter, which is crucial to perform subsequent structural assessment. In the present work, this data fusion technique has been taken as a reference approach to obtain updated values of historical masonry mechanical properties using a large set of experimental data.

3. Database definition: Adopted criteria

The work herein presented consists of a systematic review of experimental campaigns addressing the assessment of two-leaf stone masonry walls' mechanical properties. This wall morphology, highly widespread in Portugal, Italy, and other European countries, has been selected since it represents a construction technology typically applied in a considerable number of historical buildings [27].

It is noted that the work presented intends to be an exemplary application of the methodology proposed and it can be carried out for other masonry typologies typically observed in historical constructions, such as one-leaf and three-leaf stone masonry walls.

Based on the guidelines provided by Eurocode 8 – part 3 [3] and Italian Code (Table C8.5.1, Circolare n. 7–21/01/2019) [28], six different stone masonry types have been considered to build the final database (Fig. 1), namely:

- Masonry Type 1 (Irregular stone masonry) – Neither artificial nor handmade techniques have been applied to modify the stone units in terms of shape and/or geometric characteristics. The masonry bond is irregular and significantly chaotic;
- Masonry Type 2 (Roughly cut stones with wythes of irregular thickness) – Masonry wall constructed using slightly cut stone units having roughly defined shapes. Despite stone units may vary from each other both in terms of shape and size, the masonry bond often presents a regular texture and a good overall arrangement;
- Masonry Type 3 (Uncut stonework with good texture) – Masonry wall constructed using regular-shaped stone units. Stone units may vary from each other both in terms of shape and size. Additionally, they do not have experienced any kind of handmade or artificial working process. The masonry bond is considerably regular. Moreover, it can be detected the presence of horizontal bed joints;
- Masonry Type 4 (Masonry of irregular soft stone blocks) – This category proposes a classification mostly based on a specific material. Masonry units related to this wall typology can be made of roughly cut volcanic rocks (tuff) or sedimentary rocks (tufa) [29]. Throughout history, tuff has been often used in heritage constructions because it is a light and easily workable material;
- Masonry Type 5 (Regular masonry of soft stone blocks) – Similarly to the previously listed typology (Masonry Type 4), this category refers to masonry walls built with volcanic and sedimentary rocks and with masonry units that can be defined as "dressed stones", meaning that they have been worked and assembled together resulting in a masonry bond embodying the main criteria of the "rules of the art";

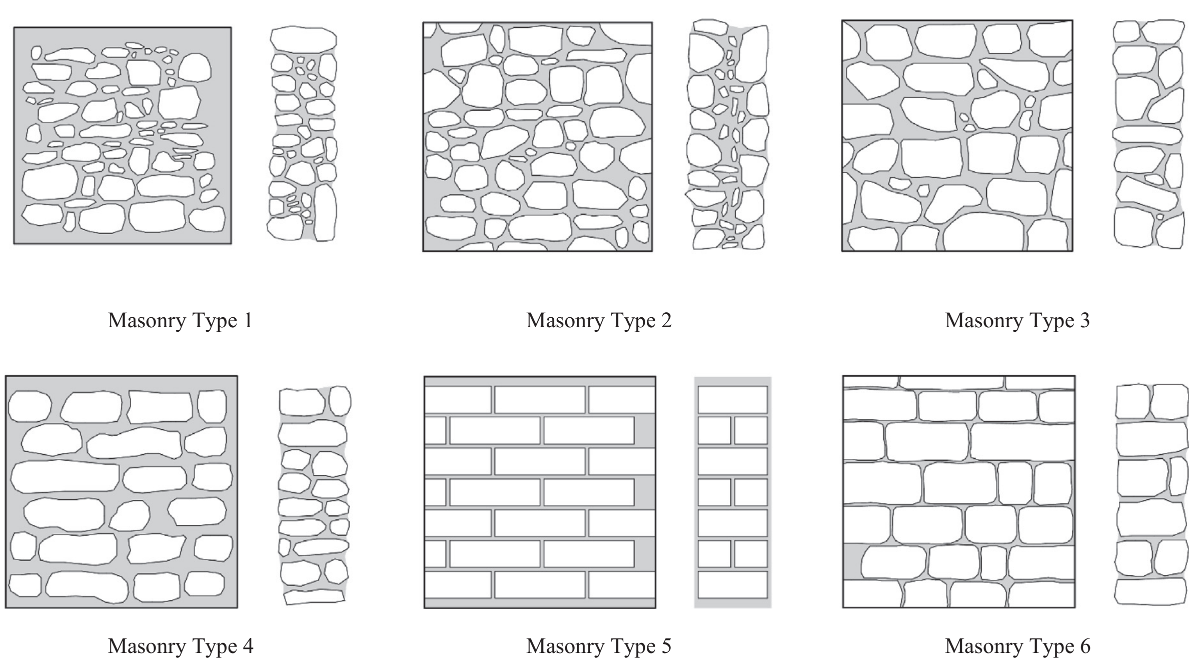

Fig. 1. Selected masonry types.

- Masonry Type 6 (Squared stone masonry) – Masonry wall constructed using stone units that can be found in quarries. Stone units may differ in terms of size, but they have been shaped to be as much regular as possible. The masonry bond is characterized by vertical and horizontal bed joints uniformly distributed throughout the entire masonry wall.

Experimental data collected for the construction of the database refers to the following mechanical parameters: Young's Modulus (E), Shear Modulus (G), Compressive Strength (f_m) and Shear Strength ($\tau 0$). The testing procedures considered are: Sonic Testing (ST), Flat-Jacks Tests (FJ), Compression Tests (CT), Diagonal-Compression (DC) and Shear-Compression Tests (SC).

The comprehensive literature search was carried out on 5 electronic indexing databases: Scopus, Science Direct (SCD), Web of Knowledge (WOK), Civil Engineering Database (ASCE), and MADA RELUIS Database [30].

In addition to the collected papers, other relevant documents were considered, such as Ph.D. thesis and technical reports of Integrated Projects (SA7) carried out within the framework of the Advanced Masters in Structural Analysis of Monuments and Historical Constructions (SAHC). These additional documents provided highly valuable information in order to fill the gap regarding the availability of experimental data from Sonic Testing procedures applied to historical masonry.

Papers whose titles were not about two-leaf stone-masonry walls tested by means of the non-destructive, minor-destructive, and destructive procedures selected for this study were excluded. On the other hand, those papers complying with the established criteria were included in the final set of data, and they were carefully screened to avoid any possible repetition. A detailed list with the final set of papers and reports, collected to extract experimental data for the present work, is provided in https://doi.org/10.17632/mprjsnr6mp.1.

Lastly, once completed the screening process, every masonry panel described in the final set of documents was evaluated by means of the Masonry Quality Index (MQI) method [31,32] in order to obtain an empirical initial estimation of the reference mechanical parameters (E, G, f_m, τ_0). The following sections present a brief overview of the assessment methods and techniques considered to gather the information later adopted to build the database.

3.1. Masonry Quality Index (MQI)

Masonry Quality Index (MQI) correlates mechanical properties and masonry bond characteristics. MQI has been developed to assess masonry walls, taking into account the traditional technical guidelines applied to build workmanlike constructions. This method is mainly based on a qualitative criterion, which consists in evaluating the presence (Fulfilled – F), the partial presence (Partially Fulfilled – PF) or the absence (Not Fulfilled – NF) of certain parameters which contribute to define the "rules of the art" for an ideal masonry wall, namely (1) conservation state of the stone units – SM, (2) stones' dimension – SD, (3) stones' shape (SS), (4) characteristics of the wall section – WC, (5) characteristics of horizontal joints – HJ, (6) characteristics of vertical joints – VJ, (7) quality of the mortar – MM. Moreover, stone units' interlock (WC) can be quantitatively determined using the concept of the minimum trace length (MTL), which is defined as the minimum length of an ideal line passing through mortar joints and connecting two vertically aligned points mutually spaced 1 m [31,32].

MQI application results in the definition of three indexes related to the vertical loads (MQI_V), to the in-plane load (MQI_I) and to the out-of-plane load (MQI_O). Once a MQI value for a loading condition is known, using specific correlation curves, it is possible to calculate the main mechanical parameters, namely compressive strength, shear strength, Young's Modulus and Shear Modulus. According to the studies present in the literature, the correlation curves related to the vertical load index are the most effective in predicting Young's modulus and compressive strength, whereas the empirical equations based on the in-plane load index proved to be more reliable in estimating shear strength and shear Modulus [33].

3.2. Sonic testing (ST)

The sonic test method is one of the most widely used non-destructive procedures. This technique is based on the generation of sonic or ultrasonic impulses by means of a transmitter (e.g. percussion or electrodynamics/pneumatic devices). The resulting elastic wave propagates through the material and is collected by a receiver. Data post processing measures the time that an impulse takes to cover the distance between the transmitter and the receiver, which can be placed in various positions throughout the structure. As a result, the sonic tests allow estimating the primary waves velocity (V_P) and the surface or Rayleigh waves (V_R), which are related to the mechanical properties of materials according to the following equations [34,35]:

$$\frac{V_P}{V_R} = \sqrt{\frac{2 \cdot (1-\nu) \cdot (1-\nu)^2}{(1-2\nu) \cdot (0.87 + 1.12\nu)^2}} \tag{3}$$

$$V_P = \sqrt{\frac{E}{\rho} \cdot \frac{(1-\nu)}{(1+\nu) \cdot (1-2\nu)}} \tag{4}$$

where E is the deformation modulus, ν is the Poisson's ratio and ρ is the material density.

Since their early application for the inspection of historical constructions, sonic testing procedures proved to be a reliable tool in providing qualitative information regarding the internal structure of masonry elements (e.g. the identification of voids and constructive flaws) [36,37], as well as the monitoring of the effectiveness of repairing solutions for damaged masonry (e.g. grout injections) [38].

3.3. Flat-jack tests (FJ)

The flat-jack tests provide information about the compressive stress level and the deformability properties of the masonry. The test consists of performing two parallel plane cuts perpendicular to the masonry surface. The flat-jacks can then be introduced in the slots and loaded progressively, applying uniaxial compressive stress to the portion of the wall delimited by the cuts, which allows estimating the Young's modulus and compressive strength. This technique is classified as minor-destructive because the damage caused to the structure can be repaired once the test is concluded [39]. The flat-jack testing protocol is defined by the American Society for Testing Materials [40,41] and by the Reunion International des Laboratoires et des Materiaux, Systemes de Construction et Ouvrages (RILEM) [42].

This method is based on the following assumptions, namely (1) masonry surrounding the slot is homogenous, (2) the stress applied to the masonry by the flat-jacks is uniform, (3) the state of stress in the tested portion of the wall is uniaxial and, therefore, lateral constraining effects of adjacent masonry can be neglected [37]. Initially, this technique was applied in the field of rock mechanics. Early stage applications of flat-jacks test to stone masonry constructions can be found in Binda [43] and Lourenço [44]. The results obtained in a considerable number of experimental campaigns showed a significant scattering rate, proving that the procedure must be adjusted according to a case-by-case approach based on preliminary evaluations of test location, materials, and local construction techniques.

3.4. Compression test (CT)

Compression tests are usually carried out to estimate the modulus of elasticity E and the compressive strength of masonry f_m, which are key parameters for the assessment of structural performances in existing buildings.

In-situ compression tests are carried out based on the guidelines provided in [40–42] and following the procedure related to the double flat jack test. The maximum pressure of the test is used to estimate the compressive strength of the masonry, while the normal elastic modulus E and the Poisson ratio (ν), derived from the measured displacement, allow to estimate the shear modulus G through Eq. (5):

$$G = \frac{E}{2(1+\nu)} \tag{5}$$

If the magnitude of horizontal displacements is too small, it can be difficult obtaining reliable measurements of the Poisson ratio and, consequently, an accurate estimation of the shear modulus [45].

Laboratory compression tests are carried out using specific equipment, often consisting of supporting metallic frames equipped with actuators [46]. Once the specimen is in position, metallic rigid plates can be applied in order to uniformly distributing the load on its upper surface. Vertical displacements are measured using Linear Variable Displacements Transducers (LVDTs) that can be placed on the sides of the masonry prism to be tested.

Both monotonic and cyclic compressive tests can be performed on the same specimen. The monotonic test enables the determination of the value of the maximum compressive strength, which can be later used to define the procedure for the cyclic tests [46,47]. Loading and unloading cycles can be performed reaching a maximum compressive strength level corresponding to a share (e.g. 25%, 50%) of the value detected during the monotonic test. The mechanical properties are then calculated based on the stress–strain curves resulted from the testing procedure.

3.5. Diagonal compression test (DC)

Diagonal-compression test is carried out to evaluate the shear behaviour of masonry panels. It can be performed both in-situ and in laboratory. During the in-situ test, 4 cuts are realized in the masonry wall to isolate the tested panel. The lower part of the masonry remains attached to the wall wing. A jack, placed on one of the two corners of the masonry panel, exerts the compressive diagonal force. In the regular test procedure, loading/unloading cycles, with a constant increment after each step, are applied until failure. The shear strength τ_k^{diag} is evaluated using the following equation:

$$\tau_k^{diag} = \frac{\sqrt{2}}{2}\frac{P_{max}}{A_n} \tag{6}$$

where P_{max} is the maximum load applied by the jack during the test and A_n is the net area of the panel as defined in ASTM guidelines, which also provide the specifications to perform the laboratory test procedure [48].

3.6. Shear compression test (SC)

Shear-compression in-situ testing procedure is based on the work carried out by Sheppard [49]. It consists of separating the tested masonry panel from the wall by means of vertical lateral cuts and a top horizontal cut. The "isolated" specimen (recommended dimensions 0.90 – 180 m^2) is then subjected to a vertical compressive stress, which is kept constant by means of a suitable system of steel plates, steel rods and jacks. During the test, a hydraulic jack exerts an increasing horizontal force to the centre of the panel. Thus, shear stresses are distributed over the whole thickness of the panel.

Panel's bottom and top are fixed to a steel structure by means of a suitable device. Hence, the specimen is ideally divided into two square specimens, subject to different shear forces [45]. The shear strength of the masonry is estimated using Eq. (7) [50]:

$$\tau_{max} = \tau_k^{sc}\sqrt{1+\frac{\sigma_0}{1.5\tau_k^{sc}}} \tag{7}$$

where σ_0 is the vertical compression stress (recommended value 0.30 MPa), τ_k^{sc} the shear strength of the masonry, whereas τ_{max} is the maximum shear stress defined as:

$$\tau_{max} = \frac{T_{max}}{A} \tag{8}$$

being T_{max} the maximum shear load in the lower half of the panel and A the horizontal cross-section of the panel. If the test is performed in laboratory, the masonry panels must be fixed at both upper and lower extremities and subjected to constant vertical load, applying increasing lateral forces on one of the two ends.

3.7. Final database

The online research on electronic indexing databases resulted in the identification of 4239 documents. The most considerable contributions are represented by the results obtained from SCOPUS and Web of Knowledge databases, with 1840 and 1738 documents, respectively.

In each database consulted, the distribution of results clearly shows the prevalence of compression tests data, which account for more than 50% of the total, followed by diagonal-compression tests. Non-destructive testing data could be obtained from all the consulted databases except for ASCE and MADA Reluis database [30].

After the removal of duplicates, 124 documents were accurately examined, leading to a final number of suitable results equal to 678. The final complete database with detailed information on the documents analysed has been published in https://doi.org/10.

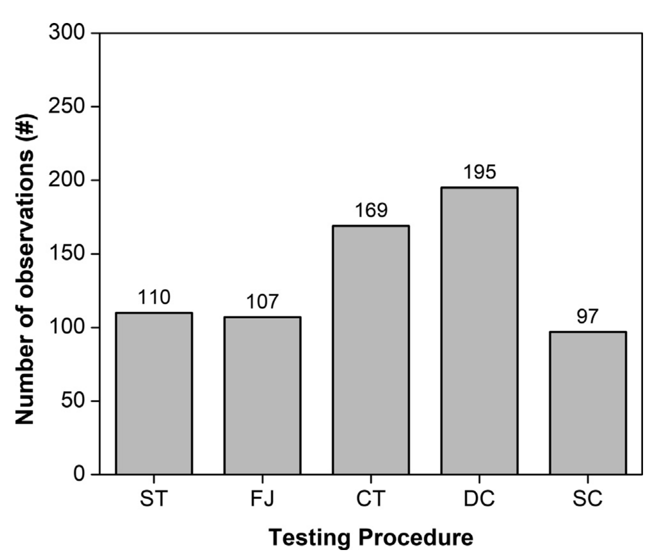

Fig. 2. Testing procedure results distribution.

17632/mprjsnr6mp.1. The highest number of observations refers to diagonal-compression tests (195), followed by compression tests (169). The lowest number of observations registered is 97 (shear-compression tests), whereas almost the same amount of data is available for sonic test and flat-jacks test, with 110 and 107 observations respectively (Fig. 2).

Looking at the distribution of experimental outcomes for each masonry type (Fig. 3), it is possible to observe that Masonry Types 1, 2 and 3 have been widely investigated through all the testing procedures considered in this study. On the other hand, only compression test, diagonal-compression test and shear-compression test results are available for Masonry Type 4 and 5. Overall, experimental results related to the first three masonry types are the majority for all the testing procedures considered.

Further data analyses have been carried out to classify the collected information depending on the country where the experimental campaign was carried out (Fig. 4). Overall, the highest number of observations refers to Mediterranean countries, where stone is a locally available material that has been commonly used throughout history in the building practice.

Portugal and Italy account for more than 50% of the total number of results in both non-destructive and destructive testing procedures. It is also worth pointing out that most of the data obtained from diagonal-compression and shear-compression testing procedures belongs to Italian experimental campaigns.

The total number of observations is almost equally distributed between in-situ testing campaigns and laboratory testing campaigns, with 336 and 342 results respectively (see Fig. 5). A detailed survey of the collected information clearly highlights that no data is available related to flat-jacks tests carried out in laboratory. Additionally, the final database includes a low number of sonic tests data related to laboratory campaigns. This trend is clearly due to the characteristics of these testing procedures, which are mainly used in on-site campaigns.

On the other hand, destructive testing procedures have been widely applied in laboratory experimental campaigns. They require, in fact, highly complex setups and instrumentations, which are often difficult to install in non-controlled environments (in-situ conditions). Moreover, the invasiveness of these procedures (compression, diagonal-compression, and shear compression tests) must not be overlooked. In order to test a masonry wall on-site, it must be isolated from the rest of the building, leading to an irreversible change in terms of the overall structural behaviour.

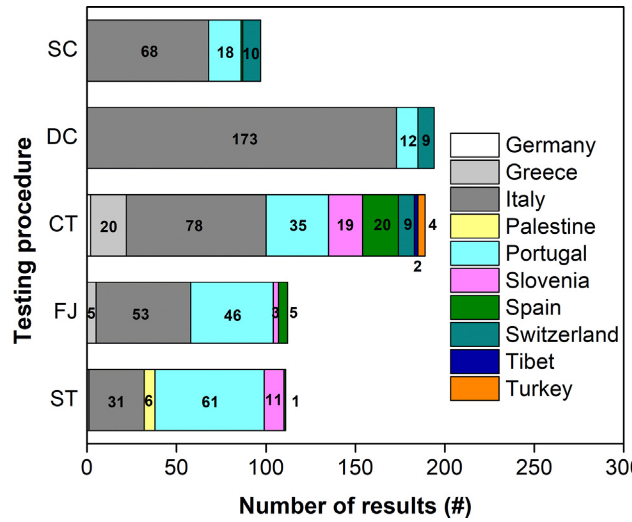

Fig. 4. Testing procedure results classified by country of origin.

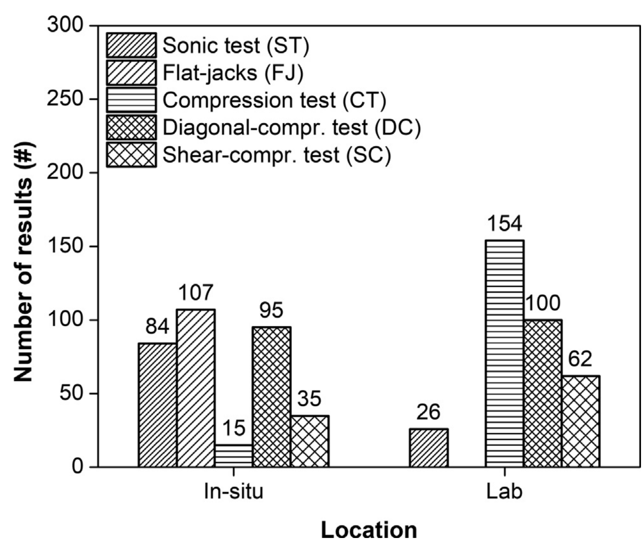

Fig. 5. Data distribution (in-situ/laboratory experimental campaigns).

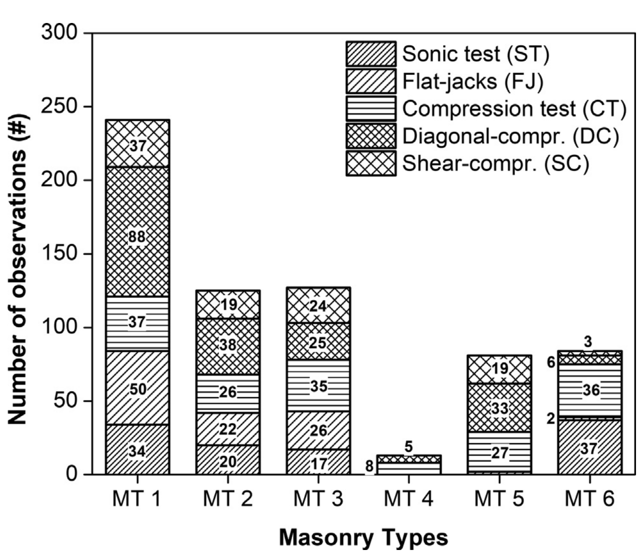

Fig. 3. Testing procedure results classified by masonry typologies.

Therefore, this aspect makes the aforementioned procedure not suitable for the assessment of existing constructions especially if they have a cultural value.

4. Data fusion for the update of masonry mechanical properties

Data collected to build the database have been further examined to filter any possible outliers that could affect the Bayesian updating process. Hence, the dispersion of the whole dataset has been assessed. The interquartile range (IQR) of data distributions has been calculated as the difference between the 75th (Q3) and the 25th (Q1) percentile (IQR = Q3 – Q1). All those observations below the limit Q1 – 1.5*IQR and above the limit Q3 + 1.5*IQR have been considered as outliers, hence not statistically valid for the purpose of this study [51].

The filtering procedure has been carried out for all the selected masonry types, mechanical parameters, and testing procedures. As an example, Fig. 6 depicts the boxplot related to the identification of outliers within the Young's Modulus data distribution.

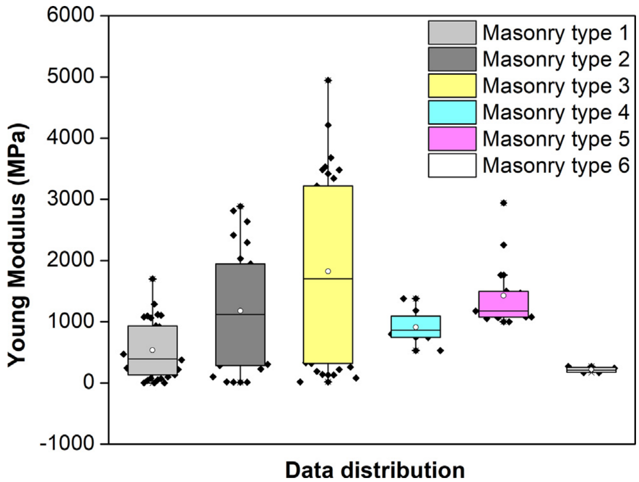

Fig. 6. Definition of outliers within the Young's Modulus dataset obtained from compression tests.

The Bayesian methodology applied in this study refers to a theoretical framework proposed by Ramos [26]. A key aspect characterizing the updating procedure is the definition of a prior knowledge, which represents the starting point of the whole data fusion technique based on Bayesian inference. As mentioned in Section 3, all masonry panels considered in the final database have been examined by means of Masonry Quality Index (MQI). This visual assessment method allowed to estimate the reference mechanical parameters considered in this study (E, G, f_m, τ_0), using the empirical equations provided in the literature [31,32]. The evaluation of all masonry specimens belonging to each masonry type using the MQI method resulted in a probabilistic distribution for each parameter, defined by a mean value and a standard deviation. These distributions were adopted as prior knowledge for the Bayesian updating process.

As presented in Ramos [26] mean (μ) and variance (σ^2) are considered random variable; their joint distribution is expressed by:

$$h(\mu|\theta) \propto \left(\frac{n_0}{\sigma^2}\right)^{1/2} exp\left[-\frac{n_0}{2\sigma_0}(-\mu_0)^2\right] \times \left(\frac{1}{\sigma^2}\right)^{\frac{v_0}{2}+1} exp\left[\frac{S_0}{2\sigma^2}\right] \quad (9)$$

where n_0 is the size of the initial sample, S_0 is the initial sum of squared differences between the values and their mean, μ_0 and σ_0 are the initial mean and initial standard deviation.

Prior and posterior distribution belong to the same family (conjugate distribution). Hence, the prior for μ conditional on σ^2 is a normal with mean μ_0 and variance σ^2/n_0:

$$\mu|\sigma^2\ N\left(\mu_0, \frac{\sigma^2}{n_0}\right) \quad (10)$$

The prior for the precision ($1/\sigma^2$) is a gamma distribution with hyperparameters $v_0/2$ and $S_0/2$:

$$\frac{1}{\sigma^2}\ gamma\left(\frac{v_0}{2}, \frac{S_0}{2}\right) \quad (11)$$

The conditional posterior density of μ, given σ^2 is given by:

$$\mu|\sigma^2, x\ N\left(\mu_1, \frac{\sigma^2}{n_1}\right) \quad (12)$$

In the data fusion model, mean (μ) and variance (σ^2) are updated as new information is gathered, resulting in the definition of a final values with reduced uncertainty. The posterior mean and the posterior sum of squared differences, which is the sum of the square of variation defined as the spread between each individual value and the mean, are expressed by Eqs. (13) and (14) respectively:

$$\mu_1 = \frac{n_0}{n_0+n}\cdot\mu_0 + \frac{n}{n_0+n}\cdot x \quad (13)$$

$$S_1 = S_0 + (n-1)\cdot s^2 + \frac{n_0\cdot n}{n_0+n}\cdot(x-\mu_0)^2 \quad (14)$$

where μ_0 is the prior mean (prior knowledge), μ_1 is the posterior mean, n_0 is the size of the initial sample, n is the size of the new data sample (new observations), x is the mean of the new data sample, S_0 is the prior sum of squared differences (to be computed for every single observation), and s is the standard deviation of the new observed data. The updated standard deviation (σ_1) can be computed as the square root of the ratio between S_1 and the total number of considered observations (n_0 + n).

The marginal posterior density of $1/\sigma^2$ is gamma:

$$\frac{1}{\sigma^2}|x\ gamma\left(\frac{v_1}{2}, \frac{S_1}{2}\right) \quad (15)$$

where

$$v_1 = v_0 + n \quad (16)$$

Once the posterior distribution has been defined, its characteristics, namely update mean and updated standard deviation, can be estimated through numerical simulations. Markov Chain Monte Carlo (MCMC) is one of the most popular and widely used method. A sequence of random variables $X_n \geq 0$ is a Markov chain if for any n, given the current value, X_n, the past $X_{j,\ j} \leq$ n-1 and the future $X_{j:j} \geq$ n + 1 is independent [26]. Moreover, the Gibbs algorithm has been selected to carry out the sampling process related to the posterior distribution.

The adopted data fusion technique combines two sources of information at a time, resulting in a posterior distribution (updated mean value and updated standard deviation) that can be used as a prior distribution for the following update. The reference sequence followed in order to carry out the whole procedure is based on the approach suggested by technical guidelines [3,6] in order to assess the performance of existing buildings. Therefore, the updating process simulates a scenario in which data collected by means of visual inspections (MQI) experiences a stepwise upgrade once new pieces of information, experimentally collected through non-destructive and destructive techniques, are available.

For all the masonry types selected, mechanical properties have been updated depending on the output obtained from each testing procedure. Therefore, in order to calculate the final value of the Young's modulus (E), data from sonic tests (ST), flat-jacks (FJ) tests and compression tests (CT) have been used, whereas the final value for the compression strength (f_m) has been updated using flat-jacks (FT) test and compression test (CT) results (Fig. 7). Lastly, diagonal-compression tests (DC) and shear-compression test results (SC) have been considered in the updating process of both shear modulus (G) and shear strength (τ_0), see Fig. 8.

Therefore, only values directly provided by the specific testing procedures were considered and computed according to the standards mentioned in Section 3. Moreover, it should be noted that, regarding the sonic tests results, based on Eqs. (3) and (4), the dynamic elastic modulus was estimated assuming a mean value of Poisson ratio (ν) equal to 0.25 and an average density (ρ) estimated on the basis of the ranges proposed in [3] and [6]. These ranges of values were adopted to build normal probability distribution functions and, by means of Monte Carlo simulation method 1000 draws of each distribution were sampled and applied in

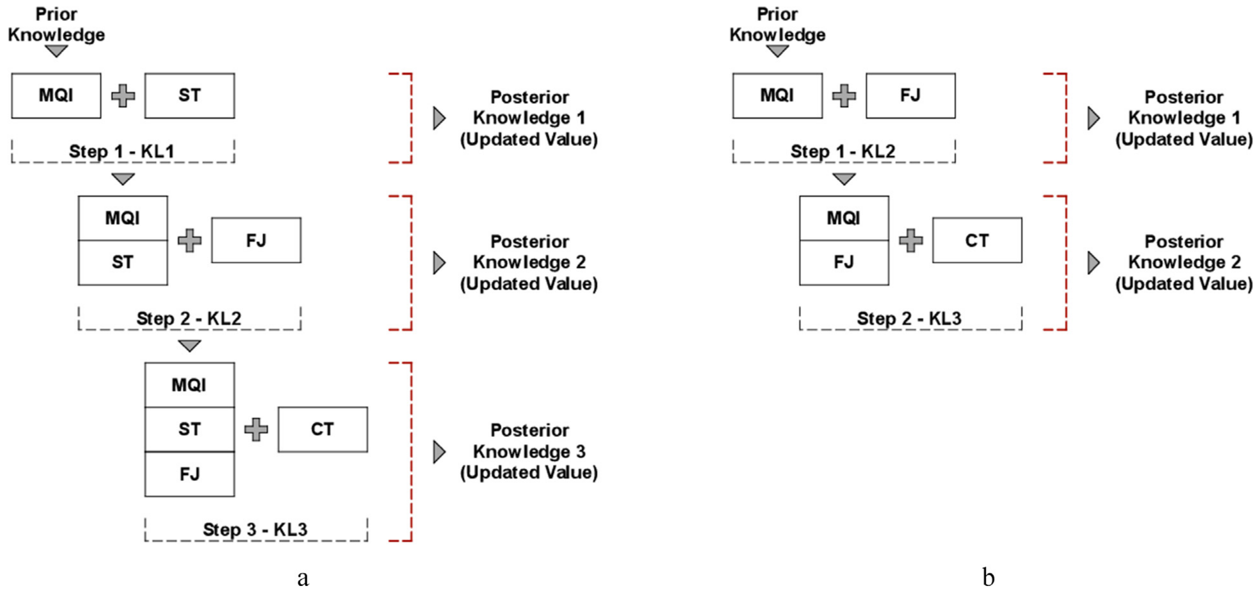

Fig. 7. Young's Modulus (a) and Compression strength (b) updating process flowchart.

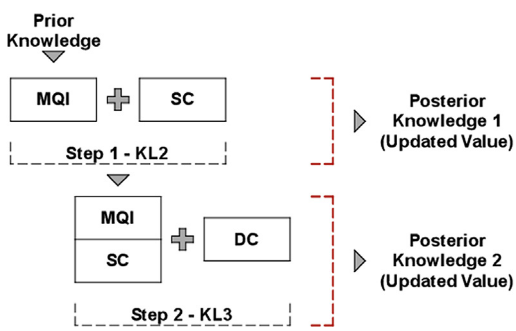

Fig. 8. Shear Modulus and shear strength updating process flowchart.

Eqs. (2) and (3) to provide a fist estimation of the dynamic modulus of elsticity.

As noted in several studies [52,53], an inequality exists between static and dynamic modulus of elasticity of masonry. Therefore, taking into consideration this aspect, the empirical equation proposed by Makoond [54] has been used in order to estimate the static modulus of elasticity (E_{st}) starting from the dynamic one (E_{dy}) resulted from sonic tests. The proposed equation reads:

$$E_{st} = 0.87E_{dy} \quad (17)$$

In order to progressively increase the accuracy of the process, data related to the testing techniques considered to be the most reliable is used in the last steps of the updating procedure. Additionally, following the code-based approach, a different *Knowledge Level* has been attributed to each testing method.

4.1. Reference update

A reference updating procedure has been carried out using all the experimental results stored in the final database. The data fusion procedure followed all the stages previously described in terms of outliers' removal and sequence of updates (see Figs. 7 and 8). Moreover, Eqs. (13) and (14) have been applied to calculate the final updated values of mean (μ) and standard deviation (σ) respectively. If no data was available for a specific testing technique, the data fusion procedure was carried out according to the reference sequence, discarding the step characterized by a lack of information.

Tables 1–6 present mean value, standard deviation, and number of observations, related to each testing procedure, and classified according to a specific masonry type.

It should be noted that data estimated through the MQI method highlights a considerable uniform distribution, resulting in low scattering rate and low standard deviation values. Experimental results show a different trend being their variability in terms of mean and standard deviation much higher if compared to the qualitative assessment results. This was expected given the simplifications assumed in the MQI method, which considers a set of parameters that are similar within each masonry type. This pattern can be also related to the fact that the experimental dataset encompasses both laboratory and in-situ testing campaigns, characterized by different environmental and boundary conditions, which leads to a significant variability in the results.

The final values of mean and standard deviation, calculated for each reference mechanical parameter and for all the selected masonry types, have been used to define Probability Density Functions (PDF) highlighting the evolution that characterizes the application of the proposed data fusion method after each stage of the updating process. The lognormal distribution was selected to represent the PDFs of the mechanical parameters since it leads only to positive values.

For the sake of brevity, only the results related to Masonry Type 1 are presented in detail (Fig. 9). Looking at the graphs, it can be inferred that, even though the standard deviation values related to the experimental results used as new information are significantly higher than the standard deviation characterizing the Prior Knowledge (see Table 1), the final standard deviation related to the considered parameters is reduced. The standard deviation related to the last updating stage is slightly higher than the one resulted from MQI assessment (Prior Knowledge). Moreover, the updated mean values appear to be closer to the Prior Knowledge data. In fact, the higher number of observations related to MQI account for a more significant contribution in the overall estimation of the updated mean values.

For instance, Table 1 shows that the updating process related to the Young modulus begins with a mean and a standard deviation equal to 1015 MPa and 166 MPa, respectively (Prior Knowledge). Similar mean values are provided by sonic and flat-jacks tests

Table 1
Prior knowledge and new information summary for Masonry Type 1 (overall data).

	Prior Knowledge			New Information			New Information			New Information		
MT1	**Masonry Quality Index**			**Sonic Test**			**Flat-jacks Test**			**Compression Test**		
	Mean	**St. Dev.**	**#**	**Mean**	**St. Dev.**	**#**	**Mean**	**St. Dev.**	**#**	**Mean**	**St. Dev.**	**#**
	Young Mod. – E (MPa)			*Young Mod. – E (MPa)*			*Young Mod. – E (MPa)*			*Young Mod. – E (MPa)*		
	1015.33	166.54	205	1135.12	662.80	9	1086.23	766.15	38	708.64	429.90	22
	Compr. Str. – f_m (MPa)			*Compr. Str. – f_m (MPa)*			*Compr. Str. – f_m (MPa)*			*Compr. Str. – f_m (MPa)*		
	2.16	0.44	205	NA	NA	NA	1.34	0.74	34	0.92	0.67	30
	Masonry Quality Index			**Shear-Compr. Test**			**Diag. Compr- Test**					
	Shear Mod. – G (MPa)			*Shear Mod. – G (MPa)*			*Shear Mod. – G (MPa)*					
	350.29	52.46	205	177.97	97.43	26	141.02	121.16	57			
	Shear Str. – τ_0 (MPa)			*Shear Str. – τ_0 (MPa)*			*Shear Str. – τ_0 (MPa)*					
	0.04	0.008	205	0.162	0.096	20	0.05	0.03	62			

Table 2
Prior knowledge and new information summary for Masonry Type 2 (overall data).

	Prior Knowledge			New Information			New Information			New Information		
MT2	**Masonry Quality Index**			**Sonic Test**			**Flat-jacks Test**			**Compression Test**		
	Mean	**St. Dev.**	**#**	**Mean**	**St. Dev.**	**#**	**Mean**	**St. Dev.**	**#**	**Mean**	**St. Dev.**	**#**
	Young Mod. – E (MPa)			*Young Mod. – E (MPa)*			*Young Mod. – E (MPa)*			*Young Mod. – E (MPa)*		
	1249.20	133.69	102	1270.42	525.74	6	1182.17	610.70	12	1759.69	737.92	16
	Compr. Str. – f_m (MPa)			*Compr. Str. – f_m (MPa)*			*Compr. Str. – f_m (MPa)*			*Compr. Str. – f_m (MPa)*		
	2.79	0.37	102	NA	NA	NA	1.45	0.72	16	1.72	0.96	18
	Masonry Quality Index			**Shear-Compr. Test**			**Diag. Compr- Test**					
	Shear Mod. – G (MPa)			*Shear Mod. – G (MPa)*			*Shear Mod. – G (MPa)*					
	406.15	32.28	102	268.53	162.02	26	198.08	95.26	5			
	Shear Str. – τ_0 (MPa)			*Shear Str. – τ_0 (MPa)*			*Shear Str. – τ_0 (MPa)*					
	0.048	0.005	102	0.187	0.057	20	0.054	0.035	10			

Table 3
Prior knowledge and new information summary for Masonry Type 3 (overall data).

	Prior Knowledge			New Information			New Information			New Information		
MT3	**Masonry Quality Index**			**Sonic Test**			**Flat-jacks Test**			**Compression Test**		
	Mean	**St. Dev.**	**#**	**Mean**	**St. Dev.**	**#**	**Mean**	**St. Dev.**	**#**	**Mean**	**St. Dev.**	**#**
	Young Mod. – E (MPa)			*Young Mod. – E (MPa)*			*Young Mod. – E (MPa)*			*Young Mod. – E (MPa)*		
	1798.13	258.77	83	1986.70	452.80	6	2385.15	492.02	19	2202.05	767.31	19
	Compr. Str. – f_m (MPa)			*Compr. Str. – f_m (MPa)*			*Compr. Str. – f_m (MPa)*			*Compr. Str. – f_m (MPa)*		
	4.38	0.78	83	NA	NA	NA	2.02	0.85	15	4.06	2.20	21
	Masonry Quality Index			**Shear-Compr. Test**			**Diag. Compr- Test**					
	Shear Mod. – G (MPa)			*Shear Mod. – G (MPa)*			*Shear Mod. – G (MPa)*					
	558.55	79.49	83	297.20	96.44	5	444.20	268.73	10			
	Shear Str. – τ_0 (MPa)			*Shear Str. – τ_0 (MPa)*			*Shear Str. – τ_0 (MPa)*					
	0.073	0.013	83	0.137	0.083	16	0.114	0.086	24			

Table 4
Prior knowledge and new information summary for Masonry Type 4 (overall data).

	Prior Knowledge			New Information			New Information			New Information		
MT4	**Masonry Quality Index**			**Sonic Test**			**Flat-jacks Test**			**Compression Test**		
	Mean	**St. Dev.**	**#**	**Mean**	**St. Dev.**	**#**	**Mean**	**St. Dev.**	**#**	**Mean**	**St. Dev.**	**#**
	Young Mod. – E (MPa)			*Young Mod. – E (MPa)*			*Young Mod. – E (MPa)*			*Young Mod. – E (MPa)*		
	1234.13	72.69	12	NA	NA	NA	NA	NA	NA	913	270.97	8
	Compr. Str. – f_m (MPa)			*Compr. Str. – f_m (MPa)*			*Compr. Str. – f_m (MPa)*			*Compr. Str. – f_m (MPa)*		
	2.74	0.20	12	NA	NA	NA	NA	NA	NA	2.20	1.30	8
	Masonry Quality Index			**Shear-Compr. Test**			**Diag. Compr- Test**					
	Shear Mod. – G (MPa)			*Shear Mod. – G (MPa)*			*Shear Mod. – G (MPa)*					
	416.27	20.74	12	NA	NA	NA	394.67	102.04	3			
	Shear Str. – τ_0 (MPa)			*Shear Str. – τ_0 (MPa)*			*Shear Str. – τ_0 (MPa)*					
	0.05	0.003	12	NA	NA	NA	0.051	0.012	5			

new information (1135 MPa and 1086 MPa respectively), whereas the standard deviation is around 660 MPa (sonic tests) and 760 MPa (flat-jacks test), hence much higher than the Prior Knowledge standard deviation. Lastly, the contribution of compressive test data consists of a mean and a standard deviation equal to 708 MPa and 429 MPa respectively. The data fusion procedure led to a final mean value and a final standard deviation equal to 1004 MPa and 376 MPa respectively, determining an overall reduction of initial standard deviation related to the experimental data. However, the final mean value resulted to be closer to the Prior Knowledge. This trend is similar in all the distributions considered.

Table 5
Prior knowledge and new information summary for Masonry Type 5 (overall data).

	Prior Knowledge			New Information			New Information			New Information		
MT5	**Masonry Quality Index**			**Sonic Test**			**Flat-jacks Test**			**Compression Test**		
	Mean	**St. Dev.**	**#**	**Mean**	**St. Dev.**	**#**	**Mean**	**St. Dev.**	**#**	**Mean**	**St. Dev.**	**#**
	Young Mod. – E (MPa)			*Young Mod. – E (MPa)*			*Young Mod. – E (MPa)*			*Young Mod. – E (MPa)*		
	1548.98	94.33	42	NA	NA	NA	NA	NA	NA	1248.54	227.78	13
	Compr. Str. – f_m (MPa)			*Compr. Str. – f_m (MPa)*			*Compr. Str. – f_m (MPa)*			*Compr. Str. – f_m (MPa)*		
	3.63	0.27	42	NA	NA	NA	NA	NA	NA	1.87	0.67	15
	Masonry Quality Index			**Shear-Compr. Test**			**Diag. Compr- Test**					
	Shear Mod. – G (MPa)			*Shear Mod. – G (MPa)*			*Shear Mod. – G (MPa)*					
	499.73	40.31	42	NA	NA	NA	411.60	188.31	5			
	Shear Str. – τ_0 (MPa)			*Shear Str. – τ_0 (MPa)*			*Shear Str. – τ_0 (MPa)*					
	0.063	0.007	42	0.067	0.048	18	0.186	0.096	10			

Table 6
Prior knowledge and new information summary for Masonry Type (overall data).

	Prior Knowledge			New Information			New Information			New Information		
MT6	**Masonry Quality Index**			**Sonic Test**			**Flat-jacks Test**			**Compression Test**		
	Mean	**St. Dev.**	**#**	**Mean**	**St. Dev.**	**#**	**Mean**	**St. Dev.**	**#**	**Mean**	**St. Dev.**	**#**
	Young Mod. – E (MPa)			*Young Mod. – E (MPa)*			*Young Mod. – E (MPa)*			*Young Mod. – E (MPa)*		
	2614.14	312.57	70	2512.66	935.48	21	2445.50	1738.98	4	3374.67	1735.19	15
	Compr. Str. – f_m (MPa)			*Compr. Str. – f_m (MPa)*			*Compr. Str. – f_m (MPa)*			*Compr. Str. – f_m (MPa)*		
	6.94	1.03	70	NA	NA	NA	3.21	1.01	4	6.14	2.76	20
	Masonry Quality Index			**Shear-Compr. Test**			**Diag. Compr- Test**					
	Shear Mod. – G (MPa)			*Shear Mod. – G (MPa)*			*Shear Mod. – G (MPa)*					
	795.94	63.33	70	NA	NA	NA	842.67	138.23	6			
	Shear Str. – τ_0 (MPa)			*Shear Str. – τ_0 (MPa)*			*Shear Str. – τ_0 (MPa)*					
	0.114	0.012	70	NA	NA	NA	0.197	0.043	6			

4.2. Updating procedure A (only Italian data)

This section summarizes the outcomes related to the application of the data fusion procedure considering only the results of Italian two-leaf stone masonry walls. Once defined the final set of information for each testing procedure according to a specific masonry type, the updating procedure has been applied following the same steps described in the previous sections. Data related to Prior Knowledge and New Information is summarized in Tables 7–12.

Overall, the reduced number of observations resulted in a decrease of experimental data mainly related to Masonry Type 4, 5 and 6, whereas the data filtering process based on the origin country resulted in a data sample able to ensure information related to all the testing procedures addressing the assessment of masonry walls classified as type 1, 2, and 3.

As highlighted in Section 4.1 regarding the trends characterizing the final results of the data fusion process, the reduction of standard deviation for all the selected mechanical parameters consists of significantly lower values than the standard deviations related to the single experimental results and slightly higher values than the standard deviations related to the Prior Knowledge, whereas updated means are closer to the outcomes provided by the MQI method (Prior Knowledge), see Fig. 10.

4.3. Updating procedure B (only Portuguese data)

Results related to Portuguese masonry walls are herein presented (Tables 13–16). The reduction of suitable information to carry out the data fusion procedure resulted in a complete application of the proposed methodology only for masonry types 1, 2, and 3. Note that Masonry type 4 and 5 data refer exclusively to Italian experimental campaigns. Moreover, despite the significant number of sonic test results related to masonry type 6, only 2 compression test observations have been considered, whereas no information could be gathered for flat-jacks, shear-compression, and diagonal-compression testing procedures.

Probability density functions (PDFs) related to the updated mechanical properties in masonry type 1 show the same pattern highlighted in the previous application of the data fusion method carried out using the whole data sample and only Italian data respectively, namely overall reduction of standard deviation and mean values close to the MQI estimation (Fig. 11).

4.4. Comparison between data fusion procedure results and technical standards reference ranges

This section presents the overall outcomes of the data fusion procedure applied to update the mechanical properties of the selected masonry types. Moreover, the final results have been compared to the range of values proposed in Eurocode 8 (Part 3 – Annex C) [3], Italian standards (Table C8.5.I – Circolare 21/01/2019) [28] and CNR-DT 212/2013 recommendations [5].

Table 17 shows the range of values proposed by the codes and those ones obtained through the Bayesian updating procedure. Results calculated using all the data of the final database (Bayesian Update_ALL) are reported together with updated values related to Italian (Bayesian Updata_ITA) and Portuguese (Bayesian Update_-POR) masonry walls. They are classified depending on the reference mechanical property and the specific masonry typology. The ranges of the mechanical properties have been defined by subtracting (lower bound) and adding (upper bound) the corresponding standard deviation to the mean value (bracketed values reported in Table 17).

Overall, the ranges obtained utilizing the Bayesian updating procedure appear to be consistent with the values recommended by Eurocode and Italian standards. Young's modulus, Shear modulus, and compression strength results show lower bound limits close to those suggested in Italian standards, whereas upper bound values are slightly higher. Eurocode's mechanical properties mean values shown in Table 17 are lower than the corresponding values resulted from the different updating scenarios considered, namely Bayesian Update_ALL, ITA, and POR. Moreover, the estimation of

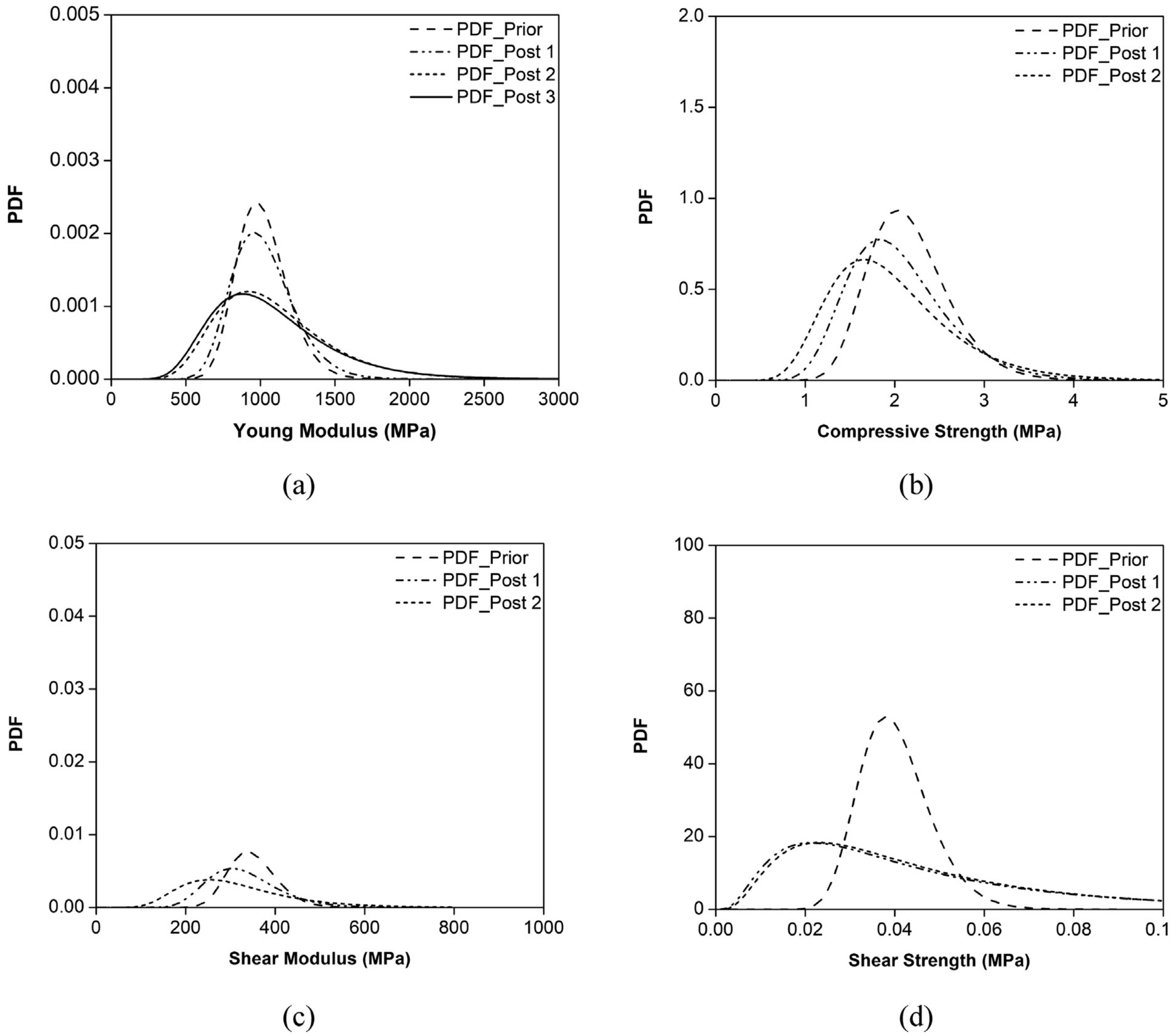

Fig. 9. Probability Density Function (PDF) updated values Young modulus (a), Compression strength (b), Shear modulus (c), Shear strength (d).

Table 7
Prior knowledge and new information summary for Masonry Type 1 (Italian data).

	Prior Knowledge			New Information			New Information			New Information		
MT1	**Masonry Quality Index**			**Sonic Test**			**Flat-jacks Test**			**Compression Test**		
	Mean	**St. Dev.**	**#**	**Mean**	**St. Dev.**	**#**	**Mean**	**St. Dev.**	**#**	**Mean**	**St. Dev.**	**#**
	Young Mod. – E (MPa)			*Young Mod. – E (MPa)*			*Young Mod. – E (MPa)*			*Young Mod. – E (MPa)*		
	1061.76	181.75	128	1003	415.62	3	1102.88	406.28	8	832	330.20	5
	Compr. Str. – f_m (MPa)			*Compr. Str. – f_m (MPa)*			*Compr. Str. – f_m (MPa)*			*Compr. Str. – f_m (MPa)*		
	2.29	0.48	128	NA	NA	NA	2.04	0.67	12	0.45	0.30	3
	Masonry Quality Index			**Shear-Compr. Test**			**Diag. Compr- Test**					
	Shear Mod. – G (MPa)			*Shear Mod. – G (MPa)*			*Shear Mod. – G (MPa)*					
	367.69	52.86	128	211.48	67.70	12	225.24	113.92	26			
	Shear Str. – τ_0 (MPa)			*Shear Str. – τ_0 (MPa)*			*Shear Str. – τ_0 (MPa)*					
	0.043	0.008	128	0.181	0.055	13	0.049	0.028	66			

shear strength is characterized by significant variability, which yields high standard deviation values and growth of the reference properties' ranges mainly for Masonry Type 1 and 2. On the other hand, Masonry Type 4 and 5 results appear to be highly consistent with the Italian standard. To this end, it is interesting to point out that data related to these masonry types only derives from Italian experimental campaigns.

It is also noted that the variability expressed by the updating process involving the whole dataset is slightly higher than the variability related to the updating procedure carried out only relying on data classified based on the country of origin. Therefore, based also on the evidence related to Masonry Type 4 and 5, it is possible to say that the characteristics of construction materials as well as environmental and boundary conditions in which the testing procedure is carried out significantly affect the homogeneity of the data sample. Hence, an increase in uncertainty reflects low homogeneity of the data sample. Conversely, high homogeneity corresponds to reduced uncertainty levels.

Table 8
Prior knowledge and new information summary for Masonry Type 2 (Italian data).

	Prior Knowledge			**New Information**			**New Information**			**New Information**		
MT2	**Masonry Quality Index**			**Sonic Test**			**Flat-jacks Test**			**Compression Test**		
	Mean	**St. Dev.**	**#**	**Mean**	**St. Dev.**	**#**	**Mean**	**St. Dev.**	**#**	**Mean**	**St. Dev.**	**#**
	Young Mod. – E (MPa)			*Young Mod. – E (MPa)*			*Young Mod. – E (MPa)*			*Young Mod. – E (MPa)*		
	1250.47	133.51	71	1611.52	416.34	3	1138.50	422.77	6	1703.33	360.40	9
	Compr. Str. – f_m (MPa)			*Compr. Str. – f_m (MPa)*			*Compr. Str. – f_m (MPa)*			*Compr. Str. – f_m (MPa)*		
	2.79	0.37	71	NA	NA	NA	2.11	0.69	4	2.36	0.45	13
	Masonry Quality Index			**Shear-Compr. Test**			**Diag. Compr- Test**					
	Shear Mod. – G (MPa)			*Shear Mod. – G (MPa)*			*Shear Mod. – G (MPa)*					
	405.10	30.56	71	352.68	127.61	10	165.64	78.93	11			
	Shear Str. – τ_0 (MPa)			*Shear Str. – τ_0 (MPa)*			*Shear Str. – τ_0 (MPa)*					
	0.048	0.005	71	0.188	0.059	16	0.060	0.035	28			

Table 9
Prior knowledge and new information summary for Masonry Type 3 (Italian data).

	Prior Knowledge			**New Information**			**New Information**			**New Information**		
MT3	**Masonry Quality Index**			**Sonic Test**			**Flat-jacks Test**			**Compression Test**		
	Mean	**St. Dev.**	**#**	**Mean**	**St. Dev.**	**#**	**Mean**	**St. Dev.**	**#**	**Mean**	**St. Dev.**	**#**
	Young Mod. – E (MPa)			*Young Mod. – E (MPa)*			*Young Mod. – E (MPa)*			*Young Mod. – E (MPa)*		
	1770.54	230.43	46	NA	NA	NA	2091.40	575.15	10	1840.08	391.11	13
	Compr. Str. – f_m (MPa)			*Compr. Str. – f_m (MPa)*			*Compr. Str. – f_m (MPa)*			*Compr. Str. – f_m (MPa)*		
	4.29	0.69	46	NA	NA	NA	2.15	0.56	8	4.29	2.36	9
	Masonry Quality Index			**Shear-Compr. Test**			**Diag. Compr- Test**					
	Shear Mod. – G (MPa)			*Shear Mod. – G (MPa)*			*Shear Mod. – G (MPa)*					
	551.77	54.05	46	297.20	96.44	5	479.14	254.46	7			
	Shear Str. – τ_0 (MPa)			*Shear Str. – τ_0 (MPa)*			*Shear Str. – τ_0 (MPa)*					
	0.072	0.009	46	0.104	0.065	9	0.073	0.053	18			

Table 10
Prior knowledge and new information summary for Masonry Type 4 (Italian data).

	Prior Knowledge			**New Information**			**New Information**			**New Information**		
MT4	**Masonry Quality Index**			**Sonic Test**			**Flat-jacks Test**			**Compression Test**		
	Mean	**St. Dev.**	**#**	**Mean**	**St. Dev.**	**#**	**Mean**	**St. Dev.**	**#**	**Mean**	**St. Dev.**	**#**
	Young Mod. – E (MPa)			*Young Mod. – E (MPa)*			*Young Mod. – E (MPa)*			*Young Mod. – E (MPa)*		
	1234.13	72.69	12	NA	NA	NA	NA	NA	NA	913	270.97	8
	Compr. Str. – f_m (MPa)			*Compr. Str. – f_m (MPa)*			*Compr. Str. – f_m (MPa)*			*Compr. Str. – f_m (MPa)*		
	2.74	0.20	12	NA	NA	NA	NA	NA	NA	2.20	1.30	8
	Masonry Quality Index			**Shear-Compr. Test**			**Diag. Compr- Test**					
	Shear Mod. – G (MPa)			*Shear Mod. – G (MPa)*			*Shear Mod. – G (MPa)*					
	416.27	20.74	12	NA	NA	NA	394.67	102.04	3			
	Shear Str. – τ_0 (MPa)			*Shear Str. – τ_0 (MPa)*			*Shear Str. – τ_0 (MPa)*					
	0.05	0.003	12	NA	NA	NA	0.051	0.012	5			

Table 11
Prior knowledge and new information summary for Masonry Type 5 (Italian data).

	Prior Knowledge			**New Information**			**New Information**			**New Information**		
MT5	**Masonry Quality Index**			**Sonic Test**			**Flat-jacks Test**			**Compression Test**		
	Mean	**St. Dev.**	**#**	**Mean**	**St. Dev.**	**#**	**Mean**	**St. Dev.**	**#**	**Mean**	**St. Dev.**	**#**
	Young Mod. – E (MPa)			*Young Mod. – E (MPa)*			*Young Mod. – E (MPa)*			*Young Mod. – E (MPa)*		
	1536.57	85.95	39	NA	NA	NA	NA	NA	NA	1229.10	325.38	10
	Compr. Str. – f_m (MPa)			*Compr. Str. – f_m (MPa)*			*Compr. Str. – f_m (MPa)*			*Compr. Str. – f_m (MPa)*		
	3.60	0.25	39	NA	NA	NA	NA	NA	NA	1.85	0.74	12
	Masonry Quality Index			**Shear-Compr. Test**			**Diag. Compr- Test**					
	Shear Mod. – G (MPa)			*Shear Mod. – G (MPa)*			*Shear Mod. – G (MPa)*					
	491.93	29.67	39	NA	NA	NA	411.60	188.31	5			
	Shear Str. – τ_0 (MPa)			*Shear Str. – τ_0 (MPa)*			*Shear Str. – τ_0 (MPa)*					
	0.062	0.005	39	0.067	0.048	18	0.186	0.096	10			

A similar pattern is highlighted in Table 18, which compares the values provided in CNR – DT 212/2013 [5], in terms of mean values and standard deviation of the natural logarithm to the updated results. In this case, an overall increase in terms of mean and standard deviation mostly affects results related to the reference Bayesian updating procedure (Bayesian Update_ALL). Furthermore, Portuguese (Bayesian Update_POR) data presents a slight variation, whereas Italian results (Bayesian Update_ITA) often highlight a significant consistency with the code values.

Table 12
Prior knowledge and new information summary for Masonry Type 6 (Italian data).

	Prior Knowledge			New Information			New Information			New Information		
MT6	**Masonry Quality Index**			**Sonic Test**			**Flat-jacks Test**			**Compression Test**		
	Mean	**St. Dev.**	**#**	**Mean**	**St. Dev.**	**#**	**Mean**	**St. Dev.**	**#**	**Mean**	**St. Dev.**	**#**
	Young Mod. – E (MPa)			*Young Mod. – E (MPa)*			*Young Mod. – E (MPa)*			*Young Mod. – E (MPa)*		
	2434.75	326.90	16	NA	NA	NA	NA	NA	NA	2394.38	418.48	8
	Compr. Str. – f_m (MPa)			*Compr. Str. – f_m (MPa)*			*Compr. Str. – f_m (MPa)*			*Compr. Str. – f_m (MPa)*		
	6.36	1.08	16	NA	NA	NA	NA	NA	NA	3.98	1.33	8
	Masonry Quality Index			**Shear-Compr. Test**			**Diag. Compr- Test**					
	Shear Mod. – G (MPa)			*Shear Mod. – G (MPa)*			*Shear Mod. – G (MPa)*					
	811.04	50.81	16	NA	NA	NA	842.67	138.23	6			
	Shear Str. – τ_0 (MPa)			*Shear Str. – τ_0 (MPa)*			*Shear Str. – τ_0 (MPa)*					
	0.117	0.009	16	NA	NA	NA	0.197	0.043	6			

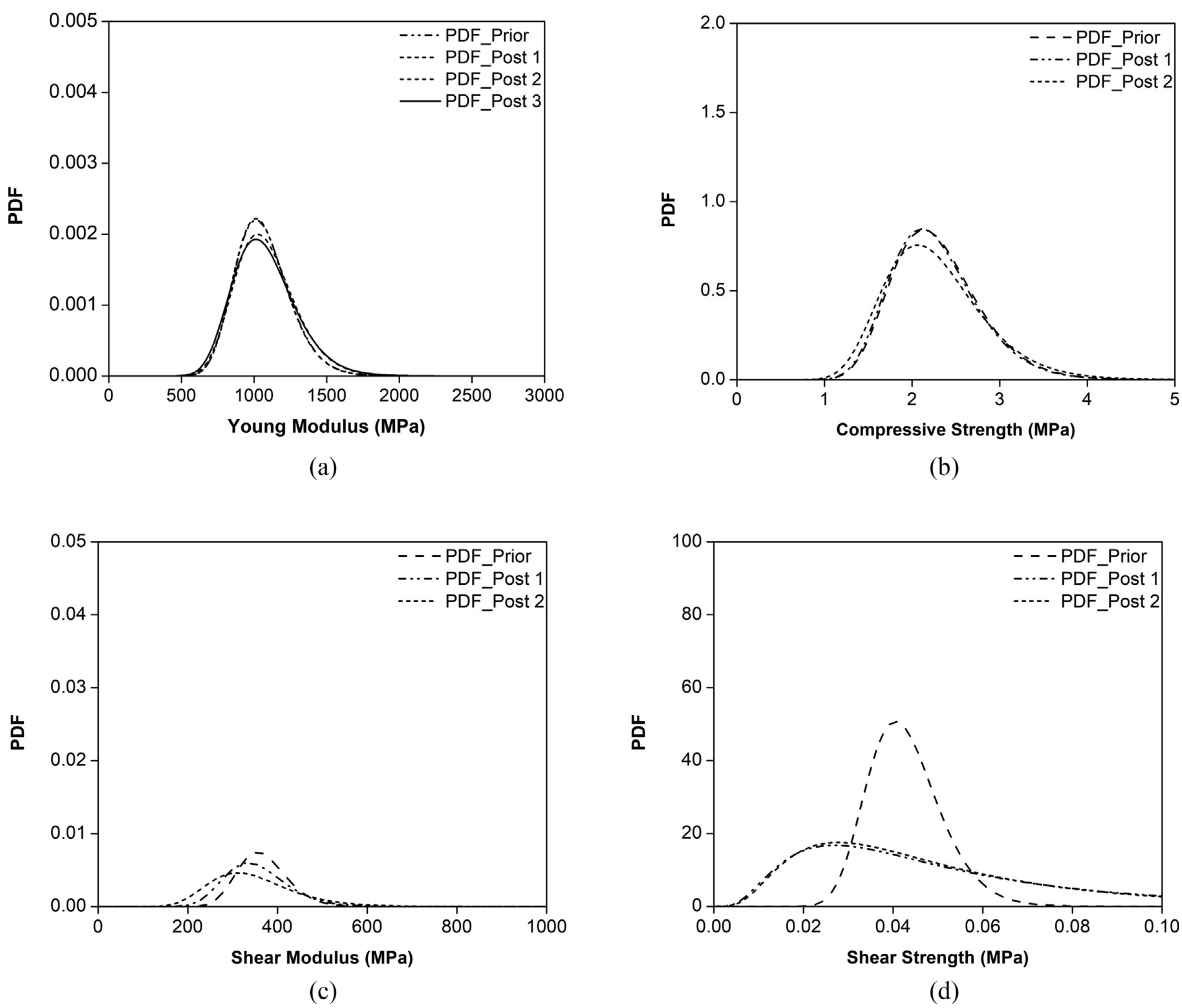

Fig. 10. Probability Density Function (PDF) updated values Italian masonry panels Young modulus (a), Compression strength (b), Shear modulus (c), Shear strength (d).

An additional aspect arisen from this study concerns the overestimation of the Bayesian results mean values. To this end, it must not be overlooked that codes suggest mechanical properties that refer to low-quality masonry walls built without following the practice-oriented set of rules (rules of the art). Conversely, data used to construct the final database involves masonry walls characterized by better mechanical properties and higher workmanship average quality compared to a reference masonry panel considered in technical standards.

4.5. Confidence actors and Bayesian update

In order to progressively increase the accuracy of the process, data related to the testing techniques considered to be the most reliable can be used in the updating procedure. Following the code-based approach [3], a different Knowledge Level can be attributed to each testing method.

Based on the approach proposed in [26] concerning the applications of Trust Factors, a modified version of equation (10) has been

Table 13
Prior knowledge and new information summary for Masonry Type 1 (Portuguese data).

	Prior Knowledge			New Information			New Information			New Information		
MT1	**Masonry Quality Index**			**Sonic Test**			**Flat-jacks Test**			**Compression Test**		
	Mean	**St. Dev.**	**#**	**Mean**	**St. Dev.**	**#**	**Mean**	**St. Dev.**	**#**	**Mean**	**St. Dev.**	**#**
	Young Mod. – E (MPa)			*Young Mod. – E (MPa)*			*Young Mod. – E (MPa)*			*Young Mod. – E (MPa)*		
	963.91	139.02	50	1185.98	692.39	5	880.95	383.75	16	1031.20	468.93	5
	Compr. Str. – f_m (MPa)			*Compr. Str. – f_m (MPa)*			*Compr. Str. – f_m (MPa)*			*Compr. Str. – f_m (MPa)*		
	2.03	0.36	50	NA	NA	NA	0.93	0.41	21	1.13	0.66	10
	Masonry Quality Index			**Shear-Compr. Test**			**Diag. Compr- Test**					
	Shear Mod. – G (MPa)			*Shear Mod. – G (MPa)*			*Shear Mod. – G (MPa)*					
	336.09	43.72	50	NA	NA	NA	198	152.78	4			
	Shear Str. – τ_0 (MPa)			*Shear Str. – τ_0 (MPa)*			*Shear Str. – τ_0 (MPa)*					
	0.038	0.006	50	NA	NA	NA	0.140	0.09	4			

Table 14
Prior knowledge and new information summary for Masonry Type 2 (Portuguese data).

	Prior Knowledge			New Information			New Information			New Information		
MT2	**Masonry Quality Index**			**Sonic Test**			**Flat-jacks Test**			**Compression Test**		
	Mean	**St. Dev.**	**#**	**Mean**	**St. Dev.**	**#**	**Mean**	**St. Dev.**	**#**	**Mean**	**St. Dev.**	**#**
	Young Mod. – E (MPa)			*Young Mod. – E (MPa)*			*Young Mod. – E (MPa)*			*Young Mod. – E (MPa)*		
	1191.81	89.69	17	1243.54	461.25	4	877.01	530.38	6	NA	NA	NA
	Compr. Str. – f_m (MPa)			*Compr. Str. – f_m (MPa)*			*Compr. Str. – f_m (MPa)*			*Compr. Str. – f_m (MPa)*		
	2.63	0.25	17	NA	NA	NA	1.09	0.22	10	NA	NA	NA
	Masonry Quality Index			**Shear-Compr. Test**			**Diag. Compr- Test**					
	Shear Mod. – G (MPa)			*Shear Mod. – G (MPa)*			*Shear Mod. – G (MPa)*					
	391.15	19.03	17	NA	NA	NA	320.50	96.87	2			
	Shear Str. – τ_0 (MPa)			*Shear Str. – τ_0 (MPa)*			*Shear Str. – τ_0 (MPa)*					
	0.046	0.003	17	0.175	0.007	2	0.244	0.033	2			

Table 15
Prior knowledge and new information summary for Masonry Type 3 (Portuguese data).

	Prior Knowledge			New Information			New Information			New Information		
MT3	**Masonry Quality Index**			**Sonic Test**			**Flat-jacks Test**			**Compression Test**		
	Mean	**St. Dev.**	**#**	**Mean**	**St. Dev.**	**#**	**Mean**	**St. Dev.**	**#**	**Mean**	**St. Dev.**	**#**
	Young Mod. – E (MPa)			*Young Mod. – E (MPa)*			*Young Mod. – E (MPa)*			*Young Mod. – E (MPa)*		
	1905.41	306.30	23	2283.57	520.46	6	2161.80	421.13	6	NA	NA	NA
	Compr. Str. – f_m (MPa)			*Compr. Str. – f_m (MPa)*			*Compr. Str. – f_m (MPa)*			*Compr. Str. – f_m (MPa)*		
	4.70	0.94	23	NA	NA	NA	2.05	1.12	6	3.27	1.33	7
	Masonry Quality Index			**Shear-Compr. Test**			**Diag. Compr- Test**					
	Shear Mod. – G (MPa)			*Shear Mod. – G (MPa)*			*Shear Mod. – G (MPa)*					
	582.87	123.89	23	NA	NA	NA	NA	NA	NA			
	Shear Str. – τ_0 (MPa)			*Shear Str. – τ_0 (MPa)*			*Shear Str. – τ_0 (MPa)*					
	0.077	0.021	23	NA	NA	NA	NA	NA	NA			

Table 16
Prior knowledge and new information summary for Masonry Type 6 (Portuguese data).

	Prior Knowledge			New Information			New Information			New Information		
MT6	**Masonry Quality Index**			**Sonic Test**			**Flat-jacks Test**			**Compression Test**		
	Mean	**St. Dev.**	**#**	**Mean**	**St. Dev.**	**#**	**Mean**	**St. Dev.**	**#**	**Mean**	**St. Dev.**	**#**
	Young Mod. – E (MPa)			*Young Mod. – E (MPa)*			*Young Mod. – E (MPa)*			*Young Mod. – E (MPa)*		
	2610.85	314.95	23	2602.21	665.07	13	NA	NA	NA	NA	NA	NA
	Compr. Str. – f_m (MPa)			*Compr. Str. – f_m (MPa)*			*Compr. Str. – f_m (MPa)*			*Compr. Str. – f_m (MPa)*		
	6.93	1.02	23	NA	NA	NA	4.02	0.65	2	NA	NA	NA
	Masonry Quality Index			**Shear-Compr. Test**			**Diag. Compr- Test**					
	Shear Mod. – G (MPa)			*Shear Mod. – G (MPa)*			*Shear Mod. – G (MPa)*					
	801.50	78.02	23	NA	NA	NA	NA	NA	NA			
	Shear Str. – τ_0 (MPa)			*Shear Str. – τ_0 (MPa)*			*Shear Str. – τ_0 (MPa)*					
	0.115	0.014	23	NA	NA	NA	NA	NA	NA			

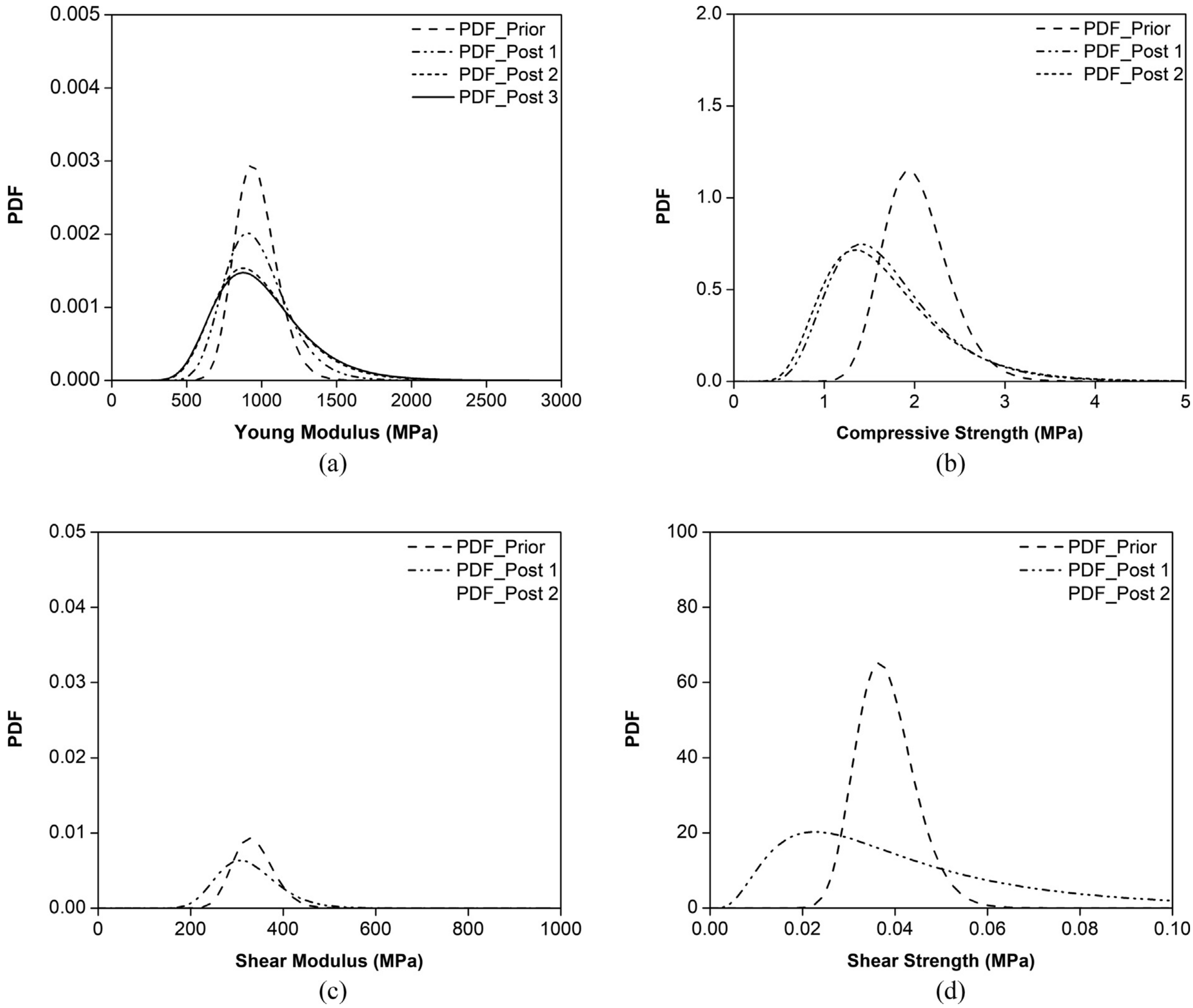

Fig. 11. Probability Density Function (PDF) updated values Portuguese masonry panels Young modulus (a), Compression strength (b), Shear modulus (c), Shear strength (d).

additionally presented, which can help to further reduce uncertainties affecting the estimation of material properties when a significant amount of data is available and, consequently, a high *Knowledge Level* is achieved. The modified equation reads:

$$S_{1\_mod} = \frac{S_0}{CF} + \frac{(n-1)\cdot s^2}{CF} + \frac{n_0 \cdot n}{n_0 + n} \cdot (x - \mu_0)^2 \quad (18)$$

The application of *Confidence Factors* (CF) included in equation (18) results in a reduction of the standard deviation obtained once the data fusion updating procedure is concluded. According to Eurocode and Italian standards [3,6], each *Knowledge Level* (KL) corresponds to a specific *Confidence Factor* (CF), namely CF = 1.35, CF = 1.20, CF = 1 for KL1, KL2, and KL3 respectively.

Inadequate knowledge of the building to be assessed causes a reduction of the mechanical parameters provided as reference values in the code; therefore, the lower is the KL, the higher the CF will be (e.g. values of mechanical parameters estimated in a KL1 scenario must be divided by a CF = 1.35). Conversely, in this study based on the flowcharts proposed in Fig. 7 and Fig. 8, high KLs correspond to high CFs (e.g. the standard deviation related to data gathered through a significantly reliable testing procedure, in a KL3 scenario, will be lower, divided by a CF = 1.35).

As an example, Table 19 reports a comparison between the results of the Bayesian procedure, related to the Young Modulus update for Masonry Type 1, carried out using equation (14) and (18), respectively.

5. Final remarks

A systematic review of experimental (in situ and laboratory) tests is herein presented, aiming at the definition of a database of mechanical properties of two-leaf stone masonry panels. Five electronic indexing databases have been accessed, namely Scopus, Science Direct, Web of Knowledge, Civil Engineering Database (ASCE), and MADA RELUIS Database [30], collecting data concerning the estimation of the following reference mechanical properties: (1) Young's modulus, (2) compression strength, (3) shear modulus, and (4) shear strength.

Additionally, six different stone masonry types, recurring in traditional constructions, have been identified based on the recommendation provided by Eurocode [3] and Italian standards [28].

Data from non-destructive (sonic tests), minor-destructive (flat-jacks tests), and destructive testing procedures (compression, shear-compression and diagonal-compression tests) have been considered as a source of information. Once the database was completed, the information gathered has been used to carry out an updating procedure based on Bayesian inference.

The procedure complies with the latest recommendation of technical guidelines and it is intended to simulate a scenario in

Table 17
Bayesian update results versus Eurocode [47] and Italian standards [26].

		Young Mod. – E (MPa)	*Comp. Str. – f_m (MPa)*	*Shear Mod. – G (MPa)*	*Shear Str. – τ_0 (MPa)*
MT1	**Eurocode 8** [3,55]	900	1.10–1.90	300	0.03–0.055
	NTC 2018 [28]	690–1050	1.00–2.00	230–350	0.018–0.032
	Bayesian Update_ALL	1004 (376)	1.92 (0.68)	293 (117)	0.051 (0.045)
		634–1386	1.24–2.60	176–410	0.006 – 0.096
	Bayesian Update_POR	955 (289)	1.63 (0.65)	326 (66)	0.046 (0.036)
		677–1255	0.98–2.28	260–392	0.004 – 0.082
	Bayesian Update_ITA	1054 (213)	2.23 (0.56)	334 (90)	0.053 (0.039)
		845–1271	1.67 – 2.79	244–424	0.014 – 0.092
MT2	**Eurocode 8**	1200	2.00–3.00	400	0.05–0.08
	NTC 2018	1020–1440	2	340–480	0.035–0.051
	Bayesian Update_ALL	1304 (383)	2.49 (0.74)	371 (97)	0.066 (0.051)
		930–1694	1.75–3.23	274–468	0.015–0.117
	Bayesian Update_POR	1105 (310)	2.06 (0.78)	384 (36)	0.077 (0.066)
		815–1445	1.28 – 2.84	348–420	0.011–0.143
	Bayesian Update_ITA	1300 (268)	2.70 (0.44)	371 (95)	0.070 (0.055)
		1042–1576	2.26 – 3.14	276–466	0.015 – 0.125
MT3	**Eurocode 8**	1700	2.60–3.80	600	0.08–0.11
	NTC 2018	1500–1980	2.60–3.80	500–660	0.056–0.074
	Bayesian Update_ALL	1955 (480)	4.03 (1.38)	533 (128)	0.089 (0.054)
		1490–2448	2.65 – 5.41	405–661	0.035–0.14
	Bayesian Update_POR	1963 (392)	3.98 (1.43)	Not Available	Not Available
		1631–2397	2.55–5.41		
	Bayesian Update_ITA	1830 (342)	4.02 (1.26)	521 (122)	0.076 (0.036)
		1448–2172	2.76–5.28	399–643	0.037–0.112
MT4	**Eurocode 8**	1100	1.40–2.20	400	0.05–0.06
	NTC 2018	900–1260	1.40–2.20	300–420	0.028–0.042
	Bayesian Update_ALL	1106 (231)	2.53 (0.83)	412 (42)	0.05 (0.006)
		875–1337	1.70 – 3.36	370–454	0.044–0.056
	Bayesian Update_POR	Not Available	Not Available	Not Available	Not Available
	Bayesian Update_ITA	1106 (231)	2.53 (0.83)	412 (42)	0.05 (0.006)
		875–1337	1.70 – 3.36	370–454	0.044–0.056
MT5	**Eurocode 8**	1400	2.00–3.20	500	0.10–0.19
	NTC 2018	1200–1620	2.00–3.20	400–500	0.09–0.12
	Bayesian Update_ALL	1478 (185)	3.17 (0.88)	490 (72)	0.088 (0.061)
		1293–1663	2.29–4.05	418–562	0.027–0.149
	Bayesian Update_POR	Not Available	Not Available	Not Available	Not Available
	Bayesian Update_ITA	1474 (174)	3.19 (0.85)	483 (68)	0.088 (0.062)
		1300–1648	2.34–4.04	415–551	0.026–0.15
MT6	**Eurocode 8**	2800	6.00–8.00	900	0.19–0.25
	NTC 2018	2400–3200	5.00–8.00	800–1100	0.09–0.12
	Bayesian Update_ALL	2692 (910)	6.61 (1.72)	799 (71)	0.121 (0.027)
		1865–3663	4.89–8.33	728–870	0.094–0.148
	Bayesian Update_POR	2485 (447)	6.70 (1.25)	799 (71)	0.121 (0.027)
		2152–3064	5.45–7.95	728–870	0.094–0.148
	Bayesian Update_ITA	2421 (344)	5.57 (1.58)	820 (79)	0.14 (0.04)
		2077–2765	3.99–7.15	741–899	0.10–0.144

which raw information related to the assessment of existing masonry buildings is progressively refined when new experimental evidence is available. Three different updates have been carried out using (1) the whole dataset, (2) only the data related to Italian experimental campaigns, and (3) only the data related to Portuguese experimental campaigns.

The comparison between updated results (Bayesian data fusion outcomes) and values provided in the codes (Eurocode and Italian standards) showed good consistency in all the reference mechanical parameters selected for each masonry type.

Overall, the standard deviation characterizing the experimental results experienced a reduction once the data fusion process was concluded but, at the same time, updated mean values have been found slightly higher than the mean values suggested by the codes.

This can be explained, on one hand, taking into account the homogeneity of the data sample, which affects the estimation of standard deviation and, on the other considering that the overall quality of the tested masonry panels can yield to an overestimation of their mechanical properties, especially if these results are compared to the values suggested in [3] and [28], which refer to low-quality masonry panels.

The outcomes of the applied data fusion procedure represent a valuable contribution in complementing the existing literature with an updated range of values potentially applicable in practice-oriented engineering activities, both in a general European context and in more specific geographical areas (Portugal and Italy).

Moreover, it must not be overlooked that the proposed values can be used, on one hand, as a reference mechanical parameter and on the other, they can be considered as a starting point of an ongoing process consisting in further updating a specific mechanical parameter if new experimental observations are available.

In conclusion, this study presents a methodology to update a set of selected mechanical properties of two-leaf stone masonry walls, by means of Bayesian inference. The proposed methodology is consistent with the guidelines provided by the Eurocode and Italian standards concerning the assessment of existing buildings. Although this work exclusively addresses two-leaf stone masonry walls, nevertheless the proposed methodology is highly versatile and applicable to others masonry types and to any kind of building regardless of its construction system.

Table 18
Bayesian update results versus Italian Research Council recommendations [5].

		Young Mod. – E (MPa)	Comp. Str. – f_m (MPa)	Shear Mod. – G (MPa)	Shear Str. – τ_0 (MPa)
MT1	**CNR-DT 212/2013** [5]	870 (σ_{ln} = 0.21)	1.40 (σ_{ln} = 0.29)	290 (σ_{ln} = 0.21)	0.026 (σ_{ln} = 0.24)
	Bayesian Update_ALL	1004 (376) (σ_{ln} = 0.36)	1.92 (0.68) (σ_{ln} = 0.34)	293 (117) (σ_{ln} = 0.38)	0.051 (0.045) (σ_{ln} = 0.72)
	Bayesian Update_POR	955 (289) (σ_{ln} = 0.30)	1.63 (0.65) (σ_{ln} = 0.39)	326 (66) (σ_{ln} = 0.20)	0.046 (0.036) (σ_{ln} = 0.69)
	Bayesian Update_ITA	1054 (213) (σ_{ln} = 0.20)	2.23 (0.56) (σ_{ln} = 0.25)	334 (90) (σ_{ln} = 0.27)	0.053 (0.039) (σ_{ln} = 0.66)
MT2	**CNR-DT 2012/2013**	1230 (σ_{ln} = 0.17)	2.50 (σ_{ln} = 0.20)	410 (σ_{ln} = 0.17)	0.043 (σ_{ln} = 0.19)
	Bayesian Update_ALL	1304 (383) (σ_{ln} = 0.29)	2.49 (0.74) (σ_{ln} = 0.26)	371 (97) (σ_{ln} = 0.26)	0.066 (0.051) (σ_{ln} = 0.68)
	Bayesian Update_POR	1105 (310) (σ_{ln} = 0.28)	2.06 (0.78) (σ_{ln} = 0.37)	384 (36) (σ_{ln} = 0.09)	0.077 (0.066) (σ_{ln} = 0.55)
	Bayesian Update_ITA	1300 (268) (σ_{ln} = 0.20)	2.70 (0.44) (σ_{ln} = 0.16)	371 (95) (σ_{ln} = 0.25)	0.070 (0.055) (σ_{ln} = 0.69)
MT3	**CNR-DT 2012/2013**	1740 (σ_{ln} = 0.14)	3.20 (σ_{ln} = 0.19)	580 (σ_{ln} = 0.14)	0.065 (σ_{ln} = 0.14)
	Bayesian Update_ALL	1955 (480) (σ_{ln} = 0.24)	4.03 (1.38) (σ_{ln} = 0.33)	533 (128) (σ_{ln} = 0.24)	0.089 (0.054) (σ_{ln} = 0.56)
	Bayesian Update_POR	1963 (392) (σ_{ln} = 0.20)	3.98 (1.43) (σ_{ln} = 0.35)	Not Available	Not Available
	Bayesian Update_ITA	1830 (342) (σ_{ln} = 0.19)	4.02 (1.26) (σ_{ln} = 0.31)	521 (122) (σ_{ln} = 0.23)	0.076 (0.036) (σ_{ln} = 0.45)
MT4	**CNR-DT 2012/2013**	1080 (σ_{ln} = 0.17)	1.90 (σ_{ln} = 0.27)	360 (σ_{ln} = 0.17)	0.035 (σ_{ln} = 0.20)
	Bayesian Update_ALL	1106 (231) (σ_{ln} = 0.21)	2.53 (0.83) (σ_{ln} = 0.32)	412 (42) (σ_{ln} = 0.10)	0.05 (0.006) (σ_{ln} = 0.12)
	Bayesian Update_POR	Not Available	Not Available	Not Available	Not Available
	Bayesian Update_ITA	1106 (231) (σ_{ln} = 0.21)	2.53 (0.83) (σ_{ln} = 0.32)	412 (42) (σ_{ln} = 0.10)	0.05 (0.006) (σ_{ln} = 0.12)
MT5	**CNR-DT 2012/2013**	1080 (σ_{ln} = 0.17)	1.90 (σ_{ln} = 0.27)	360 (σ_{ln} = 0.17)	0.035 (σ_{ln} = 0.20)
	Bayesian Update_ALL	1478 (185) (σ_{ln} = 0.12)	3.17 (0.88) (σ_{ln} = 0.27)	490 (72) (σ_{ln} = 0.15)	0.088 (0.061) (σ_{ln} = 0.39)
	Bayesian Update_POR	Not Available	Not Available	Not Available	Not Available
	Bayesian Update_ITA	1474 (174) (σ_{ln} = 0.12)	3.19 (0.85) (σ_{ln} = 0.26)	483 (68) (σ_{ln} = 0.14)	0.088 (0.062) (σ_{ln} = 0.40)
MT6	**CNR-DT 2012/2013**	2800 (σ_{ln} = 0.14)	7.00 (σ_{ln} = 0.14)	860 (σ_{ln} = 0.09)	0.105 (σ_{ln} = 0.14)
	Bayesian Update_ALL	2692 (910) (σ_{ln} = 0.33)	6.61 (1.72) (σ_{ln} = 0.26)	799 (71) (σ_{ln} = 0.09)	0.121 (0.027) (σ_{ln} = 0.22)
	Bayesian Update_POR	2485 (447) (σ_{ln} = 0.18)	6.70 (1.25) (σ_{ln} = 0.18)	Not Available	0.121 (0.027) (σ_{ln} = 0.22)
	Bayesian Update_ITA	2421 (344) (σ_{ln} = 0.14)	5.57 (1.58) (σ_{ln} = 0.28)	820 (79) (σ_{ln} = 0.10)	0.14 (0.04) (σ_{ln} = 0.29)

Table 19
Bayesian update Young Modulus Masonry Type 1 excluding Confidence Factors (Eq. (14)) and including Confidence Factor (q. 18).

	Young Modulus – E (MPa) – Masonry Type 1					
	Update 1 – KL1		**Update 2 – KL2**		**Update 3 – KL3**	
	Mean	**St. Dev.**	**Mean**	**St. Dev.**	**Mean**	**St. Dev.**
Eq. (14)	1020	208	1030	361	1004	376
Eq. (18)	1020	208	1030	329	1004	327

The methodology presented in this work can represent a valuable tool for professionals involved in practice-oriented engineering activities addressing the estimation of mechanical parameters using different types of experimental data.

CRediT authorship contribution statement

Antonio Murano: Conceptualization, Methodology, Formal analysis, Data curation, Writing - original draft. **Javier Ortega:** Conceptualization, Supervision. **Hugo Rodrigues:** Conceptualization, Supervision. **Graça Vasconcelos:** Conceptualization, Supervision.

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.

Acknowledgements

This work was partly financed by FCT/MCTES through national funds (PIDDAC) under the R&D Unit Institute for Sustainability and Innovation in Structural Engineering (ISISE), under reference UIDB/04029/2020.

This work is financed by national funds through FCT – Foundation for Science and Technology, under grant agreement SFRH/BD/147708/2019 attributed to the 1st author.

References

[1] K.-H. Chang, Computer-Aided Engineering Design, Academic Press - Elsevier, 2015.
[2] S. Cattari, S. Lagomarsino, V. Bosiljkov, D. D'Ayala, Sensitivity analysis for setting up the investigation protocol and defining proper confidence factors for masonry buildings, Bull. Earthq. Eng. 13 (1) (2015) 129–151, https://doi.org/10.1007/s10518-014-9648-3.
[3] European Committee for Standadization (CEN), Eurocode 8: Design of structures for earthquake resistance - Part 3: Assessment and retrofitting of buildings, vol. 3. Brussels: European Committee for Standadization, 2005.
[4] MIT, Norme Tecniche per le costruzioni (NTC 2008). Rome: Ministero delle Infrastrutture e dei Trasporti, 2008.
[5] A. committee on technical recommendations for Constructions, Guide for the Probabilistic Assessment of the Seismic Safety of Existing Buildings. Rome: National Research Council of Italy (CNR), 2014.
[6] MIT, Norme tecniche per le costruzioni (NTC 2018). Rome: Ministero delle Infrastrutture e dei Trasporti (MIT), 2018.
[7] M. A. Turkman Amaral, C. D. Paulino, and P. Muller, Computational Bayesian Statistics. An Introduction. Cambridge, UK: Cambridge University Press, 2019.
[8] A. German, J. Carlin, H. Stern, D. Rubin, *Bayesian Data Analysis*, Second Edi., Chapman & Hall/CRC, Boca Raton (USA), 2003.
[9] L. Held, D. Sabanés Bové (Eds.), Applied Statistical Inference, Springer Berlin Heidelberg, Berlin, Heidelberg, 2014.
[10] J.L. Beck, L.S. Katafygiotis, Updating models and their uncertainties: Bayesian statistical framework, J. Eng. Mech. 124 (1998) 455–461.
[11] C. Papadimitriou, J.L. Beck, L.S. Katafygiotis, Updating robust reliability using structural test data, Probabilistic Eng. Mech. 16 (2) (2001) 103–113.
[12] J.P. Conte, R. Astroza, H. Ebrahimian, G. Feltrin, Bayesian methods for nonlinear system identification of civil structures, MATEC Web Conf. 24 (2015) 03002, https://doi.org/10.1051/matecconf/20152403002.
[13] G. Bartoli, M. Betti, A. Vignoli, A numerical study on seismic risk assessment of historic masonry towers: a case study in San Gimignano, Bull. Earthq. Eng. 14 (6) (2016) 1475–1518, https://doi.org/10.1007/s10518-016-9892-9.
[14] G. Bartoli, M. Betti, L. Facchini, A.M. Marra, S. Monchetti, Bayesian model updating of historic masonry towers through dynamic experimental data,

Procedia Eng. 199 (2017) 1258–1263, https://doi.org/10.1016/j.proeng.2017.09.267.
[15] G. Bartoli, M. Betti, A.M. Marra, S. Monchetti, A Bayesian model updating framework for robust seismic fragility analysis of non-isolated historic masonry towers, Philos. Trans. A 377 (2155) (2019) 20190024, https://doi.org/10.1098/rsta.2019.0024.
[16] P. Gardoni, A. Der Kiureghian, K.M. Mosalam, Probabilistic capacity models and fragility estimates for reinforced concrete columns based on experimental observations, J. Eng. Mech. 1 (2002) 1024–1038.
[17] G. Monti, S. Alessandri, Application of Bayesian techniques to material strength evaluation and calibration of confidence factors, in: E. Cosenza (Ed.), Eurocode 8: Perspective from the Italian Standpoint Workshop, Doppiavoce, Naples (ITA), 2009, pp. 53–65.
[18] F. Jalayer, I. Iervolino, G. Manfredi, Structural modeling uncertainties and their influence on seismic assessment of existing RC structures, Struct. Saf. 32 (3) (2010) 220–228, https://doi.org/10.1016/j.strusafe.2010.02.004.
[19] X. Romao, R. Gonçalves, A. Costa, and R. Delgado, "Evaluation of the EC8-3 confidence factors for the characterization of concrete strength in existing structures," Mater. Struct., vol. 45, no. 11, 2012, doi: 10.1617/s11527-012-9868-4.
[20] M. Tondelli, M. Rota, A. Penna, G. Magenes, Evaluation of uncertainties in the seismic assessment of existing masonry buildings, J. Earthq. Eng. 16 (sup1) (2012) 36–64, https://doi.org/10.1080/13632469.2012.670578.
[21] P. Croce and F. Marsili, "Bayesian strategies for the reliability assessment of heritage structures," in Structural Studies, Repairs and Maintenance of Heritage Architecture XIV, 2015, no. May 2016, pp. 221–232, doi: 10.2495/STR150191.
[22] G.P. Campostrini, S. Taffarel, G. Bettiol, M.R. Valluzzi, F. Da Porto, C. Modena, A Bayesian approach to rapid seismic vulnerability assessment at urban scale, Int. J. Archit. Herit. 12 (1) (2017) 36–46, https://doi.org/10.1080/15583058.2017.1370506.
[23] M.L. Beconcini, P. Croce, F. Marsili, M. Muzzi, E. Rosso, Probabilistic reliability assessment of a heritage structure under horizontal loads, Probabilistic Eng. Mech. 45 (2016) 198–211, https://doi.org/10.1016/j.probengmech.2016.01.001.
[24] B. Conde, P. Eguía, G.E. Stavroulakis, E. Granada, Parameter identification for damaged condition investigation on masonry arch bridges using a Bayesian approach, Eng. Struct. 172 (2018) 275–284, https://doi.org/10.1016/j.engstruct.2018.06.040.
[25] T. Miranda, A. Gomes Correia, L. Sousa Ribeiro, Bayesian methodology for updating geomechanical parameters and uncertainty quantification, Int. J. Rock Mech. Min. Sci. 46 (7) (2009) 1144–1153, https://doi.org/10.1016/j.ijrmms.2009.03.008.
[26] L.F. Ramos, T. Miranda, M. Mishra, F.M. Fernandes, E. Manning, A Bayesian approach for NDT data fusion: The Saint Torcato church case study, Eng. Struct. 84 (2015) 120–129, https://doi.org/10.1016/j.engstruct.2014.11.015.
[27] L. Binda, G. Cardani, and A. Saisi, "A classification of structures and masonries for the adequate choice of repair," in International RILEM Workshop on Repair Mortars for Historic Masonry, 2005, pp. 20–34, [Online]. Available: http://www.rilem.net/images/publis/pro067-003.pdf.
[28] MIT, Circolare 21/01/2019. Rom: Ministero delle Infrastrutture e dei Trasporti (MIT), 2019.
[29] M. Como, Statics of Historic Masonry Constructions, Springer, Rome (Italy), 2015.
[30] N. Augenti, F. Parisi, and E. Acconcia, "MADA: Online experimental database for mechanical modelling of existing masonry assemblages," 2012.
[31] A. Borri, M. Corradi, G. Castori, A. De Maria, A method for the analysis and classification of historic masonry, Bull. Earthq. Eng. 13 (9) (2015) 2647–2665, https://doi.org/10.1007/s10518-015-9731-4.
[32] A. Borri, A. De Maria, Indice di Qualità Muraria (IQM): correlazione con le caratteristiche meccaniche e livelli di conoscenza, Progett. Sismica 6 (3) (2015) 45–63, https://doi.org/10.7414/PS.6.3.45-63.
[33] Vv.Aa, Manuale delle Murature Storiche - Volume 1. Rome: DEI - Tipografia del Genio Civile, 2011.
[34] L.F. Miranda, J. Rio, J. Miranda Guedes, A. Costa, Sonic impact method – A new technique for characterization of stone masonry walls, Constr. Build. Mater. 36 (2012) 27–35, https://doi.org/10.1016/j.conbuildmat.2012.04.018.
[35] L. Miranda, L. Cantini, J. Guedes, L. Binda, and A. Costa, "Applications of sonic tests to masonry elements : Influence of joints on the propagation velocity of elastic waves," J. Mater. Civ. Eng., no. June, pp. 667–682, 2013, doi: 10.1061/(ASCE)MT.1943-5533.0000547.
[36] L. Binda, A. Saisi, C. Tiraboschi, S. Valle, C. Colla, M. Forde, Application of sonic and radar tests on the piers and walls of the Cathedral of Noto, Constr. Build. Mater. 17 (8) (2003) 613–627, https://doi.org/10.1016/S0950-0618(03)00056-4.
[37] L. Binda, M. Lualdi, A. Saisi, Investigation strategies for the diagnosis of historic structures: On-site tests on Avio Castle, Italy, and Pišece Castle, Slovenia, Can. J. Civ. Eng. 35 (6) (2008) 555–566, https://doi.org/10.1139/L07-143.
[38] M.R. Valluzzi, E. Cescatti, G. Cardani, L. Cantini, L. Zanzi, C. Colla, F. Casarin, Calibration of sonic pulse velocity tests for detection of variable conditions in masonry walls, Constr. Build. Mater. 192 (2018) 272–286, https://doi.org/10.1016/j.conbuildmat.2018.10.073.
[39] P. Gregorczyk, P. Lourenço, A Review on Flat-Jack Testing, Eng. Civ. - Univ. Minho 9 (2000) 39–50.
[40] ASTM, "In-situ measurement of masonry deformability properties using flat-jack method." ASTM Standard C 1197-91, 1991.
[41] ASTM, "In-situ compressive stress within solid unit masonry estimated using flat-jack measurements." ASTM Standard C 1196-91, 1991.
[42] RILEM, "In-situ Stress Tests based on the Flat-Jack." RILEM, Bagneux, France, 2004.
[43] L. Binda, C. Tiraboschi, G. Baronio, On-site investigation on the remains of the Cathedral of Noto, Constr. Build. Mater. 17 (8) (2003) 543–555, https://doi.org/10.1016/S0950-0618(03)00057-6.
[44] J. Roque Almendra, P. Lourenço, Caracterização Mecânica de Paredes Antigas de Alvenaria. Um Caso de Estudo no Centro Histórico de Bragança, Eng. Civ. – Univ. Minho 17 (2003) 31–42.
[45] P. Croce, M.L. Beconcini, P. Formichi, P. Cioni, F. Landi, C. Mochi, F. De Lellis, E. Mariotti, I. Serra, Shear modulus of masonry walls: A critical review, Procedia Struct. Integr. 11 (2018) 339–346, https://doi.org/10.1016/j.prostr.2018.11.044.
[46] S. Moreira, "Seismic retrofit of masonry-to-timber connections in historical constructions Susana Maria Trindade Moreira Seismic retrofit of masonry-to-timber connections in historical constructions," University of Minho, Guimaraes (Portugal), 2015.
[47] G. Vasconcelos, P.B. Lourenço, Experimental characterization of stone masonry in shear and compression, Constr. Build. Mater. 23 (11) (2009) 3337–3345, https://doi.org/10.1016/j.conbuildmat.2009.06.045.
[48] "ASTM E519-02, Standard Test Method for Diagonal Tension (Shear) in Masonry Assemblages," West Conshohocken, PA, 2002.
[49] P. F. Sheppard, "In situ test of the shear strength and deformability of an 18th century stone and brick masonry wall," in Proceedings 7th International Brick Masonry Conference, 1985, pp. 149–160.
[50] V. Turnsek and F. Cacovic, "Some experimental results on the strength of brick masonry walls," in Proceedings of the 2nd International Brick Masonry Conference, 1971, pp. 149–156.
[51] D. Montgomery, G. Runger, Applied Statistics and Probability for Engineers, Sixth Edit., Wiley, Hoboken, New Jersey (USA), 2014.
[52] Y. Z. Totoev and J. M. Nichols, "A Comparative Experimental Study of the Modulus of Elasticity of Bricks and Masonry," in 11th International Brick/Block Masonry Conference, 1997, no. October, pp. 14–16.
[53] N. Makoond, L. Pelà, C. Molins, Dynamic elastic properties of brick masonry constituents, Constr. Build. Mater. 199 (2019) 756–770, https://doi.org/10.1016/j.conbuildmat.2018.12.071.
[54] Nirvan Makoond, Albert Cabané, Luca Pelà, Climent Molins, Relationship between the static and dynamic elastic modulus of brick masonry constituents, Constr. Build. Mater. 259 (2020) 120386, https://doi.org/10.1016/j.conbuildmat.2020.120386.
[55] P. Candeias, A. Correia, A. Campos Costa, J.M. Catarino, M. Pipa, H. Cruz, E. Carvalho Cansado, A. Costa, General aspects of the application in Portugal of Eurocode 8 – Part 3 – Annex C (Informative) – Masonry Buildings, Rev. Port. Eng. Estruturas 12 (3) (2020) 99–120.